

# Non-Conventional ENERGY Resources

Second Edition

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## Preface

Energy has become an important and one of the basic infrastructures for economic development of a country. Energy security is, therefore, imperative for sustained growth of economy. The oil crisis of 1973 and concern for environment due to excessive use of fossil fuels have led to remarkable global efforts in harnessing alternative energy resources. The renewable energy resources such as the sun, wind, biomass and geothermal heat are environment friendly and perennial in nature. These resources are also referred as non-conventional energy resources as, at present, their large-scale use is not common. Harnessing of energy through these resources using efficient technologies is expected to play an important role in serving as clean energy sources for mankind. Thus, processes to harness these are steadily gaining technical and economic importance worldwide. Most governments have substantial plans directed towards encouraging these technologies in order to develop them commercially. As we had hoped and wished initially, the development of these technologies have not been dramatic. They have yet to achieve the cost-benefit ratio possible with conventional fuels and are not likely to replace fossil fuels in the near future. Nevertheless, they have come to play a very important supportive role in addition to conventional sources. Therefore, it is necessary for energy planners / users to know the virtues as well as limitations of these technologies. The present book is an effort to explore these technologies in a balanced perspective.

Being a relatively recent field, the subject matter is scattered in specialized research journals and a few books of advanced levels are devoted exclusively to a particular technology. There is, however, scarcity of publications that introduce all these technologies in a single volume to a beginner. Therefore, a natural consequence of the current volume will be a much-needed and relatively inexpensive textbook at an undergraduate level. While teaching a course on non-conventional energy to undergraduate engineering students, the author himself felt this need, which encouraged him to write the present book.

Human-resource development in the area of energy, in general, and in new and renewable sources of energy, in particular, has been neglected all over the world, and more so in developing countries. Therefore, the book is primarily intended to serve as textbook for undergraduate-level courses for engineering and science students. It stresses scientific understanding, analysis and applications of non-conventional energy technologies. Many practicing engineers and scientists may not have a formal exposure to this area and may be interested to have a general training of these technologies. Therefore, the book is oriented to cover both basic study and its widespread applications. It describes the fundamental physical processes governing various non-conventional energy technologies and their applications. The book may also serve to create awareness among energy planners, policy makers and users at large about these technologies in general. Because of the spread of disciplines involved, it is not possible to discuss each of them exhaustively in a single book. Therefore, only relevant background up to a depth essential to understand the basic principles has been included.

In recent years, the harmful effects of global warming due to heavy dependence on fossil fuels are becoming more and more visible. The manifestations of global warming are appearing much earlier and much more widespread than initially expected. This has forced the global community to initiate corrective steps to check this trend. The need of developing clean, sustainable and secure energy resources is being increasingly realized. Also, the cost of fossil fuels, especially oil, is ever increasing. This has become evident that



Preface

the era of cheap and secure availability of oil is over. The economic growth cannot be sustained until reliable energy is made available at a reasonable cost.

Due to the above-mentioned developments, attention is being focused to develop and utilize renewable and non-conventional energy sources which have been largely neglected so far due to uninhibited and cheap availability of oil. As a result, extensive R & D efforts are going on towards the development of these resources and related technologies. Consequently, the knowledge related to developments in these technologies needs frequent updating. Therefore, a need was felt to bring a thoroughly revised, expedited and updated second edition of the present book.

The contents are covered in fourteen chapters. A brief review of both conventional and non-conventional energy sources highlighting the importance of non-conventional energy sources is included in Chapter 1. The concepts of energy storage and energy conservation are introduced early in the text in chapters 2 and 3 respectively. The general background of these concepts is helpful to understand these technologies and to integrate them in energy systems. The topic of solar energy is divided into three subsequent chapters. Chapter 4 covers the basics of solar energy while chapters 5 and 6 respectively cover solar thermal and solar PV systems. Chapter 7 covers wind-energy technology. The required background of fluid mechanics is also included in this chapter. Biomass energy again requires knowledge of organic chemistry and biology of the senior secondary level. The required background is also included in Chapter 8, related to biomass energy. Chapter 9 is devoted to geothermal energy, which is important only in fairly limited geographical areas. Energy resources available in the ocean, i.e., tidal, wave and ocean thermal are covered in Chapter 10. Small hydro resources are explained in Chapter 11. Emerging technologies such as fuel cell, hydrogen energy and micro hydro resources are covered in Chapter 12. Some miscellaneous technologies such as MHD, thermoelectric and thermionic are covered in Chapter 13. Finally, financial and economic calculations are explained in Chapter 14.

Useful review questions including numerical problems, wherever feasible, are also included at the end of each chapter. The answers to numerical problems are also provided. Some important units and their interrelations are given in the appendices. Useful websites covering information on supplementary material, ongoing major projects and recent updated data on the subject are also listed.

For each of the technologies covered, the following salient features are included:

- Historical background
  - Preliminary estimate and its geographical variation
  - Basic principle of energy conversion
  - System of conversion
  - Current status
  - Environmental impacts
- In the first edition (published in 2006), basic principles, system of conversion, current status and environmental effects were covered. In the second edition, the subject matter is expanded by about 34% through the inclusion of some new topics and by modifying / updating the existing material, based on feedbacks received from the readers. Some of the modifications made in the second edition are as follows:
- All chapters are thoroughly revised, expanded and data were updated to current level of developments.
  - Two new chapters are added: *Small Hydro Resources* and *Financial and Economic Evaluation*, making a total of fourteen chapters.
  - A new section on basic thermodynamics is added in Chapter 1.
  - At the end of each chapter, numerous objective-type questions (totaling 210) are included. The answer keys are given in Appendix D.
  - More than 250 review questions including those from various university examinations are included.
  - A large number of solved examples and practice problems are included.

The book deliberately contains more material than could be covered in a one-semester course. This enables the instructor to design a one-semester course including topics of his choice depending on the particular energy supplies, which are more important in his situation. Alternatively, two courses, each of one-semester duration, may be planned with broad divisions such as chapters 1–5 and Chapter 7 in the first course, and Chapter 6 and chapters 8–14 in the second course with minor adjustments.

The contents of the book have been class tested for a two-semester (one year) course offered to final-year BTech students at AMU, Aligarh. In fact the book, in its present form, is the outcome of teaching of a course 'Non-Conventional Energy Sources' for many years by the author. As a result, it has undergone extensive screening and has been revised wherever found necessary.

The web supplements for this book can be accessed at <http://www.mhhe.com/khan/ncc2e> and contain PowerPoint slides for instructors. The website also contains web links for additional reading and interactive objective questions for students.

The author had useful discussions with many individuals from different areas of specialization during the course of preparation of this book. Their cooperation is gratefully acknowledged. The author would also like to thank the following reviewers for taking out time to review the book.

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Thanks are due to my students who used the early versions of the manuscript in their course and provided valuable feedback. The author also thanks his family members for their cooperation, understanding and patience.

It is highly gratifying that the first edition of the book has been well received and appreciated. I hope the readers will welcome the second edition too and benefit from the changes made. Any suggestions/ feedbacks in the direction of further improvement in the book will be highly appreciated. In spite of best efforts, some errors might have still remained in the text. I welcome the suggestions and comments, if any, from all readers for further improvement of the book.

**B H Khan**

## VISUAL SUMMARY

Fundamentals of  
Energy—Science  
and Technology



Any physical activity in this world, whether carried out by human beings or by machines, requires energy. In order to move from one place to another, from one time to another, from one form to another, we must do work. The word "energy" is derived from the Greek word "en-ergeia", which means "work" or "work current". The source of energy depends on the energy level. The capability to do work depends on the amount of energy one can control and utilize. Energy is the most basic infrastructure upon which economic growth and development of a country.

An physical activity in this world, whatever carried out by human beings or machines can add to that, or will be used or the others need to do work. The word "energy" is derived from the Greek word "energeia", which means "work carried". The qualities to do work depend on the energy one can control and utilize. Energy is the most basic infrastructure for economic growth and development of a country.

Sections and subsections

Each chapter has been neatly divided into sections and subsections so that the subject matter is studied in a logical progression of ideas and concepts.

**Solution** Example A propeller-type wind turbine has the following data:  
Speed of free wind at a height of  $10 \text{ m} = 12 \text{ m/s}$

171

From given data,	$H = 10 \text{ m}$ ,	$\tau_c = 100 \text{ s}$
$\kappa_0 = 1.2 \text{ m/s}$ ,	$\pi = 0.34$	
$\sigma = 1.226 \text{ kg/m}^3$ ,		
$D = 80 \text{ m}$	$A_t = 5020.55 \text{ m}^2$	

$$H = 10 \text{ m}, \quad z_0 = 100 \text{ m}$$

## Worked Examples

Worked examples, totaling 51, are provided in sufficient number in each chapter and at appropriate locations, to aid in understanding of the text material.

In a typical cyclic plant, electric power is produced using two prime movers. The heat discharged from one heat exchanger can be used as the heat source for the other (i.e.,

**2.6 COMBINED CYCLE PLANTS** In a combined cycle plant, energy from one heat source is used to produce steam which drives a turbine. The heat discharged from one heat source is used as prime movers. The heat discharged from one heat source is used as prime movers. The heat discharged from one heat source is used as prime movers.

**4.12 Monthly Average Daily Diffusion Radiation**

Based on a study of data for a few countries, it has been found that the correlation is not linear throughout the day. A number of correlations have been developed. For Indian conditions, when the diffuse component is relatively larger, the monthly average daily diffusion radiation is found to predict diffused radiation with an accuracy of about 10 percent.

—

Srinivasan

**Introduction**

Each chapter begins with an introduction that includes a brief write up about the significance, historical background and content of the chapter.

**Illustrations**  
Illustrations are essential tools in a book of Engineering. Ample illustrations are provided in each chapter to demonstrate the concepts, functional relationships and definitions sketches for mathematical models.

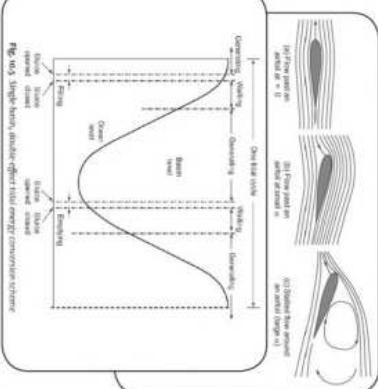


Fig. 6.32: No. of nodes required to obtain a given error.



Fig. 6.33

**Photographs**  
Photographs of important commercial systems are presented at appropriate locations.

4. What will be the amount of heat injected in an interest compounded annually at 10% for 10 years?  
**Solution:**
5. In an R-134a/air system, the effective density of air is  $1.1 \text{ kg/m}^3$ . What value of factor conversion is required to move the term/prefix close to  $\text{kg/m}^3$ ? (Ans: 0.407)
6. Calculate the optimum wavelength of light for photoelectric generation in a GaAs cell.  
**Solution:**
7. Calculate the open-circuit voltage of a silicon solar cell at  $41^\circ\text{C}$  if short circuit and reverse saturation currents are given as  $1 \text{ A}$  and  $10^{-6} \text{ A}$ , respectively.  
**Solution:**

## Practice Problems and Answers

Each chapter contains a set of practice problems, totaling 56 problems in the book. Solutions to these problems require not only the application of the material covered in the book but also enable the students to strive towards good comprehension of the subject matter. Answers are provided at the end of each problem.

### Objective-type Questions

Each chapter contains a set of objective-type questions, totalling 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) storing primary energy for future generations  
(b) storing secondary energy in an easily retrievable form

#### Objective-type Questions

1. Storage of biomass energy is  
(a) very difficult (b) relatively  
(c) expensive (d) impossible
2. Solar is predominantly  
(a) hydrogen (b) carbon monoxide  
(c) carbon dioxide (d) methane
3. Heating value of producer gas is  
(a) 4-6 MJ/m<sup>3</sup> (b) 14-18 MJ/m<sup>3</sup>  
(c) 16-18 MJ/m<sup>3</sup> (d) 34-38 MJ/m<sup>3</sup>
4. Relatively good producers  
(a) low tar and high particulates  
(b) high tar and low particulates  
(c) low exo-temperature  
(d) high exo-temperature

### Review Questions

Each chapter contains a set of review questions, totalling 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 do you explain energy conservation related with transient of energy?
2. For which type of heating is solar energy best suited?
3. What is the average range of solar insolation received on the earth's surface during a day?
4. What is the main advantage of a flat plate solar collector?
5. What are the main advantages of a flat plate solar collector?
6. Describe the flat plate collector with help of a suitable diagram.
7. What is the appropriate value of the concentration ratio obtained from a CPC collector?
8. What range of concentration can a parabolic dish collector attain?
9. What range of GHI is suitable from a central receiver receiver collector?
10. Discuss the principle of a solar collector how can collector change its heat transfer performance as a function of time?

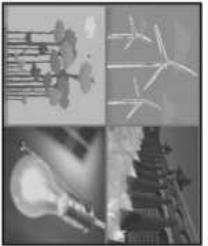
(PTU) JUNE/JULY 2009-09)

### 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://mines.india.in/>
2. <http://www.bhutanindia.com/>
3. <http://inspiration4kids.com/images/nonconventional/>
4. <http://www.tertiuscares.ca/>
5. <http://www.ramakrishna.org/>
6. <http://www.vocationalinstitute.com/efficiency/>
7. <http://www.vocationalinstitute.com/efficiency/renewable.html>
8. <http://www.vocationalinstitute.com/efficiency/renewable.html>
9. <http://www.vocationalinstitute.com/efficiency/renewable.html>
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# 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-ergeon', 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, Nikola 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.

### OIL CRISIS OF 1973

**1.2** 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.

### CLASSIFICATION OF ENERGY RESOURCES

**1.3** 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.



Non-conventional Energy Resources

#### 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

### CONSUMPTION TREND OF PRIMARY ENERGY RESOURCES

**1.4** 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.

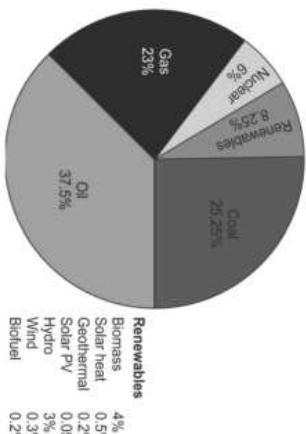


Fig. 1.1 Percentage consumption of various primary energy resources (year 2005 data)



### **IMPORTANCE OF NON-CONVENTIONAL ENERGY SOURCES**

**1.5** 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.

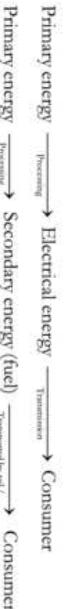
Realising the importance of non-conventional energy sources, in March 1981, the government of India established a Commission for Additional Sources of Energy (CASE) in the Department of Science and Technology, on the lines of the Space and Atomic Energy Commissions. In 1982, CASE was incorporated in 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.

### **ENERGY CHAIN**

**1.6** 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

## C<sub>6</sub> Non-conventional Energy Resources

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



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

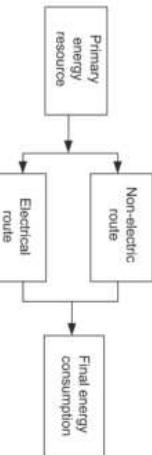


Fig. 1.2. Energy routes

## 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.



## ADVANTAGES AND DISADVANTAGES OF CONVENTIONAL ENERGY SOURCES

**1.8** 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  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{NO}_x$ ,  $\text{SO}_x$ , particulate matter and heat. These pollutants degrade the environment, pose health hazards and cause various other problems.  $\text{CO}_2$  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 possess the technology required to use nuclear energy.



## Non-conventional Energy Resources

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

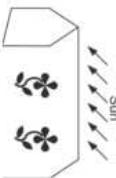
renewable and environment-friendly energy resources. To create public awareness about environment conservation, 5th June is observed as *World Environment Day*.

### 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>, other harmful gases include methane, nitrous oxide, hydrofluorocarbons, sulphur hexafluoride and water vapour. All these gases are known as greenhouse gases. The CO<sub>2</sub> 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<sub>2</sub> 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.

**(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.

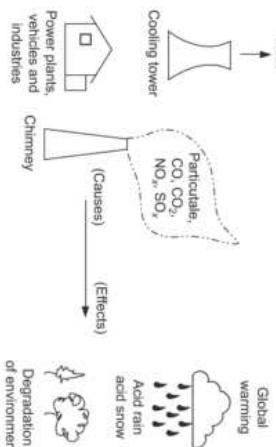
### 1.10.6 Various Pollutants and their Harmful Effects

#### i. Particulate Matter

The presence of particulate matter

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

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



**Fig. 1.4 Causes and effect of pollution**

2. **CO<sub>2</sub>** 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<sub>2</sub> adversely affects the global climate. Excess emission of CO<sub>2</sub> in the atmosphere causes global warming due to greenhouse effect.



Non-conventional Energy Resources

$\text{CO}_2$  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  $\text{CO}_2$  level is mainly due to

- large-scale combustion of fossil fuels in coal fired thermal power plants all over the world, and
- 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<sub>2</sub>** The presence of  $\text{SO}_2$  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%

$\text{SO}_2$  can further oxidize to form sulfur trioxide, which in turn forms sulphuric acid when absorbed in water.

#### Harmful Effects

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

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

**NO<sub>x</sub>** Oxides of nitrogen such as  $\text{N}_2\text{O}$ ,  $\text{NO}$ ,  $\text{NO}_2$ ,  $\text{NO}_3$ ,  $\text{N}_2\text{O}_3$ ,  $\text{N}_2\text{O}_5$  are commonly referred as  $\text{NO}_x$ . 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.  $\text{NO}_x$  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  $\mu\text{g}/\text{m}^3$ .

#### 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.

### **ENVIRONMENT-ECONOMY-ENERGY AND SUSTAINABLE DEVELOPMENT**

**1.11** 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  $\text{CO}_2$  emissions in developed countries but also at ultimately reducing man-made  $\text{CO}_2$  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

## C<sup>4</sup> Non-conventional Energy Resources

extraction) is affordable. Attempts to restrict the use of fossil fuels for environmental reasons are likely to have a negative impact on economic development and the overall availability of energy. Thus the 'three Es'—environment, energy, and economic development are closely interrelated in a complex manner.

The strategy for mitigating 'three Es' issues is a strategy for environmentally sustainable economic development. Herman Daly, a famous ecological economist, laid down three conditions for sustainability:

1. The consumption rate of renewable resources is not higher than its recovery rate.
2. The consumption rate of non-renewable resources is not higher than the rate of increase in renewable resource supply.
3. The emission of pollutants is within the absorption capacity of the environment.

Unfortunately, these conditions have been violated for years. Examples of respective violations typically include deforestation, the depletion of fossil fuels, and the increase in CO<sub>2</sub> concentration in the air. Such violations may be hard to reverse in the short term but, unless long-term remedial action is taken, present global development trends will not be sustainable. In particular, a substantial reduction in resource consumption and emissions of pollutants is essential for the development of a sustainable human society on this planet.

As evident from the above discussions, economy, environment and energy are closely interrelated and an overall policy is required to deal with them.

## 1.12 ENERGY DENSITIES (HEATING VALUES) OF VARIOUS FUELS

Table 1.2 Energy densities/heating values of various fuels

<i>Primary resource</i>	<i>Energy density</i>
Coal: Anthracite	32-34 MJ/kg
Bituminous	26-30 MJ/kg
Coke	29 MJ/kg
Brown coal; Lignite (old)	16-24 MJ/kg
Lignite (new)	10-14 MJ/kg
Peat	8-9 MJ/kg
Crude petroleum	45 MJ/kg
Petrol	51-52 MJ/kg
Diesel	45-46 MJ/kg
Natural gas	50 MJ/kg, (42 MJ/m <sup>3</sup> )
Methane (85% CH <sub>4</sub> )	45 MJ/kg, (38 MJ/m <sup>3</sup> )
Propane	50 MJ/kg, (45 MJ/m <sup>3</sup> )
Hydrogen	142 MJ/kg, (12 MJ/m <sup>3</sup> )

<i>Primary resource</i>	<i>Energy density</i>
Wood	10–11 MJ/kg
Natural uranium	0.26–0.3 × 106 MJ/kg
Enriched uranium	2.6–3.0 × 106 MJ/kg
U233	83 × 106 MJ/kg
U235	82 × 106 MJ/kg
Pu239	81 × 106 MJ/kg

## 1.13

### WORLD ENERGY STATUS

#### 1.13.1 Present Situation

At present (year 2008) the annual primary energy consumption of the world is 500 exajoules (equivalent to  $1.38.8 \times 10^{12}$  kWh of energy or average power of  $1.5 \times 10^7$  MW). Fossil fuels roughly provide about 90% of this energy and will continue to provide more than 80% of the total energy demand well into the future. Approximately 25% of this energy is consumed in transportation sector and the remaining 75% by industries, domestic, agriculture and social consumers. The energy demand has grown astronomically in recent years—with primary energy demand increasing by more than 50% since 1980. This growth is forecast to continue at an annual average rate of 2.2% during 2004–2030. Over 70% of this growth will come from developing countries.

#### 1.13.2 Availability of Resources and Future Trends

##### A. Conventional Resources

(i) **Fossil Fuels** Fossil fuels are so called because these are in fact the fossils of old biological life that once existed on the surface of the earth. It is formed in several parts of the earth at varying depths, during several million years by slow decomposition and chemical actions of buried organic matter under favourable pressure, heat and bacterial marine environment. The fossil fuels include coal, oil and gas.

Fossil fuels have been a major source of energy since about 1850, the start of the industrial era. Presently, we are passing through the peak period of the fossil age. As per an estimate, if the world continues to consume fossil fuels at year 2006 rates, the reserves of coal, oil and gas will last 200, 40 and 70 years respectively. This gives only an indication and not a very realistic figure. It is generally accepted that the rate of production of an economic commodity of which a finite quantity exists is governed by the laws of supply and demand. As the amount available depletes, the commodity becomes costlier, and its use gradually declines. Also, new reserves are continuously being discovered and new technologies are being invented for those resources which were not considered economical earlier. The locations and estimates of the world's main fossil fuel reserves are indicated in Table 1.3.



## Non-conventional Energy Resources

**Table 1.3** World's main fossil-fuel reserves, as in 2005.<sup>[16]</sup>

Region	Fossil fuel reserve (billion tonnes oil equivalent)						Fossil fuel reserve (per cent)			
	Oil	Coal	Gas	Sum	Oil	Coal	Gas	Sum		
North America	8	170	7	185	0.86	18.20	0.75	19.81		
South America	15	13	6	34	1.61	1.39	0.64	3.64		
Europe	2	40	5	47	0.21	4.28	0.54	5.03		
Africa	16	34	13	63	1.71	3.64	1.39	6.75		
Russia	18	152	52	222	1.93	16.27	5.57	23.77		
Middle East	101	0	66	167	10.81	0.00	7.07	17.88		
India	1	62	1	64	0.11	6.64	0.11	6.85		
China	2	76	2	80	0.21	8.14	0.21	8.57		
Australia and East Asia	2	60	10	72	0.21	6.42	1.07	7.71		
Total	165	607	162	934	17.67	64.99	17.34	100.00		

(ii) **Hydro Resources** Among all renewables, hydro power is the most advanced and flexible source of power. It is a well developed and established source of electric power. The early generation of electricity from about 1880, was often derived from hydro turbines. A number of large and medium-sized hydro schemes have been developed. Due to requirement of huge capital investment and strong environmental concerns about large plants, only about one-third of the realistic potential has been tapped so far. Hydro installations and plants are long lasting (turbine life is about 50 years). This is due to continuous steady operation without high temperature or other stresses. Therefore, it often produces electricity at low cost with consequent economic benefits.

The global installed generating capacity of hydro power is about 7,78,038 MW, which accounts for about 20% of the world's total installed electric power-generation capacity and about 3% of the world's primary energy supply<sup>[19]</sup>. Industrialized countries account broadly for two-thirds and developing countries for one-third of the present hydro power production. Five countries make up more than half of the world's hydro power production: China (100,000 MW), USA (77,350 MW), Canada (71,978 MW), Brazil (71,060 MW) and Russia (45,000 MW). Norway derives 90% of its required electric power from hydro resources. The world's biggest hydroelectric power station is located in Brazil, at Itaipu. Its capacity is 12,000 MW. The dam is 7.7 km long and built over the river Parana.

(iii) **Nuclear Resources**  $U^{235}$ ,  $U^{233}$  (isotopes of uranium) and  $Pu^{239}$  (plutonium) are used as nuclear fuels in nuclear reactors (thermal reactors) and are known as *fissile (or fissionable) materials*. Out of these, only  $U^{235}$  occurs in nature.  $U^{233}$  and  $Pu^{239}$  are produced from  $Th^{232}$  (Thorium) and  $U^{238}$  respectively in Fast Breeder Reactors

(FBRs).  $\text{Th}^{232}$  and  $\text{U}^{238}$  are known as *ferile materials*. Natural uranium contains 0.71% of  $\text{U}^{235}$  and 99.29% of  $\text{U}^{238}$ .

Uranium reserves in the world are small (expected to last hardly for 59 years at present, i.e., at the 2008 rate of consumption) and its recovery is expensive. Concentrated deposits of uranium are not available. The content of natural uranium in uranium ore is about 0.1–0.5%. Major available sources of uranium are in Australia, Canada, and Kazakhstan and to a lesser extent the USA. There are also a large number of smaller low-grade sites. Thorium reserves are expected to be more than those of uranium.

Nuclear power is a least-cost, low-emission technology that can provide base-load power. As on August 2008, there are around 439 nuclear power plants in the world, operating in 31 countries and generating 371,989 MW, which is about 16% of the world's electricity. France produces 78% of its total electrical power by nuclear means. In the European Union as a whole, nuclear energy provides 30% of the electricity. The nuclear energy policy differs between the European Union countries, and some, such as Austria and Ireland, have no active nuclear power stations. Presently, most commercial reactors are thermal reactors. Fast Breeder Reactors (FBRs) utilize fast neutrons and generate more fissile material than they consume. They generate energy as well as convert fertile material ( $\text{U}^{238}$ ,  $\text{Th}^{232}$ ) into fissile material ( $\text{Pu}_{239}$  and  $\text{U}_{235}$ , respectively). The breeder technology is not yet commercially developed, the main problem being their slow breeding rate and, therefore, long doubling time (the time required by an FBR to produce sufficient fissile material, to fuel a second identical reactor) of around 25 years. With continuing R and D efforts in this direction, it is hoped that by 2050, FBRs will be the main source of power after overcoming the present difficulties.

Nuclear fusion reaction has a lot more potential and vast resources are available. However, controlled fusion reaction has not been achieved yet. It is predicted that by year 2500 some breakthrough will take place in fusion technology and once this happens, nuclear fusion reaction will be the main source of energy on the earth.

## B. Non-conventional Sources

Non-conventional technologies are presently under the development stage. At present, their share is very small.

(i) **Solar Energy** Solar energy can be a major source of power and can be utilized by using thermal and photovoltaic conversion systems. The solar radiation received on the surface of the earth on a bright sunny day at noon is approximately  $1 \text{ kW/m}^2$ . The earth continuously intercepts solar power of 178 billion MW, which is about 10,000 times the world's demand. But so far, it could not be developed on a large scale. According to one estimate, if all the buildings of the world are covered with solar PV panels, it can fulfill electrical power requirements of the



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  $1.6 \times 10^7$  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  $2 \times 10^{11}$  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 and direct thermal-use installed capacity was 28,266 MW. 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 1964 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 [vi]

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 [vi]

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<sup>3</sup>, 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  $U^{235}$  in an FBR. The  $U^{231}$  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<sup>239</sup>. The plutonium<sup>239</sup>, thus obtained, will be used as fuel in a thermal reactor.

**Stage 3** In the third stage, thorium<sup>232</sup> 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.



## Non-conventional Energy Resources

India has mastered the technology of the first stage with 15 commercial PHWRs plants (located at Narora, Rawatbhatta, Kakrapar, Kaiga, Kalpakkam, Kodamkulam 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 (PFR) 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) [9]

S. N.	Source/system	Estimated potential	Cumulative achievement
<b>Rural and decentralized energy system</b>			
1.	Family type biogas plants (nos.)	120 lakhs	39,40 lakhs
2.	Solar photovoltaic programme Solar street-lighting system Home-lighting system Solar lantern	50 MW /sq. km — — —	110 MWp (p-peak) 69,849 nos. 3,63,309 nos. 5,85,001 nos. 2.28 MWp
3.	Solar power plants Solar thermal programme Solar water heating system Solar cooker	— 140 million sq. m. — —	— 2.15 million sq.m. collector area area 6.17 lakhs
4.	Wind pumps	—	1284 nos.
5.	Aero-generator/hybrid system	—	675.27 kW
6.	Solar photovoltaic pumps	—	7068 nos.

S.N.	<i>Source/System</i>	<i>Estimated potential</i>	<i>Cumulative achievement</i>
7.	Remote villages electrification	—	3568 (830) villages/hamlets
<b>Power from renewables</b>			
<b>A. Grid interactive renewable power</b>			
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>B. Captive/CHP/Distributed renewable power</b>			
14.	Biomass/cogeneration (ton bagasse)	—	95,00 MW
15.	Biomass gasifier	—	86.53 MW
16.	Energy recovery from waste	—	23.70 MW
Total			205.23 MW
<b>Other programmes</b>			
17.	Energy parks	504 nos.	
18.	Autiva solar shop	209 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

## C<sup>24</sup> Non-conventional Energy Resources

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 by-laws. 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. Nawanshahr, 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
- Sunderbans; 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 Lakshadweep.

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.



## Non-conventional Energy Resources

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<sup>[34,35]</sup>

<i>By the end of 5-year plan</i>	<i>Demand</i>	<i>Installed capacity</i>	<i>Shortage</i>
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	1,1,000 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<sup>[32]</sup>

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



**Table 1.9** Growth projections of the power sector<sup>[45]</sup>

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.

## 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

**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.



**Fig. 1.5** A system



**Closed System** If the boundary of a system is impervious to the flow of matter, it is called a closed system.

**Open System** An open system is one in which matter flows into or out of the system. Most of the engineering systems are open systems.

**Isolated System** A system that exchanges neither energy nor matter with any other system or with the environment is known as an isolated system.

**Adiabatic System** An adiabatic system is one which is thermally insulated from its surroundings, i.e., it does not exchange heat with its surroundings. It can, however, exchange work with its surroundings. If it does not, it becomes an isolated system.

**Isothermal System** An isothermal system is one which maintains constant temperature.

**Intensive Property** Intensive property is that property which does not depend on the mass of the system, e.g., pressure or temperature.

**Extensive Property** Extensive property is related with the mass of a system, e.g., volume or energy.

**Phase** A phase is that quantity of matter which is homogeneous throughout in chemical composition and physical structure.

**Homogeneous System** A system which consists of a single phase is termed a homogeneous system. Examples are a mixture having air plus water vapour, water plus nitric acid or hydrogen plus methane.

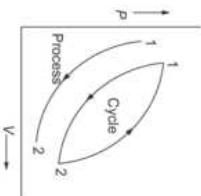
**Heterogeneous System** A system which consists of two or more phases is called a heterogeneous system. Examples are, a mixture of water plus oil, water plus steam and ice plus water.

**State** Each unique condition of the system is known as a state.

**Process** A process occurs when a system undergoes a change in state or an energy transfer at a steady state. A process is illustrated by a curve on a  $P-V$  (pressure-volume) diagram or a  $T-S$  (abs. temperature-entropy) diagram. A process has a certain path between the starting point and the end point. A process begins with a certain state and ends with certain state of working fluid.

**Fig. 1.6** A process and cycle

**Cycle** Any process, or series of processes, whose end states are identical is termed as a cycle.





**Irreversible Process** An irreversible process does not trace the same path when reversed. The irreversibility may be due to

- friction
- heat flow (always from hot to cold)
- mixing of two different fluids in different states

**Thermal Equilibrium** In thermal equilibrium, the temperature will be the same at all points of the system and it does not change with time.

**Mechanical Equilibrium** In mechanical equilibrium, there are no unbalanced forces within the system. The pressure in the system is same at all points and does not change with time.

**Chemical Equilibrium** In chemical equilibrium, no chemical reaction takes place in the system and the chemical composition which is same throughout the system does not vary with time.

**Thermodynamic Equilibrium** A system is in thermodynamic equilibrium if it has achieved the

- thermal equilibrium,
- mechanical equilibrium, and the
- chemical equilibrium states.

**Quasi-static Process** *Quasi* means 'almost'. A quasi-static process is also called a reversible process. This process is a succession of equilibrium states and portrays infinite slowness in its characteristic features.

**Specific Heat** The specific heat of a solid is usually defined as the heat required to raise the temperature of unit mass of the solid through one degree.

For a solid of mass  $m$  and specific heat  $c$ , the heat  $dQ$  required to increase the temperature by  $dT$ :

$$dQ = m c dT$$

For a gas, two specific heats are defined:

- $c_v$  specific heat at constant volume
- $c_p$  specific heat at constant pressure

Accordingly we have,

$$dQ = m c_p dT \text{ for a reversible non-flow process at constant pressure}$$

$$dQ = m c_v dT \text{ for a reversible non-flow process at constant volume}$$

The values of  $c_p$  and  $c_v$  for a perfect gas are constants.

For a temperature rise from  $T_1$  to  $T_2$ :

Flow of heat in a reversible non-flow process at constant pressure,

$$Q = m c_p (T_2 - T_1) \text{ and}$$

Flow of heat in a reversible non flow process at constant volume,

$$\dot{Q} = m \epsilon_v (T_2 - T_1)$$

For real gases  $\epsilon_p$  and  $\epsilon_v$  vary with temperature, but a suitable average values may be used for most practical purposes.

The relationship between the two specific heats may be shown to be:

$$\epsilon_p - \epsilon_v = R$$

where R is the gas constant.

The ratio of these two specific heats is denoted by  $\gamma$ .

$$\gamma = \frac{\epsilon_p}{\epsilon_v} \quad (1.1)$$

### 1.15.2 Joule's Law

Joule's law states that '*the internal energy of a perfect gas is a function of absolute temperature only*'. Mathematically,

$$u = f(T)$$

To evaluate this function, let us consider heating 1 kg of a perfect gas at constant volume. According to the non-flow energy equation:

$$dQ = du + dW$$

But  $dW = 0$ , as volume remains constant,

Therefore,  $dQ = du$

At constant volume of a perfect gas of 1 kg,

$$dQ = \epsilon_v dT$$

Therefore,  $du = \epsilon_v dT$

Integrating, we get

$$u = \epsilon_v dT + K \quad (K \text{ being the constant of integration})$$

For a perfect gas it is assumed that  $u = 0$  when  $T = 0$ , hence K is zero.

Thus, the internal energy of 1 kg of a perfect gas,

$$u = \epsilon_v T$$



Internal energy for a perfect gas of mass  $m$  is

$$U = m \epsilon_r T$$

Therefore, for a perfect gas, gains of internal energy in any process (reversible or irreversible) between two states 1 and 2 is

$$U_2 - U_1 = m \epsilon_r (T_2 - T_1) \quad (1.2)$$

**Enthalpy** Enthalpy,  $b$  is defined as the sum of internal energy,  $u$ , and the pressure-volume product,  $pV$ :

$$b = u + pV \quad (1.3)$$

The enthalpy of a fluid is the property of the fluid since it consists of the sum of a property and the product of two properties. Since enthalpy is a property, it can be introduced into both flow as well as non-flow processes.

Total enthalpy of mass,  $m$  of a fluid can be given as

$$H = mb = U + pV \quad (1.4)$$

For a perfect gas, rewriting Eq. (1.3),

$$\begin{aligned} b &= u + pV \\ &= \epsilon_r T + RT \\ &= (\epsilon_r + R)T \end{aligned} \quad (1.5)$$

$$b = \epsilon_p T \quad [\text{from Eq. (1.1)}]$$

$$\text{and } H = m \epsilon_p T \quad (1.6)$$

(Note that since  $u$  has to be zero at  $T = 0$ , therefore,  $b = 0$  at  $T = 0$ .)

### 1.15.3 First Law of Thermodynamics

In the early part of the nineteenth century, scientists discovered the concept of energy and the hypothesis that ‘energy can neither be created nor destroyed’, which came to be known as the *law of conservation of energy*. The first law of thermodynamics is merely one statement of this general law with particular reference to heat energy and mechanical energy, i.e., work.

The first law of thermodynamics can be stated as, ‘when a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to the net work done by the system on its surroundings’.

$$\oint dQ = \oint dW$$

where  $\oint$  represents the sum for a complete cycle.

### Performance of Heat Engine and Reverse Heat Engine

In Fig. 1.7, a heat engine is used to produce maximum work from a given positive heat transfer. The measure of success is called the *thermal efficiency* of the engine and is defined by the ratio

$$\eta_{th} = \frac{W'}{\dot{Q}_1} \quad (1.7)$$

where

$\dot{Q}_1$  = heat transfer to the engine

For a reversed heat engine acting as a refrigerator, when the purpose is to achieve the maximum heat transfer from the cold reservoir, the measure of success is called the *coefficient of performance* (COP). It is defined by the ratio

$$(COP)_{refrigerator} = \frac{\dot{Q}_2}{W'} \quad (1.8)$$

where

$\dot{Q}_2$  = heat transfer from the cold reservoir

$W'$  = the net work transfer to the refrigerator

For the reversed heat engine acting as a heat pump, when the purpose is to achieve maximum heat transfer to a hot reservoir, the measure of success is again called the *coefficient of performance* (COP). It is defined by the ratio

$$(COP)_{heat\ pump} = \frac{\dot{Q}_1}{W'} \quad (1.9)$$

where

$\dot{Q}_1$  = heat transfer to the hot reservoir

$W'$  = the net work transfer to heat pump

In all the above three cases, the application of the first law gives the relation  $\dot{Q}_1 - \dot{Q}_2 = W'$ , and this can be used to rewrite the expressions for efficiency and COP solely in terms of heat transfers:

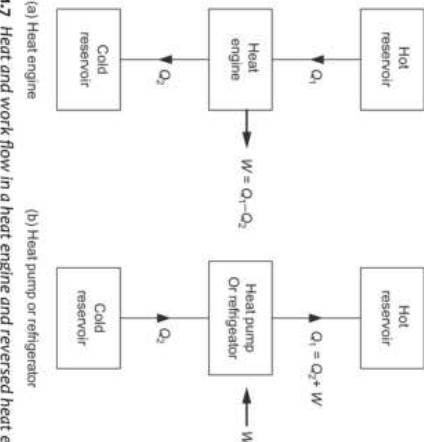
$$\eta_{th} = \frac{\dot{Q}_1 - \dot{Q}_2}{\dot{Q}_1} \quad (1.10)$$

$$(COP)_{refrigerator} = \frac{\dot{Q}_2}{\dot{Q}_1 - \dot{Q}_2} \quad (1.11)$$

$$(COP)_{heat\ pump} = \frac{\dot{Q}_1}{\dot{Q}_1 - \dot{Q}_2} \quad (1.12)$$



It may be seen that values of  $\eta_{th}$  and  $(COP)_{refrigerator}$  are always less than unity, while  $(COP)_{heat\ pump}$  is always greater than unity.



**Fig. 1.7 Heat and work flow in a heat engine and reversed heat engine**

### 1.15.4 Second Law of Thermodynamics

Before discussing the second law of thermodynamics, let us highlight the shortcomings of the first law of thermodynamics.

#### Limitations of The First Law of Thermodynamics

- It has been observed that energy can flow from a system in the form of heat or work. The first law of thermodynamics sets no limit to the amount of the total energy of the system which can be caused to flow as work. A limit is imposed, however, as a result of the principle enunciated in the second law of thermodynamics which states that heat will flow naturally from one energy reservoir at a higher temperature to another at a lower temperature, but not in the opposite direction, without assistance.
- The first law of thermodynamics establishes equivalence between the quantity of heat used and the mechanical work but does not specify the conditions under which conversion of heat into work is possible, neither the direction in which transfer can take place. This gap has been bridged by the second law of thermodynamics.

There are two classical statements of the second law of thermodynamics, known as Kelvin-Planck statement and Clausius statement.

**Kelvin-Planck Statement** It is impossible to construct an engine, which while operating in a cycle produces no other effect except to extract heat from a single reservoir and do equivalent amount of work.



**Clausius Statement** It is impossible for a self-acting machine working in a cyclic process unaided by any external agency, to convey heat from a body at a lower temperature to a body at a higher temperature.

**Entropy** Entropy is an extensive property of a substance and is designated by  $S$ . It may be defined for a reversible process in accordance with the relation:

$$dS = \left( \frac{\delta Q}{T} \right)_{rev}$$

or Incremental entropy = ratio of heat change and absolute temperature.

In simple terms, it is heat (in joules) per Kelvin. For a reversible process, if  $S_1$  and  $S_2$  are the respective entropies at the initial and final states then the change in entropy depends on the initial and final state only, and not on the path followed by the process. It is therefore a property. Thus, change in entropy when the system undergoes a reversible change from State 1 to State 2 is

$$S_2 - S_1 = \int \left( \frac{\delta Q}{T} \right)_{rev}$$

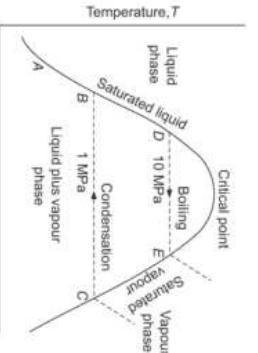


Fig. 1.8 Temperature – entropy diagram for steam

are the same for all pure substances. These diagrams are important because they enable us to visualize the changes of state that occur in various processes.

### 1.15.5 Power Cycles

**Carnot cycle** The Carnot cycle, which works on reversible cycle was suggested by the French engineer Sadi Carnot in 1824. Any fluid may be used to operate the Carnot cycle, which is performed in a cylinder as shown in Fig. 1.9(a). Heat is caused to flow into the cylinder by the application of heat from a high-energy source to the cylinder head during expansion, and to flow from the cylinder by the application of a low-temperature energy source to the head during compression.

**Isentropic Process** An isentropic process is one during which the entropy of the system remains constant. It can be proved that any reversible adiabatic process is an isentropic process.

#### Temperature-entropy Diagram for a pure substance

The thermodynamic properties of a substance are often shown on a temperature–entropy ( $T$ – $S$ ) diagram, shown in Fig. 1.8. The general features of such diagrams

The following are the four stages of a Carnot cycle:

**Stage 1: (Process 1-2)** Hot energy source is applied. Heat  $\mathcal{Q}_1$  is taken in and the fluid expands isothermally and reversibly at constant temperature  $T_1$ .

**Stage 2: (Process 2-3)** The cylinder becomes a perfect insulator so that no heat flow takes place. The fluid expands adiabatically and reversibly whilst temperature falls from  $T_1$  to  $T_2$ . Therefore, the process is an isentropic one.

**Stage 3: (Process 3-4)** Cold energy source (sink) is applied. Heat  $\mathcal{Q}_2$  flows from the fluid and it is compressed isothermally and reversibly at a constant lower temperature,  $T_3$ .

**Stage 4: (Process 4-1)** The cylinder head becomes a perfect insulator so that no heat flow occurs. The compression is continued adiabatically and reversibly during which temperature is raised from  $T_2$  to  $T_1$ .

The work delivered by the system during the cycle is represented by the enclosed area of the cycle. Again, for a closed cycle, according to the first law of thermodynamics, the work obtained is equal to the difference between the heat  $\mathcal{Q}_1$  supplied by the source and the heat  $\mathcal{Q}_2$  rejected to the sink.

$$W' = \mathcal{Q}_1 - \mathcal{Q}_2$$

The thermal efficiency,  $\eta_{th}$

$$= \frac{\text{Work output}}{\text{Heat supplied by the source}} = \frac{\text{Area under curve } 1-2-3-4}{\text{Area under curve } 1-2-3'-4'} = \frac{\mathcal{Q}_1 - \mathcal{Q}_2}{\mathcal{Q}_1}$$

$$\eta_{th} = 1 - \frac{T_2}{T_1} \quad (\text{as } \frac{\mathcal{Q}_2}{\mathcal{Q}_1} = \frac{T_2}{T_1}) \quad (1.13)$$

The Carnot cycle is an ideal condition requiring a reversible heat engine and cannot be performed in practice because of the following reasons.

- It is impossible to perform a frictionless (i.e., reversible) process.
- An isothermal process can be achieved only if the piston moves very slowly to allow some time for heat transfer so that the temperature remains constant. An adiabatic process requires the piston to move as fast as possible so that the heat transfer is negligible due to a short interval of time available. The adiabatic and isothermal processes take place during the same stroke, requiring the piston to move very slowly for the initial part of the stroke and very fast for the remaining part of the stroke. This extreme variation of motion of the piston during the same stroke is not possible.



Though it is not a practical engine cycle, the conceptual value of the Carnot cycle is that it establishes the maximum possible efficiency for an engine cycle operating between  $T_1$  and  $T_2$ . The Carnot cycle can be thought of as the most efficient heat engine cycle allowed by physical laws. When the second law of thermodynamics states that not all the supplied heat in a heat engine can be used to do work, the Carnot efficiency sets the limiting value on the fraction of the heat which can be so used.

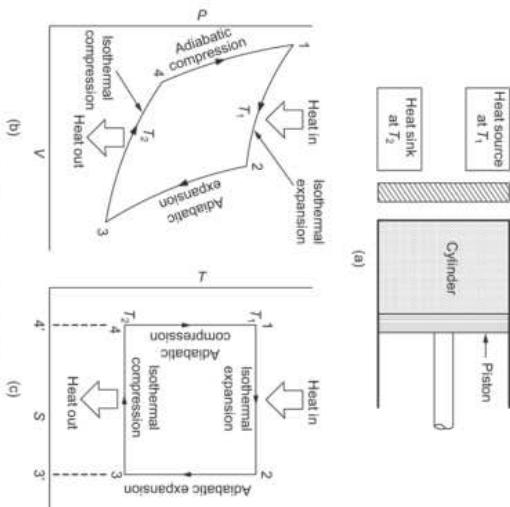


Fig. 1.9 Carnot engine cycle

### Example

A reversible cyclic heat engine operates between source temperatures of 500°C and 100°C. Find the rate of heat rejection per kW net output of the engine.

#### 1.1

**Solution**

Temperature of source  $T_1 = 500 + 273 = 773$  K

Temperature of sink  $T_2 = 100 + 273 = 373$  K

Output  $\dot{W} = 1$  kW

Thermal efficiency of the reversible engine from Eq. (1.13);

$$\eta_{th} = 1 - \frac{T_2}{T_1} = 1 - \frac{373}{773} = 0.349$$

$$\text{or } \eta_{th} = 34.9\%$$

Now from Eqn. (1.7),



$$\eta_b = \frac{W}{Q_1}$$

$$0.349 = \frac{1}{Q_1}$$

Heat supplied,  $Q_1 = 2.865 \text{ kW}$

Now, heat rejected,  $Q_2 = Q_1 - W = 2.865 - 1 = 1.865 \text{ kW}$   
Therefore, the rate of heat rejection per kW of net output

$= 1.865 \text{ kW}$

### Example

#### 1.2

A domestic food refrigerator maintains a temperature of  $-10^\circ\text{C}$ . The ambient air temperature is  $40^\circ\text{C}$ . If heat leaks into the freezer at a continuous rate of  $2 \text{ kJ/s}$ , determine the least power necessary to pump this heat out continuously.

#### Solution

Ambient temperature  $T_1 = 40 + 273 = 313 \text{ K}$

Freezer temperature  $T_2 = 10 + 273 = 263 \text{ K}$

Rate of heat leakage into the freezer =  $2 \text{ kJ/s}$

The refrigerator cycle removes heat from the freezer at the same rate at which heat leaks into it (to maintain constant temperature), thus  $Q_2 = 2 \text{ kJ/s}$

For minimum power requirement,

$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$$

$$Q_1 = T_1 \times \frac{Q_2}{T_2} = 313 \times \frac{2}{263} = 2.38 \text{ kJ/s}$$

$$W = Q_1 - Q_2 = 2.38 - 2 = 0.38 \text{ kW}$$

Therefore, the least power required to pump the heat continuously =  $0.38 \text{ kW}$

### Example

A house requires  $3 \times 10^4 \text{ kJ/h}$  of heating in winter. A heat pump is used to absorb heat from the cold air outside the house. The work required to operate the heat pump is  $2 \times 10^3 \text{ kJ/h}$ . Determine:  
(i) Heat abstracted from outside (ii) Coefficient of performance

#### 1.3

#### Solution

Heat required for the house,  $Q_1 = 3 \times 10^4 \text{ kJ/h}$

Work required to operate the heat pump,  $W = 2 \times 10^3 \text{ kJ/h}$



Heat abstracted from the outside air,  $\mathcal{Q}_2 = \mathcal{Q}_1 - W' = 28 \times 10^3$  kJ/h

$$(COP)_{heat\ pump} = \frac{\mathcal{Q}_1}{\mathcal{Q}_1 - \mathcal{Q}_2} = \frac{3 \times 10^4}{2 \times 10^3} = 15$$

### Example 1.4

There are two alternative sources of heat energy. Source 1 can supply energy at the rate of 10,000 kJ/min at 320°C. Source 2 can supply energy at the rate of 120,000 kJ/min at 65°C. If an ideal reversible engine is used to produce power, which source out of these two will provide larger power if the temperature of the surroundings is 35°C?

#### Solution

Supply of energy  
Source 1,  $\mathcal{Q}_1 = 10,000$  kJ/min at  $T_1 = 320 + 273 = 593$  K

Source 2,  $\mathcal{Q}_2 = 120,000$  kJ/min at  $T_1 = 65 + 273 = 338$  K

Temperature of surrounding,  $T_2 = 35 + 273 = 308$  K

The efficiency of the Carnot engine from the two sources is given by:

$$\text{Source 1, } \eta_1 = 1 - \frac{308}{593} = 0.48$$

$$\text{Source 2, } \eta_2 = 1 - \frac{308}{338} = 0.088757$$

Work delivered by Source 1,  $W'_1 = 10,000 \times 0.48$

= 4,800 kJ/min

Work delivered by Source 2,  $W'_2 = 120,000 \times 0.088757$

= 10,650.84 kJ/min

Therefore, Source 2 will provide larger amount of power (even though its efficiency is lower).

**Rankine Cycle** The rankine cycle is a vapour-power cycle on the basis of which a steam turbine (or engine) works. The various components and the processes involved in a Rankine cycle are shown in Fig. 1.10(a). It comprises of the following processes:

**Process 1-2** Reversible adiabatic expansion in the turbine (or steam engine) to produce output work  $W'_T$

**Process 2-3** Constant pressure transfer of heat in the condenser. Steam is condensed to water and heat  $\mathcal{Q}_2$  is removed.

**Process 3-4** Reversible adiabatic pumping process, where the system accepts some work  $W'_P$  as input. However, this work is negligible compared to work output of the turbine, especially when the boiler pressure is low.

**Process 4-1** Constant pressure transfer of heat  $\mathcal{Q}_1$  in the boiler.

Thermodynamic changes during the Rankine cycle are shown on **P-V** and **T-S** diagrams given in Fig. 1.10 (b, c). The area under the closed loop 1-2-3-4 represents the net work output.

The efficiency of a Rankine cycle can be written as

$$\eta_{\text{Rankine}} = \frac{W'_{\text{net}}}{Q_1} = \frac{W_T - W_p}{Q_1} = \frac{(h_1 - h_2) - (h_4 - h_1)}{h_1 - h_4}$$

Usually, the pumping power is very small as compared to power produced by a turbine,  $W_T \gg W_p$

$$\text{Therefore, } \eta_{\text{Rankine}} \approx \frac{h_1 - h_2}{h_1 - h_4} \quad (1.14)$$

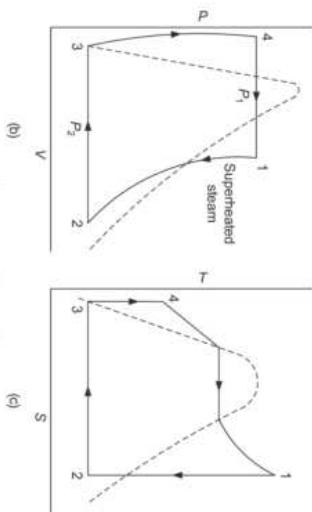
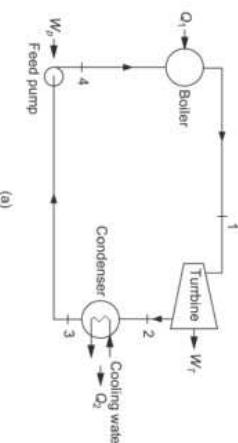


Fig. 1.10 Rankine cycle

### Effects of Operating Conditions on Rankine Cycle Efficiency

Rankine cycle efficiency can be improved by

- increasing the temperature at which steam is supplied to the turbine
- decreasing the temperature at which steam is rejected by the turbine



This can be achieved by making suitable changes in the conditions of the boiler and condenser.

1. **Increasing Boiler Pressure** It has been observed that by increasing the boiler pressure (other factors remaining the same), the efficiency rises first and then drops after reaching its peak value (of about 35–45%) at about 166 bar.
2. **Superheating the Steam** If the steam is superheated before it enters the turbine, the efficiency of the Rankine cycle increases, other factors remaining the same. This also increases the life of the turbine blades due to absence of water particles.

3. **Reducing the Condenser Pressure** By reducing the condenser pressure, the temperature at which heat is rejected can be reduced, thus increasing the thermal efficiency of the cycle. However, this would also increase the cost of condensation apparatus.

The efficiency of the Rankine cycle is also improved by use of following methods.

- (a) regenerative feed heating
- (b) reheating of steam
- (c) water extraction
- (d) using binary vapour

Typical data for a Rankine-cycle-based steam turbine (coal fired):

Steam inlet temperature = 540°C

Steam inlet pressure = 160 atm

Efficiency ≈ 35%

**Brayton Cycle** The Brayton cycle is a gas-power cycle on the basis of which a thermodynamic device (engine or turbine) works to produce mechanical power. The various components and the processes involved in a Brayton cycle are shown in Fig. 1.11(a). It uses air as a working fluid and works at temperatures well in excess of 500°C. The expansion and compression processes are reversible and adiabatic while heat addition and rejection takes place at constant pressure. The hot compressed gas is allowed to expand through a turbine performing work. The exhaust gas from the turbine is fed to a heat exchanger where the heat is rejected and then compressed by the compressor to complete the cycle. It comprises of the following processes:

Process 4-1 Reversible adiabatic (i.e., isentropic) compression. Here, a work  $W_e$  is accepted by the system as input.

Process 1-2 Constant pressure transfer of heat  $\mathcal{Q}_1$  in the combustor.

Process 2-3 Reversible adiabatic expansion in the turbine. A work  $W_T$  is produced.



**Process 3–4** Constant pressure heat output  $\mathcal{Q}_2$  by the condenser,

Thermodynamic changes during the Brayton cycle are shown on  $P$ – $V'$  and  $T$ – $S$  diagrams given in Fig. 1.11 (b, c). The area under the closed loop 1–2–3–4 represents the net work output ( $W_T' - W_C$ ). The performance of a Brayton cycle can be improved by inserting a regenerator between the turbine exhaust and the cooler for preheating the compressed gas prior to the combustor. The efficiency of a Brayton cycle can be written as

$$\eta_{\text{Brayton}} = 1 - \frac{1}{r_p^{\gamma-1}} \quad (1.15)$$

where  $r_p$  is the compression ratio ( $\frac{p_1}{p_2}$ ) and  $\gamma$  is the ratio of the two specific heats. In terms of pressure ratios  $r_p$ :

$$\eta_{\text{Brayton}} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}} \quad (1.16)$$

In a Brayton cycle, the work input during compression is a significant amount as the working fluid is gas. The compressor consumes roughly 50% of the power produced by the turbine, reducing the overall efficiency of the cycle. This is in contrast to a Rankine cycle where pumping power is negligible as the working fluid is in liquid form (which is incompressible) during the compression (pumping) process.

Typical data for a Brayton cycle based gas turbine (coal fired):

Inlet temperature = 540°C, –1425°C

Inlet pressure ≈ 30 atm

Efficiency ≈ 26%–39%

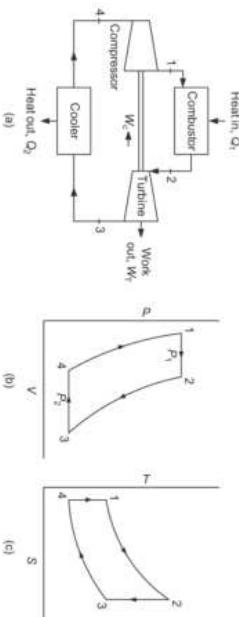


Fig. 1.11 Brayton cycle

**Stirling Cycle** The Stirling cycle is similar to a Carnot cycle, except that two adiabatic processes are replaced by two constant volume processes. A suitable gas or air is used as working fluid. The system components are shown in Fig. 1.12(a). The heat addition and rejection takes place at constant temperatures. The cycle comprises of the following processes:

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**Process 4-1** The working fluid receives heat at constant volume in a regenerative heat exchanger from the exhaust fluid returning from the turbine.

**Process 1-2** In this process, the working fluid receives heat at constant (high) temperature and expands in a turbine producing  $W_T$  output.

**Process 2-3** The working fluid loses heat at constant volume to the fluid incoming to the turbine.

**Process 3-4** The working fluid is compressed at constant (low) temperature and heat  $Q_2$  is rejected to the ambient.

The heat transfer in a regenerative heat exchanger is accomplished reversibly by a matrix of wire gauze or small tubes. The main difficulty in a Stirling cycle lies in making an efficient regenerator of reasonable size which can operate at a temperature comparable to that used in internal combustion engines. The efficiency of a Stirling cycle is given as

$$\eta_{\text{Stirling}} = \frac{T_1 - T_2}{T_1} \quad (1.17)$$

Typical data for a Stirling-cycle-based gas turbine:

Turbine inlet temperature = 750°C–800°C

Inlet pressure = 30 atm

Efficiency ≈ 30%–40%

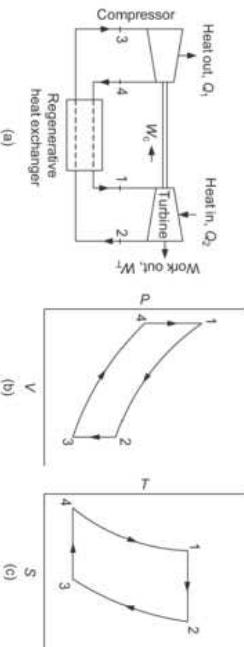
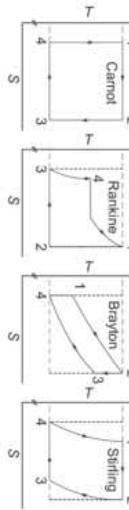


Fig. 1.12 Stirling cycle

### 1.15.6 Comparison of Various Power Cycles

The performance of various thermodynamic cycles can be compared qualitatively on a  $T-S$  diagram shown in Fig. 1.13. These diagrams are not drawn on a common scale and only their shapes are compared. The temperature, pressure and entropy ranges are different for different cycles. As seen from this figure, the Carnot cycle is represented by a rectangle and produces maximum output. The Stirling cycle produces the next maximum in the remaining three cycles. The main

limitation however, is the design of a suitable, efficient regenerator, especially in large sizes. Also, the Stirling cycle is not preferred in large power plants due to many other practical problems. The Rankine cycle is generally preferred and is widely used due to its superior overall cycle efficiency and component sizes.



**Fig. 1.13** Comparison of power cycles

### Review Questions

1. How is per capita energy consumption related with standard of living?
2. Comment on the oil crisis of 1973.
3. What are primary and secondary energy sources?
4. What are conventional and non-conventional energy sources?
5. List various non-conventional energy resources. Give their availability, relative merits and their classification.
6. Discuss the main features of various types of renewable and non-renewable energy sources and explain the importance of non-conventional energy sources in the context of global warming. (UPTU Lucknow 2005–06)
7. What is meant by renewable energy sources?
8. What do you understand by commercial energy?
9. What are the advantages and limitations of non-conventional energy sources?
10. What is the percentage share of fossil fuels in the total energy consumption of the world?
11. What percentage of energy requirement is met by coal in India?
12. Discuss the main feature of non-conventional energy sources. (UPTU Lucknow 2003–04)
13. Discuss different renewable sources of energy with special reference to the Indian context.
14. What do you understand by energy chain?
15. What are the advantages and disadvantages of conventional energy sources?
16. What do you understand by greenhouse effect and what are its consequences? How is it caused?
17. What are greenhouse gases?
18. What do you understand by green power?
19. Which is the cleanest of all fuels and what is its heating value?
20. Indicate the heating values of bituminous coal, coke, peat, diesel, propane and natural uranium.
21. What is the present annual primary energy consumption of the world? At what rate is it growing?
22. Comment on the future availability trend of fossil fuels in the world.

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23. What is the present world hydro-power potential and how much has been tapped so far?

24. Which country relies the most on nuclear energy for its energy requirements?

25. What is the present status of nuclear energy and what are its future prospects?

26. What is the potential in solar energy the world over? On an average, how much solar power is received on the surface of the earth at noon during a bright sunny day?

27. What are the prospects of wind and biomass energy?

28. Comment on the prospects of fossil fuels in India.

29. What is the status of non-conventional energy sources in India and what are their future prospects?

30. Comment on the growth of the energy sector in India.

31. Comment on the rural electrification plans of the government of India.

32. Discuss different renewable sources of energy with special reference to the Indian context.

(UPTU Lucknow 2003-04)

33. Describe the main features of various types of renewable and non-renewable energy resources and explain the importance of non-conventional energy sources in the context of global warming.

(UPTU Lucknow 2003-04)  
and non-renewable energy  
sources in the

Objective-type Questions

1. Which parameter is used as an index for the standard of living of the people of a country?  
 (a) Industrial production      (b) Number of vehicles per house  
 (c) Per capita energy consumption      (d) Population density

2. What is the per capita electrical energy consumption of India?  
 (a) 100 kWh/year      (b) 150 kWh/year  
 (c) 400 kWh/year      (d) 700 kWh/year

3. Which year is said to be the starting point for large scale planning of renewable energy globally?  
 (a) 1973      (b) 1942      (c) 1850      (d) 1991

4. What is the percentage share of fossil fuel in the global consumption of primary energy?  
 (a) 86%      (b) 50%      (c) 10%      (d) 99%

5. Out of thermal, electrical, mechanical and chemical, which energy form is considered as top grade energy?  
 (a) Mechanical      (b) Chemical      (c) Thermal      (d) Electrical



6. Out of energy, economy and environment  
 (a) only energy and environment are related  
 (b) only energy and economy are related  
 (c) all the three are interrelated  
 (d) all the three are independent
7. Global warming is mainly caused due to  
 (a) emission of heat from engines  
 (b) emission of  $\text{CO}_2$  due to burning of fossil fuels  
 (c) use of nuclear energy  
 (d) air pollution
8. Use of nuclear energy is opposed due to  
 (a) rapid depletion of nuclear uranium reserves  
 (b) its high cost  
 (c) ecological imbalance caused due to its use  
 (d) possibility of accident and radioactive pollution due to nuclear waste
9. Global warming would lead to  
 (a) increase of agriculture production  
 (b) acid rains  
 (c) change of climatic pattern and its severity  
 (d) increase in the efficiency of heat engines
10. What is the energy density of petrol?  
 (a) 100 MJ/kg      (b) 51 MJ/kg      (c) 10 MJ/kg      (d) 150 MJ/kg
11. What percentage of global fossil fuel reserves are found in India?  
 (a) 20%              (b) 17%              (c) 6.85%              (d) 4%
12. What is the potential of power generation from renewable sources in India?  
 (a) 1,00,000 MW      (b) 8,00,000 MW      (c) 10,000 MW      (d) 7,000 MW
13. The most desirable option for energy farming of bio-diesel is the cultivation of suitable plants on  
 (a) good fertile land of the country  
 (b) roof tops of buildings  
 (c) sea  
 (d) marginal and fallow land, not suitable for normal agriculture
14. For a reversible adiabatic process, the change in entropy is  
 (a) zero              (b) minimum              (c) infinite              (d) unity
15. The processes of a Carnot cycle are  
 (a) two adiabatic and two constant volume  
 (b) two isothermal and two constant volume  
 (c) two adiabatic and two isothermal  
 (d) two constant volume and two constant pressure
16. In a Carnot engine, when working fluid gives heat to the sink, the temperature of the sink increases  
 (a) temperature of the source decreases  
 (c) temperature of both the source and the sink decreases  
 (d) temperature of the sink remains the same
17. The efficiency of an ideal Carnot engine depends on  
 (a) the working substance  
 (b) the temperature of both the source as well as sink

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Non-conventional Energy Resources



# 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.

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**(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<sup>1</sup>. 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 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).

## **SALIENT FEATURES OF "ENERGY CONSERVATION ACT, 2001"**

### **2.1**

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 through 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%.

## **2.2 VARIOUS ASPECTS OF ENERGY CONSERVATION**

**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 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 turbines, 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).

**(i) Proper Operation and Maintenance** Leaks 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.

## 2.5

### COGENERATION

A procedure for generating electric power and useful heat in a single installation is known as cogeneration. Heat may be supplied in the form of steam, hot water or hot air. The net result is overall increase in the efficiency of fuel utilization.

#### 2.5.1 Types of Cogeneration Principles

**1. The Topping Cycle** Primary heat (heat at high temperature) is used to generate high pressure and temperature steam for electrical-energy generation. The discharged low-grade heat, which would otherwise be dispersed to the environment, is utilized in an industrial process or in other ways.

**2. The Bottoming Cycle** Primary heat at high temperature is used directly for industrial process requirements. The remaining low-grade heat is then used for electrical-power generation, e.g., high-temperature cement kiln.

Cogeneration is advisable for industries, which can produce electricity in a cheaper and more convenient way than buying from utility.

The efficiency,  $\eta_{eo}$  of a cogeneration plant is given by

$$\eta_{eo} = \frac{E + \Delta H}{Q_a}$$

where  $E$ = electric energy generated

$\Delta H_f$  = heat energy utilized from process steam (hot water)

$Q_a$  = heat added to plant (in coal, fuel, etc.)

For separate generation of electricity and process steam, the heat added per unit of total energy output is

$$\frac{e}{\eta_e} + \frac{(1-e)}{\eta_u}$$

where  $e$ = electrical fraction of total energy output

$$e = \frac{E}{E + \Delta H_f}$$

$\eta_e$  = efficiency of electric plant

$\eta_u$  = efficiency of process steam generation plant

The overall efficiency,  $\eta_{eo}$  of separate generation of electricity and process heat is given by:

$$\eta_c = \frac{1}{\frac{e}{\eta_e} + \frac{(1-e)}{\eta_h}}$$

Cogeneration is economical only if the efficiency of the cogeneration plant exceeds that of the overall efficiency of separate generating plants for electricity and heat.

There are three general types of cogeneration systems:

**(i) Waste Heat Utilization** The major purpose of this system is to generate electricity (i.e., by a utility in a central power system) with heated water as a byproduct. The heat thus available can be used at a location near an electric power plant. This type of cogeneration is referred as *waste heat utilization*.

The heat discharged in steam turbine condenser cooling water from an electric power generation plant is utilized for some beneficial purpose. About 50 to 65% of the heat supplied either by fossil fuel or by nuclear fuel in existing steam plants is removed by cooling water. This heat is dissipated to the environment by direct discharge of warm water to the ocean or a river by passing through a cooling lake or cooling tower. Various possibilities are being considered for the large amount of heat that is lost in this way.

**(a) Space Heating and Cooling** Warm water can be distributed to homes, offices, stores and industry for space heating and domestic use. This is referred as *district heating*. Cooling can also be achieved with hot water using the absorption cooling principle. However, to be useful for space heating and cooling, the temperature of water should be 49–100°C.

**(b) Warm Water in Agriculture** Warm water at a temperature 24–46°C can be used to heat greenhouses, and for soil warming in order to extend growing season of trees and vegetables in winter.

**(c) Warm Water in Aquaculture** The yield of fish from a given pond relative to nutrients supplied increases if a temperature of about 32°C is maintained throughout the year. An essential requirement for economic aquaculture is a supply of low-cost nutrients. Various small plants and animal organisms upon which fish normally feed can also be produced in warm water ponds supplied with various animal and food processing wastes.

**(ii) Total/Integrated Energy System for Residential Complex** This system is designed to meet both the electrical demand (for lighting, refrigeration, domestic electrical appliances, elevators, etc.) and heat demand (for hot water and space heating and cooling) of a large building complex or a community. The TES (Total Energy System) is a self-contained system, which works independent of external power sources. The IES (Integrated Energy System) is a more flexible utility-



connected system and energy can be bought from or sold to utility depending upon power demand and availability situation.

A total energy system utilizes a heat engine (diesel engine, gas turbine or steam turbine) to convert a part of heat to useful mechanical energy, which in turn is converted to electrical energy by a generator. The remaining rejected heat is used for thermal requirements. The electric generation efficiency of total energy system may be lower than that of a central-station power plant, but the utilization of rejected heat that would otherwise be dissipated to surroundings can result in an increase of some 25% in overall fuel utilization efficiency.

**(iii) Total Energy System (TES) for Industry** Here, the objective is to produce both electricity and industrial process heat for an industry. The heat component may be supplied in the form of steam, hot water and/or hot air. Many industries (e.g., petroleum refineries, chemical plants, pulp and paper industries, etc.) use a large amount of process heat as well as electrical energy to operate pumps, etc. In these cases, cogeneration can result in 30% saving of fuel compared to separate generation of electricity and process heat.

### Example

#### 2.1

An industry has a daily requirement of 200 tonnes of coal to meet its electrical energy and thermal energy requirements of  $1.2 \times 10^6$  MJ and  $1.6 \times 10^6$  MJ respectively. It uses a cogeneration plant for this purpose. What is the overall efficiency of the plant? If it makes use of two separate plants for electrical and thermal power production instead of a cogeneration plant, what will be the combined overall efficiency? The efficiency of the individual electrical and thermal plants is 30% and 80% respectively. The heating value of the coal may be assumed as 20 MJ/kg.

#### Solution

Total thermal input to the plant,  $\mathcal{Q}_h = 200 \times 10^3 \times 20 = 4 \times 10^6$  MJ

Electrical energy generated,  $E = 1.2 \times 10^6$  MJ

Heat energy generated,  $\Delta H_s = 1.6 \times 10^6$  MJ

The efficiency of cogeneration plant,

$$\eta_{hs} = \frac{E + \Delta H_s}{\mathcal{Q}_h} = \frac{1.2 \times 10^6 + 1.6 \times 10^6}{4 \times 10^6} = 70\%$$

The electrical fraction of total output,

$$\epsilon = \frac{E}{E + \Delta H_s} = \frac{1.2 \times 10^6}{1.2 \times 10^6 + 1.6 \times 10^6} = 0.4286$$

Given, the efficiency of electrical plant,  $\eta_e = 30\%$

Also, given, the efficiency of thermal plant,  $\eta_{hs} = 80\%$

The overall efficiency for separate generation of electrical and thermal energy is given by



$$\eta_t = \frac{1}{\frac{\epsilon}{\eta_r} + \frac{(1-\epsilon)}{\eta_b}} = \frac{1}{\frac{0.4286}{0.30} + \frac{0.5714}{0.80}} = \frac{1}{1.4286 + 0.714} = 0.466$$

$$\eta_t = 46.6\%$$

## COMBINED CYCLE (BINARY CYCLE) PLANTS

**2.6** In a combined cycle plant, electric power is produced using two heat engines in tandem as prime movers. The heat discharged from one heat engine is not wasted into the atmosphere but serves as the source for the next heat engine. The net result is a greater overall operating temperature range (i.e., between the initial heat source and final heat sink) than is possible with a single heat engine. The thermal efficiency of a combined cycle system is thus greater than that for the two heat engines operating independently.

The highest inlet steam temperature for a steam turbine is limited by the properties of the materials to about 540°C. However, the flame temperatures of burning fossil fuel in a boiler may be more than 1650°C. Consequently, in a combined cycle system, steam turbine is preceded by a topping cycle heat engine, which can utilize heat at higher temperatures. The working fluid leaves the topping cycle at a sufficiently high temperature to generate steam for the steam turbine.

Because the technology is well developed for the gas turbine, it is most commonly used as a topping cycle engine. The turbine exhaust gases at a temperature of 600°C or more pass through a waste heat (heat recovery steam generator) boiler where steam is produced from water under pressure. In addition to using fuel more efficiently, a combined gas and steam turbine generating system requires lesser condenser cooling water for a given electrical output than a steam turbine generator alone.

A gas turbine works on the Brayton cycle and has an efficiency of about 20%. The steam turbine works on the Rankine cycle and has an efficiency of about 35%. The efficiency of combined cycle power plant is about 45–50%. Figures 2.1 to 2.4 show various schemes of open cycle and combined cycle power plants.

An Integrated Gasification Combined Cycle (IGCC) generating plant uses a cheaper fuel i.e., coal, after converting it to gas. Gasification is the cleanest method of utilization of coal, while combined cycle generation gives maximum efficiency. There is no air pollution due to fly ash, as it is collected as bottom ash in the gasifier and CO<sub>2</sub> emissions are also much less compared to coal combustion in solid form. In an IGCC plant, gasification of coal along with combined cycle generation is integrated in a single installation. The higher efficiency of IGCC also results in reduction in coal consumption per MW of power generated. Cogeneration, utilizing waste heat would further increase the efficiency. It is being developed indigenously by BHEL, India.

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### Non-conventional Energy Resources

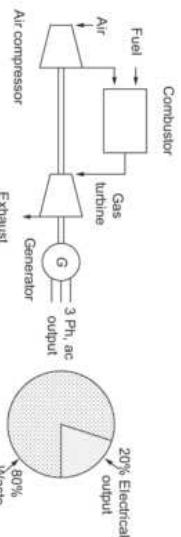


Fig. 2.1 (a) Open cycle (simple cycle) gas turbine power plant

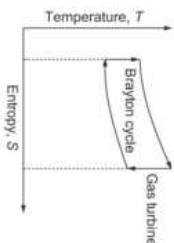


Fig. 2.1 (b) T-S diagram of open cycle (simple cycle) gas turbine power plant

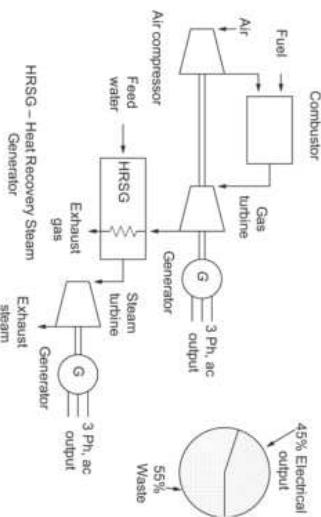


Fig. 2.2 (a) Combined-cycle power plant

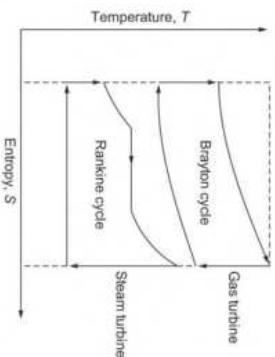


Fig. 2.2 (b) T-S diagram of combined-cycle power plant

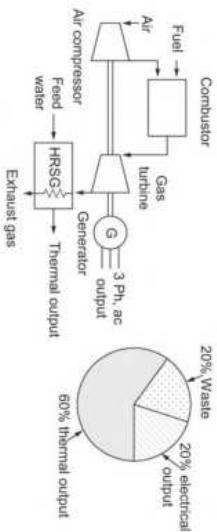


Fig. 2.3 Open cycle (simple cycle) gas turbine power plant with cogeneration

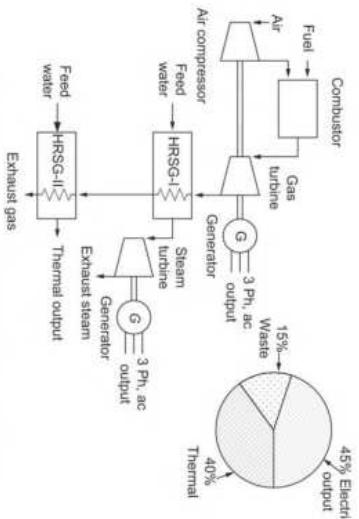


Fig. 2.4 Combined cycle power plant with cogeneration



### Review Questions

- What do you understand by energy conservation? Explain its various aspects.
- For solving a problem of increased energy demand, evaluate the benefits of energy conservation as compared to increasing the generation capacity.
- Write your views on the energy planning issues aiming to bridge the gap between the energy demand and supply situation in India.
- How much energy-saving potential exists in the Indian industry without any major investment?
- What do you understand by energy audit?
- What is meant by ECOs and ECMS? Enumerate some general ECOs.
- Explain the different categories of ECOs. Explain ECOs of electrical industry.
- Explain the terms energy management, energy strategy, energy policy and energy planning.
- What do you understand by cogeneration? How is TES different from Integrated Energy System?
- Explain the principle of waste heat utilization and its various applications.
- Why is a binary cycle plant more efficient than an open cycle plant? Comment on the amount of energy saved by using a gas-steam binary cycle plant instead of a simple open cycle steam turbine based generating plant.
- What are the advantages of an IGCC generating plant?
- What are the various principles of energy conservation?
- Explain the concept of daylight saving as a means for energy conservation.
- Explain various aspects of energy conservation.

(Ans. Cogeneration)

### Problem

- An industry requires 20 MW electrical power and 40 MW process heat for production. There are two alternative options to meet the requirements: (i) use a cogeneration unit having an overall efficiency of 65%, or (ii) use two separate units for electrical and thermal outputs. The efficiencies of electrical and thermal power units are 25% and 80% respectively. Which option out of the above two will best serve the interest of the owner on the basis of overall efficiencies in each case?

### Objective-type Questions

- Why should energy conservation be encouraged?
  - To halt further growth of GDP
  - To encourage use of manual labour
  - To discourage people using luxuries
  - To conserve non-renewable energy sources and environment
- What percentage of energy saving potential exists in the total spectrum of industries in India?
  - 5%
  - 50%
  - 10%-25%
  - 90%

Energy Conservation



3. Energy conservation means
  - (a) reducing energy consumption by reducing the production
  - (b) reducing the energy consumption without compromising the quantity or quality of production
  - (c) increasing the output by consuming more energy
  - (d) reducing energy consumption by reducing the output
4. Energy audit is carried out to
  - (a) check energy theft
  - (b) verify adherence of rules and regulations in financial matters
  - (c) calculate total annual energy consumed by a user
  - (d) check any lapses in respect of efficient use of energy and to suggest measures for its correction
5. Recycling of waste
  - (a) encourages production of second-grade product
  - (b) conserves both material and energy
  - (c) causes environmental pollution
  - (d) consumes more energy as compared to manufacturing from fresh material
6. Cogeneration means
  - (a) power production using binary cycle
  - (b) power production using two types of primary energy sources
  - (c) generation of ac as well as dc powers in the same installation
  - (d) generation of electricity and heat in a single installation
7. From the energy-conservation point of view, which type of energy source would you prefer for the purpose of space heating in winter?
  - (a) Electrical energy
  - (b) Low-grade thermal energy available as a by-product of a process
  - (c) Heat energy available from burning of petrol
  - (d) Heat energy available from burning of biomass
8. Simple electrical ECOS
  - (a) increase the power consumption
  - (b) are difficult to implement
  - (c) are very expensive to implement
  - (d) require least cost



# Energy Storage

## Introduction

In contrast to fossil-fuel and nuclear-fuel-based energy, the initial input power of a renewable energy source is outside our control. The use of renewable energy supplies constitutes a diversion of a continuing natural flow of energy; there are problems in matching supply and demand in a given time domain, i.e., matching the rate at which energy is used. The mismatch varies with time on scales of months (e.g., house heating in temperate climates), days (e.g., artificial lighting) and even seconds (e.g., starting motors).

The means of storing energy in a readily recoverable form when the supply exceeds the demand for use at other times is known as energy storage. Storage of primary fuels (e.g., coal, oil and gas) is also a form of energy storage, but the term 'energy storage' generally applies to secondary energy rather than to primary energy.

The performance of various energy-storage mechanisms can be measured and compared in (i) MJ<sup>-1</sup>; (ii) MJ m<sup>-3</sup>; (iii) MJ kg<sup>-1</sup>. The first is a very important and deciding factor but is difficult to estimate. The second is important where space is a prime consideration (e.g., indoor applications). The third is considered when weight is vital (e.g., in aircrafts).

## 3.1

### NECESSITY OF ENERGY STORAGE

1. The effective utilization of intermittent and variable energy sources such as sunlight, wind, etc. often requires energy storage.
2. In some circumstances, electrical energy may be generated either on land or at sea, at a location that is too distant from a consumption centre for conventional transmission lines to be used, for example, Ocean Thermal Energy Conversion. Means must then be found for both storing the energy and transporting it economically, to a load centre.
3. Electrically propelled vehicles, which are expected to come into increasing use, also require some form of energy storage. Since the vehicle must carry its energy supply, the storage system must be readily transportable.
4. Energy storage is also required for 'load levelling' in an electric utility to reduce the overall cost of generating electrical power. More efficient plants may be operated continuously at a rated power level, and the excess power during off-peak period is stored for use when the demand exceeds the base load. Thus, the use of less efficient units to meet the additional demand for power during peak load periods is eliminated.



## ENERGY STORAGE METHODS

**3.2** Energy can be stored in various forms and the storage methods are classified on the basis of the form in which it is stored. Some of the important energy storage methods are the following :

1. Mechanical energy storage
  - (a) Pumped storage
  - (b) Compressed air storage
  - (c) Flywheel storage
2. Chemical energy storage
  - (a) Batteries storage
  - (b) Hydrogen storage
  - (c) Reversible chemical reactions storage
3. Electromagnetic energy storage
4. Electrostatic energy storage
5. Thermal (heat) energy storage
  - (a) Sensible heat storage
  - (b) Latent heat storage
6. Biological storage

### 3.2.1 Mechanical Energy Storage

**(a) Pumped Storage** Pumped storage is the most successful, economical and widely used energy-storage technique presently available to electrical utilities for load levelling (peak shaving). It could also be used for storing electrical energy produced from solar and wind energy. Electrical power in excess of immediate demand is used to pump water from a supply (lake, river or reservoir) at a lower level to a reservoir at a higher level. During peak demand period when the demand exceeds the normal generating capacity, water is allowed to flow backwards through a hydraulic turbine, which drives an electric generator and produces power to meet additional demand. The layout diagram of a typical pumped storage system is shown in Fig. 3.1.

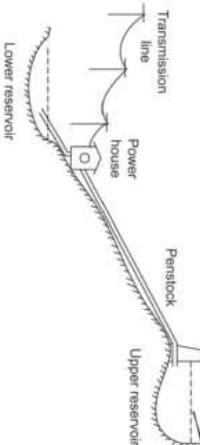


Fig. 3.1 Pumped storage system

  
Non-conventional Energy Resources

In most pumped storage plants, the turbine generator system is reversible and can serve to pump water as well. In the pumping mode, the generator works as motor and draws electrical power from the electrical network. The turbine then operates as a pump driven by the motor. Start up of the turbine-generator or reversal from motor-pump to turbine-generator requires only a few minutes. The overall energy recovery efficiency of pumped storage, that is, the recovered electrical energy as a percentage of electrical energy used to pump water, is about 70 per cent.

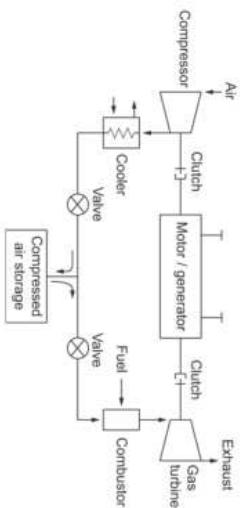
There are relatively few suitable sites where there is water supply at a lower level and a reservoir can be constructed at a higher level. However, the use of natural or excavated underground caverns as lower reservoirs, now being developed, should greatly increase the number of possible sites.

**(b) Compressed Air Storage** In a compressed-air storage system, excess electrical energy is used to compress air, which is stored in a reservoir to be used later in the combustor of a gas turbine to generate electric power. In a gas turbine, roughly 60% of the power output is consumed in compressing air for combustion of the gas. Compressed air can also be used to produce mechanical output through an air turbine.

Electric power in excess of immediate demand is supplied to the motor/generator unit which drives the compressor. The compressed air, at about 70 atm, is stored in a suitable reservoir. The air is heated during compression and may have to be cooled prior to storage to prevent damage to the reservoir walls. When additional power is needed to meet the demand, the compressed air is released and heated in a combustor using gas or oil fuel. The hot compressed air is then expanded in a gas turbine connected to the motor/generator unit which now acts as generator. The schematic diagram is shown in Fig. 3.2. The overall recovery efficiency is 65 to 70 per cent. A clutch is used for coupling and decoupling the motor/generator unit with a compressor/turbine.

Compressed-air storage reservoirs would probably be too large and too expensive for above-the-surface construction; hence underground reservoirs preferably the naturally existing ones, are being considered. Among the possibilities are natural caverns, deep aquifers, depleted gas or oil reservoirs, mined-out rocks or salt caverns, and abandoned mines. A commercial installation is in operation near Bremen, Germany.

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**Fig. 3.2** Compressed-air energy storage

**(c) Flywheel Storage** Flywheels have been used extensively to smooth out power pulses from reciprocating engines. The same principle may be extended to store surplus electric energy. A specially designed flywheel, known as *super flywheel*, is used for energy storage. The flywheel driven by an electric motor during off-peak hours stores mechanical energy (kinetic energy) as its speed is increased. The stored energy may be retrieved when required to produce electrical energy by coupling a generator to it. The same machine serves both as a motor when electric energy is supplied and as a generator when the flywheel serves as a prime mover and electrical energy is regenerated. The energy recovery efficiency is estimated to be up to 90 per cent.

The kinetic energy of rotation of an object is

$$E = \frac{1}{2} I \omega^2$$

where  $I$  is the moment of inertia of the object about its axis, and  $\omega$  is its angular velocity (rad/s). For a uniform disk of mass  $m$  and radius  $a$ , the moment of inertia,  $I$ , is given by

$$I = \frac{1}{2} m a^2$$

Thus, energy density of a uniform disk is

$$W_s = E / m = \frac{1}{4} a^2 \omega^2$$

When energy is added to the flywheel, its speed rises to a higher value. Similarly, when energy is retrieved, its speed falls. For a flywheel to serve as a useful store of energy (and not just a smoothing device), it must rotate as fast as possible. However, its angular velocity is limited by the strength of the material, which has to resist the centrifugal forces tending to fling it apart. For a uniform wheel of density  $\rho$ , the maximum tensile stress is

$$\sigma_{\max} = \rho a^2 \omega^2$$

In general, for a particular shape,

$$W_{\pi} = \frac{1}{4} K \sigma^2 \omega^2$$

and

$$W_{\pi}^{\max} = \frac{K \sigma^{\max}}{4\rho}, \text{ where } K \text{ is a constant } \approx 1.$$

Conventional materials such as steel give rather low energy densities (typically 0.06 MJ/m<sup>3</sup>). Much higher energy densities can be obtained by using lightweight fiber composite materials, such as fiberglass in epoxy resin, which has a higher tensile strength  $\sigma^{\max}$  and lower density  $\rho$ . To make the best use of these materials, flywheels should be made in unconventional shapes with the strong fibers aligned in the direction of maximum stress. Such systems can have energy densities of 0.5 MJ/kg or even higher.

Advanced (or super) flywheels are those which operate at a very high speed, have high mechanical strength and low frictional losses. For eliminating bearing friction, the rotor can be magnetically levitated by permanent magnets. Wind friction is eliminated/reduced by putting the flywheel in a sealed vacuum chamber. These super flywheels are used for storing mechanical energy for long / short-term bases.

Flywheel storage can be installed anywhere and takes up little land area, a distinct advantage over pumped storage. Units with 100-tonne flywheels would have a storage capacity of about 10 MWh. Larger storage demands would probably best be met by cascading many such units. Mobile storage is also possible with flywheels.

Flywheels also offer an interesting alternative to storage batteries for use in battery-powered vehicles, especially since the energy in a flywheel can be replenished more quickly than a battery. Flywheel storage can also be used to improve transient stability of a power supply network due to its large rotational inertia and the capability to quickly discharge a high energy level in a short duration.

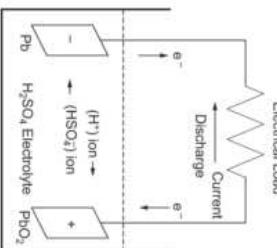
### 3.2.2 Chemical Energy Storage

**(a) Battery Storage** A storage battery receives electrical energy as direct current and stores it in the form of chemical energy by a reversible electrochemical reaction. On connecting to an electrical load, it supplies electrical energy by converting the stored chemical energy back into electrical energy as direct current. Thus, both input and output are in the form of electrical energy though storage is in the form of chemical energy. Due to this reason, some people classify it in the category of electrical storage. The energy recovery efficiency depends on the type of battery and the rate of discharge; the typical value is around 75%.



## Energy Storage

Although many electrochemical reactions are reversible in theory, few are suitable for a practical storage battery. The most widely used storage battery is the *lead-acid battery*, invented by Gaston Planté of France in 1859. The lead-acid battery technology has attained maturity and has high performance over cost ratio, even though it has the least energy density by weight and volume compared to other rechargeable batteries.



**Fig. 3.3 Lead-acid cell**

**Theory** A battery consists of a combination of individual cells. In any electrochemical cell, two plates (positive and negative) are immersed in a conducting solution (electrolyte). In this case the plates are in the form of grids, holding pastes of lead and lead oxides respectively. The electrolyte is sulphuric acid, which ionizes as  $H^+$  and  $HSO_4^-$ . Figure 3.3 shows one such cell.

**During Discharge** The reaction at the negative electrode is given by



The lead at the negative electrode is converted to lead sulphate and takes the place of the lead paste in the plate. The electrons so liberated travel through the external circuit to the positive electrode.

The reaction at the positive electrode is



This  $PbSO_4$  likewise replaces the  $PbO_2$  in that plate. The electrical current through the solution is carried by  $H^+$  and  $HSO_4^-$  ions through the sulphuric acid. The reactions are reversed during the charging operation and the original active materials are regenerated at the positive and negative plates.

The emf of a lead-acid cell depends on the concentration of sulphuric acid. The voltage of a fully charged cell is close to 2.1 V and the specific gravity of the electrolyte is 1.26 to 1.28 at 25°C. On discharge, the sulphuric acid is consumed at both electrodes, as both Pb and  $PbO_2$  are converted to lead sulphate. Water is produced, which dilutes the acid. With reduced acid concentration, the emf of the cell also decreases steadily. The cell is generally regarded as fully discharged when the specific gravity is about 1.08 at 25°C and the emf is roughly 1.7 V. Both acid concentration and emf are restored when the cell is charged.

The amounts of active materials do not affect the cell emf, but they determine the energy storage capacity of the cell (or battery). The storage capacity is increased by increasing the area of active materials exposed to the electrolyte. This is achieved by connecting in parallel a substantial number of alternate positive and negative plates.



## Non-conventional Energy Resources

Lead-acid batteries are commonly used as mobile source of energy for SLI (starting-lighting-ignition) systems of automobiles. Except when starting the engine, the current drain from the battery is relatively small. Also, these are nearly always maintained in a fully charged state by the generator coupled to the engine.

Batteries for emergency or portable power systems, vehicle propulsion and electric utility applications, however, may be subjected to almost complete (or deep) discharge before being recharged. Special heavy-duty batteries are needed to withstand a series of such deep charge-discharge cycles. Tubular positive plates are often utilized in heavy-duty batteries. The plates are actually a set of connected tubes, made from an inert porous material (e.g., woven glass or plastic fibers), containing chemically prepared active lead dioxide. A central spine of lead provides electrical connection.

Battery storage is utilized for battery-operated vehicles, solar PV systems and small wind electric systems.

**Advantages of Storage Batteries** These are modular in nature and are easily adaptable to any type of storage with varying capacity by suitably combining a number of units.

1. These are capable of rapid reversal of operation between charging and discharging. This makes the batteries especially convenient for electric utility applications.
2. They permit dispersed distribution by locating storage facilities near load centers.

**Limitations of Storage Batteries** The chief limitations are high cost and short life of the battery.

1. Battery life is limited due to two reasons mentioned below:
    - Solid Pb is almost twice as dense as  $\text{PbSO}_4$  formed during the discharging process. Therefore, it is difficult to fit the  $\text{PbSO}_4$  crystals into the space originally occupied by the Pb paste in the negative electrode. In practice, some  $\text{PbSO}_4$  falls to the bottom of the cell during every discharge. This constitutes an irreversible loss of active material.
    - In SLI batteries of automobiles, the material of the grid is not pure lead but a [lead-antimony] alloy, which is stronger and better able to withstand the mechanical stresses during motion. But this causes self-discharge of the positive electrode as antimony promotes the following reaction:
- $$5\text{PbO}_2 + 2\text{Sb} + 6\text{H}_2\text{SO}_4 \longrightarrow (\text{SbO})_{2/3}\text{SO}_4 + 5\text{PbSO}_4 + 6\text{H}_2\text{O}$$
- This slow but irreversible reaction removes active material from the plate and reduces the life of the battery. The normal life of an SLI battery is one to two years.

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Batteries for stationary applications (photovoltaic lighting systems, etc.) can use Sb free plates and have longer life (up to 7 years) if not excessively discharged.

2. An ordinary battery cannot be allowed to discharge more than about 50% of its stored energy. Such a discharge is known as *deep discharge*. Sometimes, it may not be possible to recharge or revive the battery after a deep discharge. The reason is explained below:
- If the discharge reaction is allowed to go to completion, all the lead may be consumed and there would be no electrode left for reverse reaction. Similarly, if the concentration of  $\text{H}_2\text{SO}_4$  is allowed to fall too low, the electrolyte ceases to be an adequate conductor.

3. Heavy weight of the battery is another serious drawback. Non-active materials (separators, case, water, etc.) contribute significantly to the total weight of the battery. Therefore, the energy density of a storage battery is low (typically 0.09 MJ/kg).
4. The cost of the battery storage is high.
5. The internal impedance of a battery is high, which causes voltage fluctuations during transient load.

Other types of rechargeable batteries, specially being developed for mobile applications are briefly discussed below:

- (i) **Nickel-Cadmium (NiCd) Battery** The NiCd cell has a positive electrode made of cadmium and the negative electrode of nickel hydroxide. A nylon separator separates the two electrodes. The electrodes are contained in a sealed stainless steel casing having potassium hydroxide electrolyte. Due to the sealed casing and light weight (half that of the lead-acid cell), these are preferred for most rechargeable consumer applications. They have a longer deep-cycle life and are more temperature tolerant than the lead-acid batteries. However, this cell has a memory effect, which degrades its capacity if not used up to full discharge state for a long time. Also, its disposal poses environment problems due to the use of cadmium.

- (ii) **Nickel-Metal Hydride Battery** In this cell, the cadmium anode is replaced by a metal hydride anode. This eliminates the environmental concern related to cadmium. This also improves the energy density and has negligible memory effect. The NiMH cell, however, is less capable of delivering high peak power, has high self-discharge rate, is susceptible to damage due to overcharging and is more expensive compared to an NiCd cell.

- (iii) **Lithium-ion Battery** This is a newly developed technology and offers three times the energy density over that of a lead acid-battery. This is due to (i) low atomic weight of 6.9 versus 207 for lead, and (ii) higher cell voltage of 3.5 V versus 2.0 V for lead-acid cells. This requires fewer cells in series for a given battery voltage, thus reducing the cost.



On the other hand, the lithium electrode reacts with any liquid electrolyte, creating a sort of passivation film. Every time when the cell is discharged and then charged, the lithium is stripped away, a free metal surface is exposed to the electrolyte and a new film is formed. This would shorten the life of the cell. To compensate for the loss, the cell uses a thick electrode, adding to the cost.

(iv) **Lithium-Polymer Battery** It has a film of metallic lithium bonded to a thin layer of solid polymer electrolyte. The solid polymer enhances the cell's specific energy by acting both as electrolyte as well as separator. Moreover, the metal in a solid electrolyte reacts less than it does with a liquid electrolyte.

(v) **Zinc-air Battery** It has a zinc negative electrode, a carbon positive electrode, which is exposed to air (also known as air electrode) and a potassium-hydroxide electrolyte. During discharge, it absorbs oxygen from the air, converts it into oxygen ions for transport to the zinc electrode, which in turn gets oxidized. During the charging operation, it evolves oxygen. Efficient air management is essential for good performance of a zinc-air battery.

### **(b) Hydrogen Storage**

Energy can be both stored and transported as hydrogen, which serves as a secondary fuel. The input energy, usually electrical, serves to decompose water by electrochemical (electrolysis) reaction into its constituent elements—hydrogen and oxygen. These substances can then be combined to release the stored energy as required. Instead of using the oxygen produced from water, oxygen from the air is commonly employed. The pure oxygen from water can then be sold for industrial application. In case of thermal energy input, it is possible to decompose water by heat (thermolysis) as a result of a series of chemical reactions. The heat from a solar concentrator may be cheaper than electricity.

The chemical energy in hydrogen (and oxygen) can be converted into thermal, mechanical, or electrical energy. One possibility is to burn hydrogen in air, in a manner similar to natural gas, to produce thermal energy for use in home or industry. Hydrogen can also serve as fuel, in place of gasoline in automobiles, to obtain mechanical energy. Hydrogen-fired steam turbines may also be used to obtain mechanical energy. Electrical energy can then be generated from mechanical energy thus obtained by using a generator. Electrical energy may also be obtained more efficiently (at about 55 to 60% conversion efficiency) directly from hydrogen by means of a fuel cell.

Hydrogen can be stored in three ways:

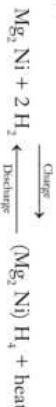
**Gas Form** Hydrogen in large quantities can be stored in underground caverns such as those from which natural gas has been extracted. But storage of hydrogen gas, even if compressed, is bulky. It occupies more volume than natural gas.

**Liquid Form** Hydrogen can be liquefied for storage. But since its boiling point is 20 K, these stores are difficult to maintain due to refrigeration requirements.

## Energy Storage



**Metal-hydride Form Hydrogen** can be stored as reversible metal hydrides in large volumes. When required, hydrogen is released by heating the hydride. One such example is given below:



This reaction is reversible and the hydride store can be replenished with hydrogen. A portable hydride store can be used for distribution of energy like a conventional mobile fuel tank. The store can be replenished with hydrogen at a central filling station. The main difficulty is the weight and cost of the metals used.

### (c) Reversible Chemical Reactions Storage

Thermal energy can be stored in chemical bonds by means of reversible thermochemical reactions. A reversible chemical reaction is one that proceeds simultaneously in both directions. In this class of energy storage, a type of reversible reaction  $\text{AB} + \Delta\text{H} \leftrightarrow \text{A} + \text{B}$  takes place that occurs predominantly in one (forward) direction at higher temperature with absorption of heat, and predominantly in the opposite (reverse) direction at a lower temperature with emission of heat. The temperature above which the equilibrium shifts to the forward direction and below which it shifts to the reverse direction is known as the *turning temperature*. Such types of chemical reactions can be used for energy storage. The products of the forward reaction (endothermic decomposition), which store thermal energy (heat) as chemical energy, can be stored separately for a long duration at ambient temperature. The thermal energy may be recovered when the products are brought together and the conditions are changed to permit the reverse reaction (exothermic recombination) to occur.

Reversible thermochemical reactions of the type  $\text{A} + \text{B} + \Delta\text{H} \leftrightarrow \text{C} + \text{D}$  may also be used for the same purpose. Some of the possible reactions suitable for thermochemical energy storage are given in Table 3.1 below:

**Table 3.1** Thermochemical storage reactions

S.No.	Reaction	$\Delta H_{\text{KJ}}/(\text{kmol of reactants or products})$	Turning Temp, °C
1.	$\text{Mg(OH)}_2 \leftrightarrow \text{MgO} + \text{H}_2\text{O}$	81.6	258
2.	$\text{NH}_4\text{HSO}_4 \leftrightarrow \text{NH}_3 + \text{H}_2\text{O} + \text{SO}_4^{2-}$	337	467
3.	$2\text{NH}_3 \leftrightarrow \text{N}_2 + 3\text{H}_2$	92.26	466
4.	$\text{CH}_4 + \text{CO}_2 \leftrightarrow 2\text{CO} + 2\text{H}_2$	247.4	960
5.	$\text{CH}_4 + \text{H}_2\text{O} \leftrightarrow \text{CO} + 3\text{H}_2$	250.31	677



To be suitable for heat storage, the reaction system should involve the materials that are inexpensive and not too difficult to handle. Also, the forward and reversible reactions should occur at reasonable temperatures. One or more catalyst may be needed to speed up the desired reaction, especially at lower temperature.

Some of the advantages of reversible chemical reaction storage systems are

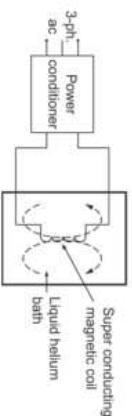
1. high energy density (much higher than sensible or latent heat storage)
2. storage at ambient temperature
3. low storage-related investment cost
4. suitable for both long-duration thermal storage and for long-distance thermal energy transport at ambient temperature

The main disadvantage is that the technology is still immature.

These methods are suitable for solar thermal power generation.

### 3.2.3 Electromagnetic Energy Storage (Superconducting Magnetic Energy Storage, SMES)

In this system, energy is stored in a magnetic field. As an example, a coil with an inductance of 300 H carrying a current of 5000 A can store energy of  $0.51I^2 = 3.75 \times 10^9 \text{ J}$ , (which is nearly 1 MWh, since  $1 \text{ MWh} = 3.6 \times 10^9 \text{ J}$ ) in its magnetic field. Under ordinary conditions, losses result from the resistance of the wire, and energy must be supplied continuously to maintain the current. However, if the resistance of the wire were made zero, the current would remain almost constant, once initiated, without requiring any external source of voltage (energy). Therefore, the stored energy in the magnetic field would be maintained indefinitely. By connecting the coil to a load, the stored energy could be recovered as electrical energy. This concept forms the very basis of electromagnetic energy storage.



**Fig. 3.4** Superconducting magnetic energy storage system

Electromagnetic energy storage requires the use of superconducting materials. These materials suddenly lose essentially all resistance to the flow of electric current when cooled below a critical temperature or transition temperature. All superconducting metals have transition temperatures in the *oxygenic* range (low temperature of the order of  $-273^\circ\text{C}$  to  $-150^\circ\text{C}$  or  $0 \text{ K}$  to  $123 \text{ K}$ ). It is also observed that if a magnetic field were applied on the superconducting material, the property of superconductivity vanished abruptly at a certain value of the magnetic field. Thus, the property of superconductivity is balanced precariously on the magnetic field and the temperature.

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In the SMES (shown schematically in Fig. 3.4), the coil, immersed in a cryogenic fluid like liquid helium, is charged by pumping direct current. The current then keeps on circulating and there results a high magnetic field surrounding the coil. This gives rise to axial (compression) and radial (expansion) magnetic forces. The radial expansion force, is very powerful, the coil swells and this must be constrained. It is therefore usual to embed the coil in a tunnel bored from underground bedrock by suitable structural members. These forces occur with a periodicity when the coil is charged and discharged. Also, as the material crosses the critical state and loses its superconducting stage, explosive forces are produced, and so the coil must be braced suitably.

Useful superconducting materials available commercially are niobium-titanium (Nb-Ti) alloy at temperatures below  $-263^{\circ}\text{C}$  and a compound of niobium and tin ( $\text{Nb}_3\text{Sn}$ ) below  $-255^{\circ}\text{C}$ . Efforts are on for developing high-temperature superconductors using oxides of yttrium and other elements. The prospects of using superconductor materials are far reaching not only for energy storage but also in other fields of electrical engineering.

A number of problems are associated with SMES. They include

1. Operation and maintenance of cryogenic (i.e., refrigeration) plant for producing the liquid helium required for low temperatures.
2. Special structures be needed to withstand strong magnetic forces

One very interesting SMES being used by the Bonneville Power Administration in the USA has the following details:

Maximum power capability	10 MW
Maximum stored capacity	30 MJ (8.33 kWh)
Coil current at full charge	4.9 kA
Maximum coil terminal voltage	2.18 kV
Coil operating temperature	4.5 K
Magnetic field strength	2.8 Tesla

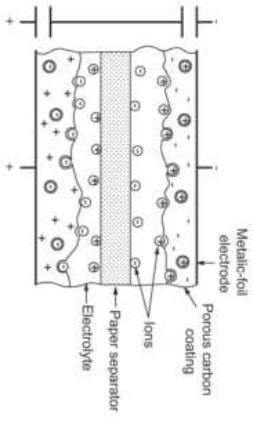
The coil is restrained from deforming axially by winding pre-stressed stainless steel strips at 816 atm.

### 3.2.4 Electrostatic Energy Storage

A capacitor stores energy in an electrostatic field when charged. To store a significant amount of energy, very large capacity (in kilofarads range) capacitors, known as *super/ultra capacitors* are required. The capacity of a capacitor can be increased by increasing the area of the electrodes (plates) and minimizing the distance between them. This is achieved in ultra-capacitors by coating a layer of activated porous carbon on metal-foil electrodes. These foils are separated by a paper separator and dipped in an electrolyte. The paper separator prevents

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electrical connection between the electrodes but allows free movement of ions across it. When connected to a dc voltage source, the electrons accumulate at the carbon coated on the foil attached to the negative terminal of voltage source. These electrons in turn, attract positive ions from the electrolyte into the pores of the carbon on that electrode. In the other electrode, meanwhile, positive charges accumulate, attracting negative ions into the pores of the carbon as shown in Fig. 3.5. The activated carbon's huge surface area comes from the great porosity of its microscopic nodules. It enables the positive and negative ions migrating through the electrolyte to find plenty of nooks and crannies to occupy as they insinuate themselves as closely as possible (atomically close) into the oppositely charged carriers inside the carbon. Notice that this is actually a pair of capacitors connected in series. At each electrode there is a separation of charges—electrons and positive ions at the negative electrode, and positive charges and negative ions at the positive electrode, each constituting a capacitor. So at each electrode there are two layers of charges, which is why ultra-capacitors are also known as electric double-layer capacitors. There are at present about ten manufacturers of ultra-capacitors. NessCap is producing a unit of 5000 farads at 2.7 V in a package slightly bigger than a half-litre soda bottle.



**Fig. 3.5** Ultra-capacitor construction

A super-capacitor/ultra-capacitor has much better cycle life (typically above 5,00,000) compared to batteries. These ultra-capacitors can be charged in seconds rather than hours and can function at more extreme temperatures. Commercially available ultra-capacitors can store about 3–4 watt-hours per kilogram compared to 60–70 Wh/kg typical of nickel–metal hydride batteries or 110–130 Wh/kg delivered by lithium ion batteries. An ultra-capacitor with battery-like energy density would be irresistible to a large number of users, especially hybrid electric vehicles. With their lightning-fast charge and discharge capability, ultra-capacitors could handle the power surges needed for accelerating, allowing the use of smaller battery packs in the vehicle (and eventually, perhaps no battery pack at all). It can also be used for 'stop-and-go' operation in hybrid gasoline cars. In this operation, the gasoline engine is extinguished at stops and started instantly again when required. An ultra-capacitor and a powerful starter motor would instantly jolt the engine back to life. Such vehicles would also make use of regenerative braking for charging of ultra-capacitors. In fuel-cell powered cars, ultra-capacitors may play a very important role. Fuel cells, by themselves deliver power too sluggishly to briskly accelerate a

## Energy Storage

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full-size car. They must be mated to a faster energy storage device, and for this, coupling with ultra-capacitors is superior in many respects to batteries.

### 3.2.5 Thermal Energy Storage

#### (a) Sensible Heat Storage

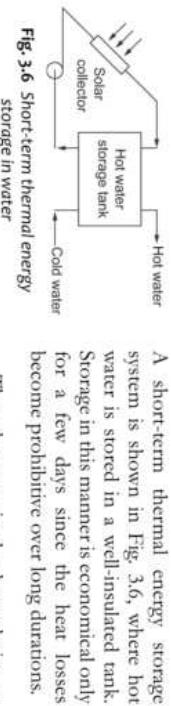
In this type of storage, thermal energy is stored by virtue of heat capacity and the change in temperature of the material during the process of charging and discharging. The temperature of the storage material rises when energy is absorbed and drops when energy is withdrawn. The charging and discharging operations, in a sensible heat-storage system, can be expected to be completely reversible for an unlimited number of cycles over the lifespan. On the basis of heat-storage media, it can be classified as (i) liquid media storage, (ii) solid media storage, and (iii) dual media storage.

(i) **Liquid Media Storage** Of available liquids, water can be considered to be the most suitable liquid media for storage below 100°C. Water has the following advantages:

1. It is abundant and inexpensive.
2. It is easy to handle, non-toxic and non-combustible.
3. Its flow can take place by thermo-siphon action.
4. It has high density, high specific heat, good thermal conductivity and low viscosity.
5. Can be used both as storage medium as well as working medium (thus eliminating the need for a heat exchanger, e.g., in a space-heating system)
6. Charging and discharging of heat can occur simultaneously;
7. Control of water system is flexible.

The main disadvantages with water as storage media are

1. Limited temperature range (0°C to 100°C).
2. Corrosive medium
3. Low surface tension (i.e., leaks easily)



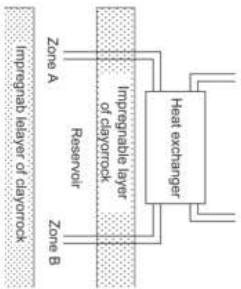
Though water is the best choice as a heat-storage medium in a space-heat system; other liquids such as oils, liquid metals and molten salts have also been used in solar thermal power plants. Table 3.2 shows the thermophysical properties of selected liquids for sensible heat

storage. Out of these, water appears to be the best sensible storage liquid available because it is inexpensive and has high specific heat. However, above 100°C, the storage tank must be able to contain water at its vapour pressure, and therefore, the storage-tank cost rises sharply; Organic oils, molten salts and liquid metals circumvent this problem.

**Table 3.2 Thermophysical properties of selected liquids for sensible heat storage**

S.N.	Medium	Temp. range ( $^{\circ}\text{C}$ )	Density ( $\text{kg}/\text{m}^3$ )	Heat capacity ( $\text{J}/\text{kg}^{\circ}\text{K}$ )
1.	Water	0 to 100	1000	4190
2.	Thermionial 66	-9 to 343	750	2100
3.	Hitec (molten salt)	142 to 540	1680	1560
4.	Engine oil	Up to 160	888	1880
5.	Lithium	180 to 1300	510	4190
6.	Sodium	100 to 760	960	1300
7.	Octane (organic liquid)	Up to 126	704	2400

Large size and long-term storage of hot water in underground reservoirs is possible without the use of special insulating materials. Figure 3.7 shows one such system schematically. Here, cold ground water from Zone A of an aquifer is heated by passing it through a heat exchanger and returned to Zone B where it is stored. In the discharge mode, the hot water from Zone B flows back through the heat exchanger where it gives out the stored heat and returns to Zone A. The heat from such aquifers can be retrieved with negligible losses, which may be of the order of one per cent only.



**Fig. 3.7 Long-term thermal storage in underground layers**

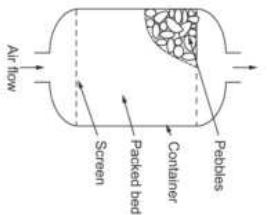
(ii) **Solid Media Storage (Packed Bed Storage)** It utilizes the heat capacity of a bed of loosely packed solid materials such as rocks, metals, concrete, sand, bricks, etc., to store energy. A fluid, usually air, is circulated through the bed to add or remove energy. Here, energy can be used at low or high temperature since these will neither freeze nor boil. The energy change for  $50^{\circ}\text{C}$  is about  $10 \text{ Wh/kg}$  for most rocks, concrete and iron ore.

A packed-bed storage unit consists of a container, a screen to support the bed, support for the screen and inlet and outlet ducts. Flow is maintained through the bed in one direction, during addition of heat and in the opposite direction during removal of heat. A typical packed-bed storage is shown in Fig. 3.8.

## Energy Storage



The main advantages and disadvantages of such a system are the following



**Fig. 3.8** Packed-bed storage unit

- |                      |   |
|----------------------|---|
| <b>Advantages</b>    | <ul style="list-style-type: none"> <li>• Rocks are abundant, low cost, easy to handle, non-toxic and non-combustible</li> <li>• High storage temperatures are possible</li> <li>• Heat exchanger can be avoided</li> <li>• No freezing problem</li> <li>• No corrosion problem</li> </ul> |
| <b>Disadvantages</b> | <ul style="list-style-type: none"> <li>• Storage volumes are large</li> <li>• High pressure drop</li> <li>• Simultaneous charging and discharging are not possible</li> </ul>   |

**(iii) Dual Media Storage** In dual media storage, both solid and liquid sensible heat storage materials are used. These solid and liquid materials may be combined in a number of ways. One of them is to jointly use the bedrock and water tank—a hybrid system, with water tank surrounded by bedrock.

### **(b) Latent Heat Storage (Storage in Phase Change Materials)**

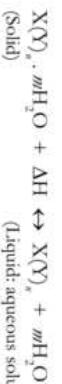
In this class of storage, energy is stored by virtue of latent heat of change of phase of the storage medium. Phase change materials have considerably higher thermal energy storage densities as compared to sensible heat storage materials and are able to absorb or release large quantities of energy at a constant temperature. Therefore, these systems are more compact but more expensive than sensible heat-storage systems. Various phase changes that can occur are

- solid-solid (lattice change)
- solid-gas
- solid-liquid
- liquid-gas

Solid-gas and liquid-gas transformations are not employed in spite of large latent heats as large changes in volume make the system complex and impracticable. In solid-solid transition, heat is stored as the material is transformed from one crystalline form to another. These transitions involve small volume changes, however, most of them have small latent heats.

The solid-liquid transformations include storage in salt hydrates. Certain inorganic salts, which are soluble in water and form crystalline salt hydrates, are employed. Let an inorganic salt, which is soluble in water be represented by

$X(Y)_n \cdot mH_2O$ . The crystalline salt hydrate is symbolized by  $X(Y)_n \cdot mH_2O$ . On heating up to the transition temperature, the hydrate crystals release water of crystallization and the solid remainder (anhydrous salt) dissolves in the released water as the following reaction takes place:



One problem with most salt hydrates is that the released water of crystallization is not sufficient to dissolve all the solid phase present. Due to density difference, the anhydrous salt settles down at the bottom of the container. This incongruent melting makes the process irreversible since the anhydrous salt at the bottom is unable to find water for recrystallization to the original hydrate. The recrystallization of an incongruently melting salt can be achieved either by (i) the use of suspension media or thickening agent or by (ii) mechanical means (vibration, stirring, etc.)

The heat transfer properties of some phase change materials are given in Table 3.3.

Table 3.3 Heat-transfer properties of phase-change storage materials

S/N	Material	Chemical compound	Melting point ( $^{\circ}C$ )	Heat of fusion ( $kJ/kg$ )	Density ( $kg/m^3$ )
1.	Sodium sulphate decahydrate (Glauber's salt)	$Na_2SO_4 \cdot 10H_2O$	31-32	251	1534
2.	Sodium thiosulphate	$Na_2S_2O_3 \cdot 5H_2O$	48-49	209	1666
3.	Calcium chloride hexahydrate	$CaCl_2 \cdot 6H_2O$	29-39	177	1634
4.	Sodium carbonate decahydrate	$Na_2CO_3 \cdot 10H_2O$	32-36	247	1442
5.	Disodium phosphate decahydrate	$Na_2HPO_4 \cdot 12H_2O$	36	265	1522

Other potential phase change materials apart from salt hydrates are paraffins (e.g.,  $C_{18}H_{38}$  etc., alkanes containing 14 to 40 C-atoms) and non-paraffin organic materials (e.g., esters, fatty acids, alcohols and glycols), which are suitable at certain situations.

### 3.2.6 Biological Storage

Solar energy can be stored biologically in plants by fixing carbon from  $CO_2$  available in the atmosphere. The fixation of carbon atoms from atmospheric  $CO_2$  to carbohydrates proceeds by a series of stages in green plants. This process

is known as *photosynthesis*. Photosynthesis is the synthesis (making) of organic structure and chemical energy by the action of solar radiation.

If this material (dry) is burnt in oxygen, the heat released is 470 kJ per mole of carbon or 4.8 eV per carbon atom. This biomass can also be converted into various types of solid, liquid and gaseous fuels.

### Review Questions

- What do you understand by energy storage?
- Under what circumstances does storage of energy become necessary?
- On what basis are energy storage systems classified? Can energy available in one form be stored in another form?
- Which types of energy-storage systems are suitable for peak shaving in electrical utility?
- State the main applications of flywheel energy storage.
- Which type of energy-storage method is employed in hybrid vehicles?
- Which type of energy-storage method is suitable to improve the transient stability of an electric-power grid?
- What are the main advantages and limitations of a battery-storage system?
- Describe various methods of storing hydrogen. Mention their relative advantages and limitations.
- How are electrical and thermal energies converted to hydrogen energy?
- Discuss the basic principle of storing energy in reversible chemical reactions. What are their main advantages? What do you understand by turning temperature?
- Explain the basic principle of superconducting magnetic energy storage. What are the possible superconducting materials for this system at present?
- What are the problems associated with SMES?
- What types of forces are produced while using SMES?
- What are the main advantages and disadvantages of sensible heat storage with water as storage media? Compare them with that of solid media storage?
- Why are solid-gas and liquid-gas phase changes not considered suitable for phase change storage?
- What are the main problems associated with use of salt hydrate as phase-change storage media?
- Describe the thermal energy-storage system of solar energy.  
(UPRU Lucknow 2003–04)
- What are the main limitations of compressed-air energy storage?
- Explain the main features of various types of storage batteries.
- Explain the construction of an ultra-capacitor. What features are provided to increase the amount of energy stored?

### Objective-type Questions

- Energy storage means
  - sparing primary energy for future generations
  - storing secondary energy in an easily recoverable form

  
Non-conventional Energy Resources

1. Which of the following statements is true about energy storage?
  - (a) conserving energy
  - (b) storing primary energy
2. Why is energy storage required?
  - (a) To match energy supply and demand in time domain
  - (b) To conserve energy
  - (c) To increase energy consumption
  - (d) To supply energy for many years to come
3. What is the approximate energy recovery efficiency of pumped storage?
  - (a) 90%
  - (b) 50%
  - (c) 70%
  - (d) 20%
4. Which statement is not true about pumped storage method?
  - (a) It is a well developed technology.
  - (b) It is site-specific and is not feasible everywhere.
  - (c) It is a very costly method.
  - (d) It is a portable energy storage medium.
5. Underground compressed air storage reservoirs are being considered
  - (a) as above-the-surface construction would be too large and too expensive
  - (b) for safety reasons
  - (c) to make use of geothermal heat
  - (d) none of the above
6. The energy-recovery efficiency of a flywheel storage is of the order of
  - (a) 50%
  - (b) 30%
  - (c) 10%
  - (d) 90%
7. The energy-storage capacity of a flywheel is increased by increasing the
  - (a) mass of the flywheel
  - (b) speed of rotation of the flywheel
  - (c) density of the material of the flywheel
  - (d) thickness of the flywheel
8. Energy loss of the flywheel is reduced by
  - (a) reducing its diameter
  - (b) reducing its inertia
  - (c) putting the flywheel in a sealed vacuum chamber and by providing magnetically levitated bearings
  - (d) increasing its speed
9. Compactness of a flywheel storage
  - (a) leads to storage of only a small amount of energy
  - (b) makes its handling difficult
  - (c) enables a portable energy storage medium
  - (d) none of the above
10. Which of the following statements is not true about battery storage?
  - (a) It has a long life
  - (b) it has the ability of rapid switchover between charging and discharging operations
  - (c) it is a modular and portable source of energy
  - (d) The cost of battery storage is high
11. The best way to generate electrical power from hydrogen is through
  - (a) a hydrogen-fired steam turbine coupled to a generator
  - (b) conversion of hydrogen to some other liquid fuel and using an IC engine coupled to a generator
  - (c) direct conversion using fuel cell
  - (d) none of the above

## Energy Storage



12. Name the method used for conversion of thermal energy into hydrogen energy:

- (a) Electrolysis
- (b) Hydrolysis
- (c) Thermolysis
- (d) None of the above

13. What is the main difficulty in storing hydrogen in liquid form?

- (a) It is difficult to maintain it due to refrigeration requirement.
- (b) It is very heavy in liquid form.
- (c) It is very light in liquid form.
- (d) It is very difficult to liquify it.

14. What is the main difficulty in storing hydrogen in a metal-hydride form?

- (a) Releasing hydrogen from metal hydride
- (b) Very little amount of hydrogen can be stored
- (c) These metals are difficult to obtain
- (d) Weight and cost of metal as well as heat management

15. In a reversible chemical-energy storage, the input energy is in the form of

- (a) Electrical energy
- (b) Thermal energy
- (c) Chemical energy
- (d) Mechanical energy

16. The main drawback of electromagnetic energy storage is that it requires

- (a) a very bulky inductor coil
- (b) a very strong magnetic field
- (c) A very strong electrostatic field
- (d) a superconducting material

17. Ultra-capacitors have capacitances in the range of

- (a) Few microfarads
- (b) Few farads
- (c) Several thousand farads
- (d) Several hundred microfarads

18. The energy density of an ultra-capacitor is in the range of

- (a) 3-4 Wh/kg
- (b) 3-4 kWh/kg
- (c) 60-70 Wh/kg
- (d) 110-130 Wh/kg

19. Which of the following statements is not true for solid medium sensible heat storage?

- (a) No freezing problem
- (b) No corrosion problem
- (c) Low cost
- (d) Simultaneous charging and discharging are possible

20. Phase-change energy storage with solid-to-gas and liquid-to-gas transformations are not employed in spite of large latent heats because it

- (a) has low heat storage capacity
- (b) makes use of toxic materials
- (c) requires large change in volume that makes the system impractical
- (d) requires a prohibitively wide temperature range



# Solar Energy – Basics

## *Introduction*

# 4

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 insulation (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  $2.8 \times 10^{33}$  kJW/year. The energy reaching the earth is  $1.5 \times 10^{16}$  kJW/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  $1700^{\circ}\text{C}$  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

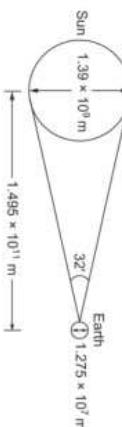
The sun, which is the largest member of the solar system, is a sphere of intensely hot gaseous matter having a diameter of  $1.39 \times 10^9$  m, and at an average distance of  $1.495 \times 10^{11}$  m from the earth. As observed from the earth, the sun rotates on its axis about once in every four 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  $8 \times 10^6$  to  $40 \times 10^6$  °K. The core has a density of about 100 times that of water and a pressure of  $10^{10}$  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:



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

## THE EARTH

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  $1.275 \times 10^7$  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  $\pm 1.7\%$ . The sun subtends an angle of 32° on the earth

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

### 4.3

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

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

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

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

Using this formula, the energy-density distribution of solar radiation at the surface of the sun considering the surface temperature to be  $5760^{\circ}\text{K}$  can be calculated. Also, the same for the earth surface can be found out assuming the average earth temperature to be  $288^{\circ}\text{K}$  ( $15^{\circ}\text{C}$ ). 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  $5760^{\circ}\text{K}$  lies in the range of short wavelengths, peaking around  $0.48 \mu\text{m}$  and that from the earth at  $288^{\circ}\text{K}$  ( $15^{\circ}\text{C}$ ) lies in the range of long wavelengths, peaking around  $10 \mu\text{m}$ .

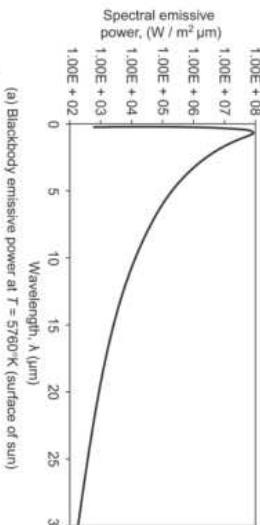
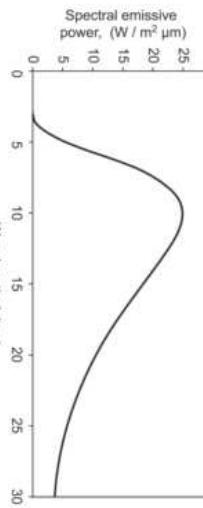
(a) Blackbody emissive power at  $T = 5760\text{ K}$  (surface of sun)(b) Blackbody emissive power at  $T = 288\text{ K}$  (surface of earth)

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  $\text{W/m}^2$ . *Irradiation* is the measure of energy density of sunlight and is measured in  $\text{kWh/m}^2$ . It is generally denoted by the symbol  $H$ . Irradiance and irradiation apply to all components of solar radiation.

#### EXTRATERRESTRIAL AND TERRESTRIAL RADIATIONS

**4.4** 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*,  $I_{\infty}$ . The *solar constant*,  $I_s$  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  $1367 \text{ W/m}^2$  ( $1,940 \text{ cal/cm}^2 \text{ min}$ ,  $432 \text{ Btu/ft}^2 \text{ h}$  or  $4,921 \text{ MJ/m}^2 \text{ h}$ ). 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  $\pm 1.5\%$  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  $\pm 3\%$  and is given by

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

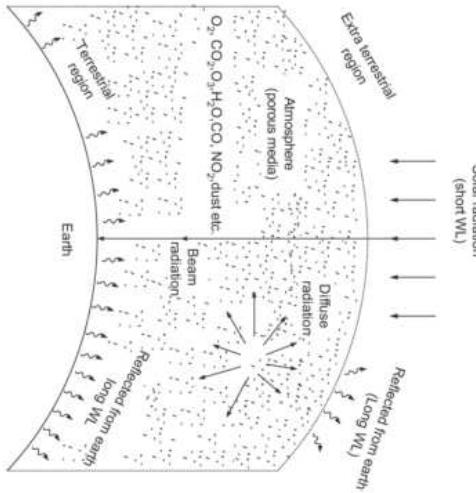
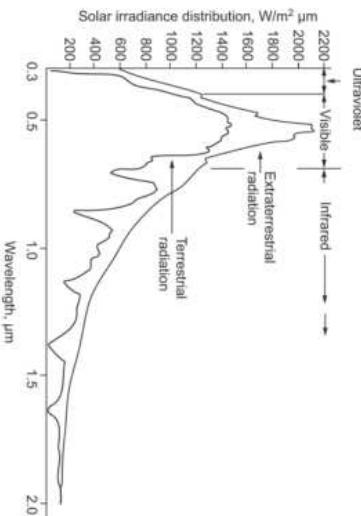


Fig. 4.3 Propagation of solar radiation through the atmosphere

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 insulation* (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.

### SPECTRAL ENERGY DISTRIBUTION OF SOLAR RADIATION

**4.5** 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  $\mu\text{m}$  with maximum spectral intensity at 0.48  $\mu\text{m}$  (green portion of visible range). About 6.4% of extraterrestrial radiation energy is contained in the ultraviolet region ( $\lambda < 0.38 \mu\text{m}$ ); another 48% is contained in the visible region ( $0.38 \mu\text{m} < \lambda < 0.78 \mu\text{m}$ ) and the remaining 45.6% is contained in the infrared region ( $\lambda > 0.78 \mu\text{m}$ ). There is almost complete absorption of short-wave radiation in range ( $\lambda < 0.29 \mu\text{m}$ ) and infrared radiation in range ( $\lambda > 2.3 \mu\text{m}$ ) 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  $\mu\text{m}$  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  $\text{W/m}^2$  respectively for extraterrestrial and terrestrial regions.



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

### DEPLETION OF SOLAR RADIATION

**4.6** 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 ( $\lambda < 0.38 \mu\text{m}$ ).
  - (c) Water vapour ( $\text{H}_2\text{O}$ ) and carbon dioxide absorb almost completely the infrared radiation in the range ( $\lambda > 2.3 \mu\text{m}$ ) 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 than what is received outside the earth's atmosphere and this reduction in intensity depends on the atmospheric conditions (amount of dust particiles, 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  $\alpha$  is  $90^\circ$ . Mathematically,

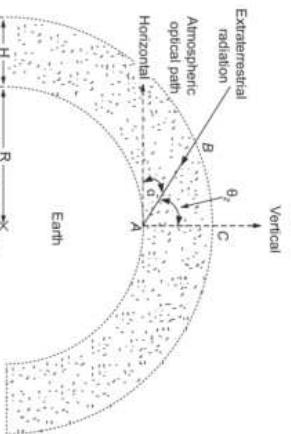
$$\text{Air mass, } m = \frac{\text{path length traversed by beam radiation}}{\text{vertical path length of atmosphere}}$$

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  $m = 2$  ( $\theta_z = 60^\circ$ ); and so on.

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

$$\begin{aligned} m &= (B/A)/(C\lambda) \\ &= \sec \theta_z \\ &= \csc \alpha \quad (\text{as } \alpha + \theta_z = 90^\circ) \end{aligned}$$

where  $\alpha$  is the inclination angle  
and  $\theta_z$  is the zenith angle



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

## MEASUREMENTS OF SOLAR RADIATION

**4.7** 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  $9\mu\text{V}/\text{W/m}^2$  and has an output impedance of  $650\ \Omega$ . A precision spectral pyranometer (model: PSP) of Eppley Laboratory is shown in Fig. 4.6. The pyranometer, when provided

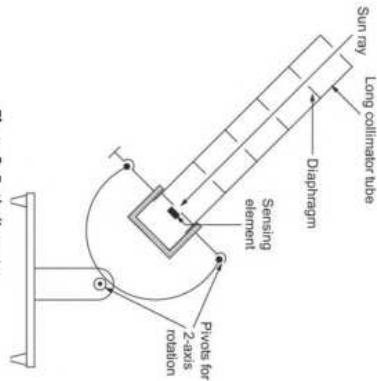
with a shadow band (or occulting disc), to prevent beam radiation from reaching the sensing element, measures the diffused radiation only. Such an arrangement of shadow band stand (model: SBS) is shown in Fig. 4.7.



**Fig. 4.6 Pyranometer (Courtesy: Eppley Laboratory)**

Many inexpensive instruments are also available for measuring light intensity, including instruments based on cadmium-sulphide photocells and silicon photodiodes. These instruments give good indication of relative intensity but their spectral response is not linear, and thus they cannot be accurately calibrated.

#### 4.7.2 Pyrheliometer



**Fig. 4.8 Pyrheliometer**

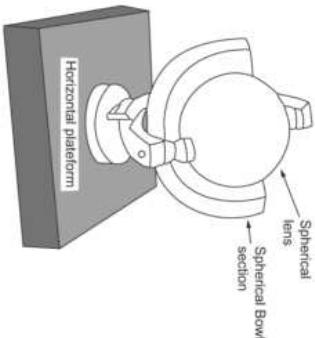


**Fig. 4.7 A pyranometer with shadow band (courtesy: Eppley laboratory)**

The normal incidence pyranometer, shown in Fig. 4.8 uses a long collimator tube to collect beam radiation whose field of view is limited to a solid angle of  $5.5^\circ$  (generally) by appropriate diaphragms inside the tube. The inside of the tube is blackened to absorb any radiation incident at angles outside the collection solid angle. At the base of the tube a wire wound thermopile having a sensitivity of approximately  $8 \mu\text{V}/\text{W}/\text{m}^2$  and an output impedance of approximately  $200 \Omega$  is provided. The tube is sealed with dry air to eliminate absorption of beam radiation within the tube by water vapour. A tracker is needed if continuous readings are desired.



#### 4.7.3 Sunshine Recorder

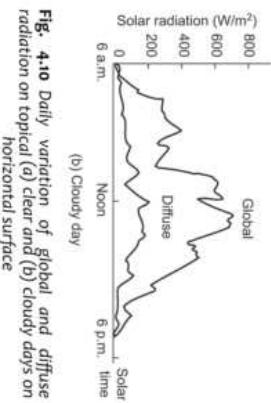


**Fig. 4.9** Sunshine recorder  
the measure of the duration of the bright sunshine. Three overlapping pairs of grooves are provided in the spherical segment to take care of the different seasons of the year.

This instrument measures the duration in hours of bright sunshine during the course of a day. It essentially consists of a glass sphere (about 10 cm in diameter) mounted on its axis parallel to that of the earth, within a spherical section (bowl), as shown in Fig. 4.9. The bowl and glass sphere are arranged in such a way that the sun's rays are focused sharply at a spot on a card held in a groove in the bowl. The card is prepared from a special paper bearing a time scale. As the sun moves, the focused bright sunshine burns a path along this paper. The length of the trace thus obtained on the paper is the path taken by the sun over the sky bearing a time scale. Three overlapping pairs of grooves are provided in the spherical segment to take care of the different seasons of the year.

#### SOLAR RADIATION DATA

**4.8** The radiation data are mostly measured on a horizontal surface. Typical records of global and diffused radiation versus solar time on a horizontal surface for a clear day and partially cloudy day are shown in Fig. 4.10. Daily radiant energy is obtained from the area under the corresponding curve. The monthly average of the daily radiation is obtained by averaging over a span of the corresponding month, and expressed in  $\text{kJ}/\text{m}^2\text{-day}$ . An alternative unit for expressing solar radiation is langley per unit time, where one langley is equal to  $1 \text{ cal}/\text{cm}^2$ .



**Fig. 4.10** Daily variation of global and diffuse radiation on topical (a) clear and (b) cloudy days on horizontal surface

## 92 Non-conventional Energy Resources

Thus, solar radiation data are presented in three ways:

- (i) Flow of energy per unit area per second, ( $\text{kJ}/\text{m}^2\text{s}$ )
- (ii) Flow of energy per unit area per hour, ( $\text{kJ}/\text{m}^2\text{h}$ )
- (iii) Flow of energy per unit area per day, ( $\text{kJ}/\text{m}^2\text{-day}$ )

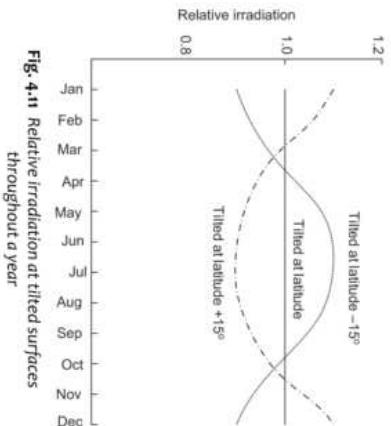


Fig. 4.11 Relative irradiation at tilted surfaces throughout a year

enhanced radiation collection. However, the overall strategy changes from place to place and also on the type of application.

The maximum solar radiation is received on a collector surface placed normal to incident rays. But as the position of the sun in the sky changes throughout the day, the collector has to adjust itself continuously to collect maximum radiation. Therefore, maximum energy can be collected if the collector tracks the sun along two axes. However, providing for two-axis tracking is expensive and complicated. A compromising but less expensive option is to fix the collector at a suitable tilt and track the sun along a single axis only. The most cost-effective method with further compromise in the performance is to have a fix orientation for a collector and possibly with some arrangement for seasonal adjustments only.

For designing a solar system or for predicting the potential of any solar application at a location, we need monthly average, daily solar radiation data (both global and diffused) on a horizontal and possibly at certain positions of the tilt angle of the surface. These data are measured at certain measuring stations in a country (at present 16 locations in case of India) and computed for other locations. This record is produced in the form of charts and tables and an atlas is prepared to help in solar-systems design. The typical record of measured daily solar radiation data for New Delhi is shown in Tables C1, C2 and C3 in Appendix C.

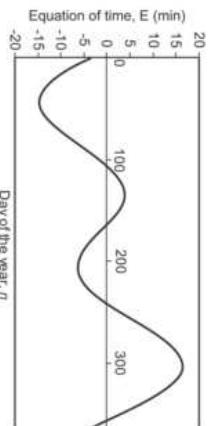
The incident solar radiation is also a function of the orientation (or tilt, due south in the northern hemisphere) of a solar collector from the horizontal. A typical pattern of relative irradiation throughout a year for three tilt angles, equal to: (i) latitude, (ii) (latitude  $-15^\circ$ ), and (iii) (latitude  $+15^\circ$ ) is shown in Fig. 4.11. The radiation pattern indicates favouring of a certain tilt during certain periods of the year. Therefore, seasonal adjustment of the tilt angle may result in tilt angle changes from place to place and also on the type of application.



### SOLAR TIME (LOCAL APPARENT TIME)

**4.9** Solar time is measured with reference to *solar noon*, which is the time when the sun is crossing the observer's meridian. At solar noon, the sun is at the highest position in the sky. The sun traverses each degree of longitude in 4 minutes (as the earth takes 24 hours to complete one revolution). The standard time is converted to solar time by incorporating two corrections, as follows:

$$\text{Solar time} = \text{Standard time} \pm 4(L_{\text{st}} - L_{\text{hc}}) + E \quad (4.3)$$



**Fig. 4.12** The equation of time as function of day of the year

the correction arising out of the variation in the length of the solar day due to variations in the earth's rotation and orbital revolution, and is called the *equation of time*. The *solar day*, which is the duration between two consecutive solar noons is not exactly of 24 hours throughout the year.  $E$  can be determined either by using the following equation or from the chart given in Fig. 4.12.

$$E = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B \text{ min.} \quad (4.4)$$

where

$$B = (360/364)(n-81)$$

$n$  = day of the year, starting from 1st January

## 4.10 SOLAR RADIATION GEOMETRY

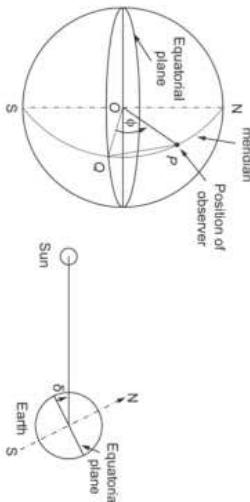
**(a) Latitude (Angle of Latitude), ( $\Phi$ )** The latitude of a location on the earth's surface is the angle made by a radial line joining the given location to the centre of the earth with its projection on the equator plane, as shown in Fig. 4.13  
 (a) The latitude is positive for northern hemisphere and negative for southern hemisphere.

**(b) Declination, ( $\delta$ )** It is defined as the angular displacement of the sun from the plane of the earth's equator, as shown in Fig. 4.13 (b). It is positive when

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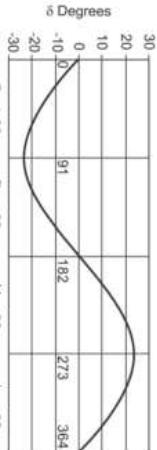
measured above the equatorial plane in the northern hemisphere. The declination  $\delta$  can be approximately determined from the equation

$$\delta = 23.45 \times \sin \left[ \frac{360}{365} (284 + n) \right] \text{ degrees} \quad (4.5)$$



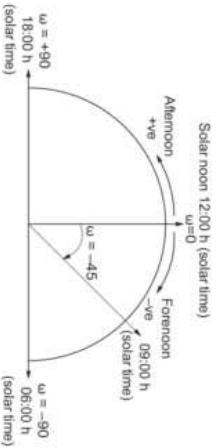
**Fig. 4.13** Latitude and declination angle

where  $n$  is day of the year counted from 1st January.



**Fig. 4.14** Variations in sun's declination

**(c) Hour Angle, ( $\omega$ )** The hour angle at any moment is the angle through which the earth must turn to bring the meridian of the observer directly in line with the sun's rays.



**Fig. 4.15** Hour angle

In other words, at any moment, it is the angular displacement of the sun towards east or west of local meridian (due to rotation of the earth on its axis). The earth completes one rotation in 24 hours. Therefore, one hour corresponds to  $15^\circ$  of rotation. At solar noon, as the sun's rays are in line with the local meridian, the hour angle is zero. It is  $-ve$  in the forenoon and  $+ve$  in the afternoon. Thus, at 06:00 h it is  $-90^\circ$  and at 18:00 h it is  $+90^\circ$  as shown in Fig. 4.15.

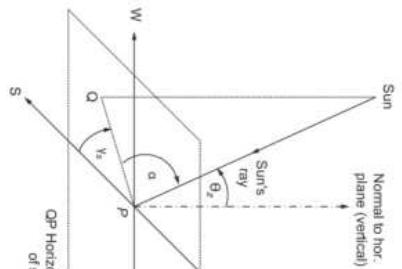
It can be calculated as:

$$\omega = [\text{Solar Time} - 12:00] \text{ (in hours)} \times 15 \text{ degrees} \quad (4.6)$$

**(d) Inclination Angle (altitude), ( $\alpha$ )** The angle between the sun's ray and its projection on a horizontal surface is known as the inclination angle, as shown in Fig. 4.16.

**(e) Zenith Angle, ( $\theta_z$ )** It is the angle between the sun's ray and the perpendicular (normal) to the horizontal plane. (Ref. Fig. 4.16)

**(f) Solar Azimuth Angle ( $\gamma_s$ )** It is the angle on a horizontal plane, between the line due south and the projection of the sun's ray on the horizontal plane. It is taken as  $+ve$  when measured from south towards west. (Ref. Fig. 4.16)



**(g) Slope (Tilt Angle), ( $\beta$ )** It is the angle between the inclined plane surface (collector), under consideration and the horizontal. It is taken to be positive for the surface sloping towards south. (Ref. Fig. 4.17)

**(h) Surface Azimuth Angle, ( $\gamma$ )** It is the angle in the horizontal plane, between the line due south and the horizontal projection of the normal to the inclined plane surface (collector). It is taken as  $+ve$  when measured from south towards west. (Ref. Fig. 4.17)

**(i) Angle of Incidence, ( $\theta_i$ )**

It is the angle between the sun's ray incident on the plane surface (collector) and the normal to that surface. (Ref. Fig. 4.18)

These angles are shown in Fig. 4.17–19. In general, the angle of incidence can be expressed as



$$\cos \theta_i = (\cos \phi \cos \beta + \sin \phi \sin \beta \cos \gamma) \cos \delta \cos \omega + \cos \delta \sin \omega \sin \beta \sin \gamma \quad (4.7)$$

### Special Cases

(i) For a surface facing due south,  $\gamma = 0$

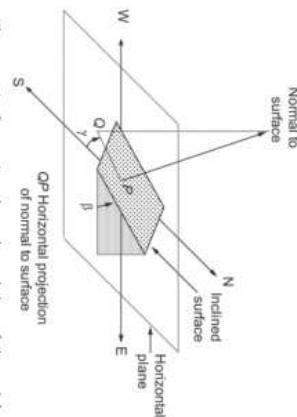
$$\cos \theta_i = \cos(\phi - \beta) \cos \delta \cos \omega + \sin \delta \sin(\phi - \beta) \quad (4.8)$$

(ii) For a horizontal surface,  $\beta = 0, \theta_i = \theta_z$  (zenith angle)

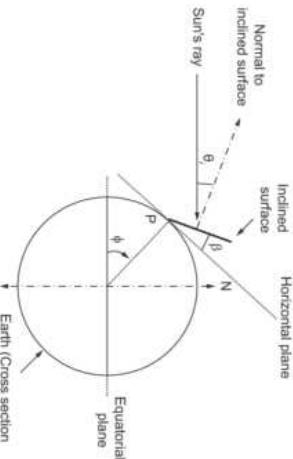
$$\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \delta \sin \phi \quad (4.9)$$

(iii) For a vertical surface facing due south,  $\gamma = 0, \beta = 90^\circ$

$$\cos \theta_i = -\sin \delta \cos \phi + \cos \delta \cos \omega \sin \phi \quad (4.10)$$



**Fig. 4.17 Surface azimuth angle and slope (tilt angle)**



**Fig. 4.18 Angle of latitude, tilt angle, angle of incidence**



## SOLAR DAY LENGTH

**4.11** At sunrise, the sun's rays are parallel to the horizontal surface. Hence the angle of incidence,  $\theta_i = \theta_z = 90^\circ$ , the corresponding hour angle,  $\omega_i$ , from Eq. (4.7):

$$\cos \theta_i = 0 = \cos \phi \cos \delta \cos \omega_i + \sin \delta \sin \phi$$

$$\omega_i = \cos^{-1}(-\tan \phi \tan \delta) \quad (4.11)$$

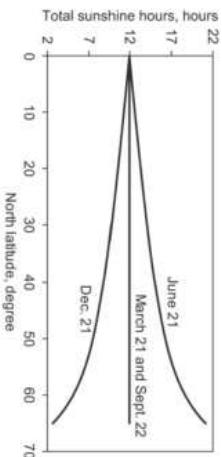
The angle between sunrise and sunset is given by

$$2\omega_i = 2\cos^{-1}(-\tan \phi \tan \delta)$$

Since  $15^\circ$  of hour angle is equivalent to one-hour duration, the duration of sunshine hours,  $t_s$  or daylight hours is given by

$$t_s = (2/15) \cos^{-1}(-\tan \phi \tan \delta) \quad (4.12)$$

The variation of  $t_s$  with latitude ( $\phi$ ) for different days ( $\eta$ ) of the year is shown in Fig. 4.19.



**Fig. 4.19** Variation of sunshine hours,  $t_s$ , with latitude, on certain days of the year

The hour angle,  $\omega_i$ , at sunrise (or sunset) for horizontal (collector) surface is given by Eq. 4.11., which yields positive and negative values for  $\omega_i$ . The negative value corresponds to sunrise while the positive to sunset. The hour angle at sunrise as seen by the observer on an inclined surface facing south (i.e.,  $y = 0$ ) will also be given by Eq. 4.11 if the day under consideration lies between September 22 and March 21, and the location is in the northern hemisphere. However, if the day under consideration lies between March 21 and September 22, the hour angle at sunrise or sunset would be smaller in magnitude than the value given by Eq. 4.11 and would be obtained by substituting  $\theta_i = 90^\circ$  in Eq. 4.8. Thus,

$$\omega_i = \cos^{-1}[\tan(\phi - \beta) \tan \delta] \quad (4.13)$$

**Example**

**4.1** Calculate the angle of incidence of beam radiation on a plane surface, tilted by  $45^\circ$  from the horizontal plane and pointing  $30^\circ$  west of south located at Mumbai at 1:30 P.M. (IST) on 15th November. The longitude and latitude of Mumbai are  $72^\circ 49' E$  and  $18^\circ 54' N$  respectively. The standard longitude for IST is  $81^\circ 44' E$ .

**Solution**

From the given data,

$$\theta = 319$$

From Eq. (4.5)  $\delta = -19.148^\circ$

From Eq. (4.4)  $E = 14.74 \text{ min.}$

Standard Time = 1:30 p.m. = 13:30 h.

From Eq. (4.3), Solar Time =  $13 \text{ h } 30 \text{ min} - 4(81.733^\circ - 72.816^\circ)$

$$\text{min} + 14.74 \text{ min}$$

$$= 13 \text{ h } 9.072 \text{ min}$$

From Eq. 4.6 hour angle,  $\omega = 17.27^\circ$

$\gamma = 30^\circ$ ;  $\beta = 45^\circ$ ;  $\phi = +18.9^\circ$

Now the angle of incidence can be calculated using Eq. 4.7  

$$\cos \theta_i = [\cos (+18.9^\circ) \cos (45^\circ) + \sin (+18.9^\circ) \sin (45^\circ) \cos (30^\circ)]$$

$$+ \sin (-19.148^\circ) [\sin (+18.9^\circ) \cos (45^\circ) - \cos (+18.9^\circ) \sin (45^\circ)]$$

$$\cos (30^\circ)]$$

$$\theta_i = \cos^{-1}(0.99686) = 4.54^\circ$$

**Example**

**4.2** Calculate the number of daylight hours (sunshine hours) in Srinagar on January 1 and July 1. The latitude of Srinagar is  $34^\circ 05' N$ .

**Solution**

From the given data,

$\theta = 1$  and  $182$  respectively for January 1 and July 1.

From Eq. 4.5,  $\delta = -23.01^\circ$  and  $23.12^\circ$  respectively for January 1 and July 1.

From Eq. 4.12,

$$\begin{aligned} \text{on January 1, } t_d &= (2/15) \cos^{-1}[-\tan(34.083^\circ) \tan(-23.01^\circ)] \\ &= 9.77 \text{ h} \end{aligned}$$

$$\begin{aligned} \text{on July 1, } t_d &= (2/15) \cos^{-1}[-\tan(34.083^\circ) \tan(23.12^\circ)] \\ &= 14.24 \text{ h} \end{aligned}$$



### EMPIRICAL EQUATIONS FOR ESTIMATING SOLAR RADIATION AVAILABILITY ON HORIZONTAL SURFACE FOR CLOUDY SKIES

Since measurements of solar radiation are often not available at every location of the earth, attempts have been made by many researchers to establish relationships linking the values of radiation (global or diffuse) with meteorological parameters like number of sunshine hours, cloud cover and precipitation, etc. Some of these equations will be given in the following sections. These equations are generally valid for cloudy skies.

#### 4.12.1 Monthly Average, Daily Global Radiation

The correlation for estimating the monthly average daily total (global) radiation on a horizontal surface can be given as

$$\frac{\bar{H}_g}{\bar{H}_o} = a + b \left( \frac{\bar{n}}{\bar{N}} \right) \quad (4.14)$$

where  $\bar{H}_g$  = monthly average, daily total radiation on a horizontal surface at a location

$\bar{H}_o$  = monthly average, daily extraterrestrial radiation that would fall at the location on a horizontal surface (in the absence of an atmosphere)

$\bar{n}$  = monthly average, daily hours of bright sunshine obtained from actual records at the location (i.e., bright sunshine hours)

$\bar{N}$  = monthly average of maximum possible daily hours of sunshine (i.e., the day length of the average day of the month)

$$\frac{\bar{n}}{\bar{N}} = \text{p.u. possible bright sunshine}$$

$a, b$  = regression parameters are constants for a particular location and obtained by fitting data

Values of  $a$  and  $b$  have been obtained for many cities of the world. These values are given for some Indian cities in Table 4.1.

**Table 4.1** Constants  $a$  and  $b$  for some Indian cities [6]

S.N.	Name of the city	$a$	$b$	Mean error (percent)
1.	Ahmedabad	0.28	0.48	3.0
2.	Bengalore	0.18	0.64	3.9
3.	Bhavnagar	0.28	0.47	2.8
4.	Chennai	0.30	0.44	3.5

S.N.	Name of the city	a	b	Mean error (percent)
5.	Goa	0.30	0.48	2.1
6.	Jodhpur	0.33	0.46	2.0
7.	Kodikkanal	0.32	0.55	2.9
8.	Kolkata	0.28	0.42	1.3
9.	Mangalore	0.27	0.43	4.2
10.	Minicoy	0.26	0.39	1.4
11.	Nagpur	0.27	0.50	1.6
12.	New Delhi	0.25	0.57	3.0
13.	Pune	0.31	0.43	1.9
14.	Shillong	0.22	0.57	3.0
15.	Srinagar	0.35	0.40	4.7
16.	Thiruvanan-	0.37	0.39	2.5
17.	Vishakhapatnam	0.28	0.47	1.2

In Eq. 4.14,  $\bar{H}_o$  is the mean or average of  $H_o$  for each day of the month, which can be calculated as follows:

From Eq. 4.2, the extraterrestrial radiation in  $\text{kW/m}^2$  may be given as

$$I_{\text{ext}} = I_{\infty} \left[ 1.0 + 0.033 \cos \left( \frac{360n}{365} \right) \right]$$

On a horizontal surface, this would become,  $I_{\text{ext}} \cos \theta_z$

Using Eq. 4.9, the extraterrestrial radiation that would fall on a horizontal surface at the location may be written as

$$I_{\infty} \left[ 1.0 + 0.033 \cos \left( \frac{360n}{365} \right) \right] (\cos \phi \cos \delta \cos \omega + \sin \delta \sin \phi) \text{ (kW/m}^2\text{)}$$

To get hourly radiated energy per square metre (i.e. in  $\text{kJ/m}^2\text{h}$ ), the above term is to be multiplied by a factor of 3600:

$$3600 \times I_{\infty} \left[ 1.0 + 0.033 \cos \left( \frac{360n}{365} \right) \right] (\cos \phi \cos \delta \cos \omega + \sin \delta \sin \phi) \text{ (kJ/m}^2\text{ h)}$$

One day radiation,  $H_o$  (in  $\text{kJ/m}^2\text{ day}$ ) can be obtained by integrating the above expression over the day length where time is expressed in hours.

$$(4.15) \quad H_o = 3600 \times I_{\infty} \left[ 1.0 + 0.033 \cos \left( \frac{360n}{365} \right) \right] \int (\cos \phi \cos \delta \cos \omega + \sin \delta \sin \phi) dt$$

As explained in Section 4.10, since an hour of  $15^\circ$  is equivalent to 1 hour duration of sunshine, we have,

$$t = \frac{\omega}{15} \times \frac{180}{\pi}$$

where  $t$  is hours and  $\omega$  is in radians.

$$\text{Hence, } dt = \frac{180}{15\pi} d\omega$$

From Eq. 4.14, we have

$$\begin{aligned} H_o &= 3600 \times \frac{12}{\pi} I_{sc} \left[ 1.0 + 0.033 \left( \frac{360n}{365} \right) \right] \int_{-\omega_0}^{+\omega_1} (\cos \phi \cos \delta \cos \omega + \sin \delta \sin \phi) d\omega \\ &= 3600 \times \frac{24}{\pi} I_{sc} \left[ 1.0 + 0.033 \cos \left( \frac{360n}{365} \right) \right] (\cos \phi \cos \delta \sin \omega_s + \omega_s \sin \phi \sin \delta) \end{aligned} \quad (4.16)$$

The calculation of  $H_o$  can be simplified from the fact that in each month, there is a particular day on which  $H_o$  is nearly equal to the monthly mean value  $H_m$ . The dates on which the value of  $H_o$  is equal to  $H_m$  are January 17, February 16, March 16, April 15, May 15, June 11, July 17, August 16, September 15, October 15, November 14 and December 10. As expected, these dates are close to the middle of the month. The values of sunshine hours for these dates are used as  $\bar{N}$  for that month.

Equation 4.16 can be used to determine the monthly average of daily global radiation on a horizontal surface at a location for known sunshine hours and where the values of  $a$  and  $b$  are known for a nearby location.

Other meteorological parameters have also been used for predicting the availability of solar radiation. These include cloud cover and precipitation. However, in general, the sunshine ratio parameter  $\frac{n}{N}$  has been found to be the most reliable predictor.

### Example

Estimate the monthly average of the daily global radiation on a horizontal surface at Agra ( $27^\circ 10' N$ ,  $78^\circ 05' E$ ) during the month of January, if the average sunshine hour per day is 7 h.

## 4.3

**Solution** Here, we shall use the values of  $a$  and  $b$  available for New Delhi

as this is the closest town of known data. Therefore,

$$a = 0.25, b = 0.57$$

For Agra,  $\phi = 27.166^\circ$

For the month of January we shall use the 17th day of the month as the day for which  $H_o$  is equal to  $H_m$ .

Thus, the day of the year,  $n = 17$



Also it is given that average sunshine hours,  $\bar{n} = 7$  h

$$\begin{aligned}\text{Using Eq. 4.5, } \delta &= 23.45 \times \sin \left[ \frac{360}{365} (284 + 17) \right] \text{ degrees} \\ &= -20.96^\circ\end{aligned}$$

The hour angle at sunrise may be calculated from Eq. 4.11

$$\omega_s = \cos^{-1} [\tan(27.166) \tan(-29.96)]$$

$$\omega_s = 78.66^\circ \text{ or } 1.7328 \text{ radians}$$

Using Eq. 4.12, day length,  $\bar{N} = \frac{2}{15} \times 78.66 = 10.488$  h

From Eq. 4.16,

$$\begin{aligned}\bar{H}_o &= 3600 \times \frac{24}{\pi} \times 1.367 \times [1.0 + 0.033 \cos \left( \frac{360 \times 17}{365} \right)] \\ &\times [\cos(27.166) \times \cos(-20.96) \times \sin(78.66) + 1.3728 \times \sin(27.166) \times \sin(-20.96)] \\ &= 37540.195 \times [1.031597] \times [0.81459 - 0.2242] \\ &= 22863.3 \text{ kJ/m}^2\text{-day}\end{aligned}$$

Now, from Eq. 4.13,

$$\frac{\bar{H}_d}{H_o} = a + b \left( \frac{\bar{n}}{\bar{N}} \right)$$

$$\frac{\bar{H}_d}{H_o} = 22863.3 \times [0.25 + 0.57 \times \frac{7}{10.488}]$$

$$\bar{H}_d = 14413.82 \text{ kJ/m}^2\text{-day}$$

#### 4.12.2 Monthly Average, Daily Diffused Radiation

Based on a study of data for a few countries, it has been found that the correlation is not same throughout the globe. A number of correlations have been developed. For Indian conditions where the diffuse component is relatively larger, the following correlation is found to predict diffused radiation with an accuracy of about 10 per cent.

$$\frac{\bar{H}_d}{H_s} = 1.354 - 1.57 \bar{K}_T \quad (4.17)$$

where  $\bar{H}_d$  = monthly average, daily diffused radiation on a horizontal surface at a location.

$$\bar{K}_T = \frac{\bar{H}_d}{H_o}, \text{ known as monthly average daily clearness index}$$

The correlation is valid in the range  $0.3 < \bar{K}_T < 0.7$ .

### Example

From the data given in Example 4.3 for Agra, estimate the monthly average of the daily diffused and beam radiations on a horizontal surface.

## 4.4

**Solution** As per calculation of Example 4.3,

$$\frac{\bar{H}_d}{H_o} = 22863.3 \text{ kJ/m}^2\text{-day} \text{ and } \frac{\bar{H}_s}{H_o} = 14413.82 \text{ kJ/m}^2\text{-day}$$

$$\text{Therefore, } \bar{K}_T = \frac{\bar{H}_s}{H_o} = \frac{14413.82}{22863.3} = 0.63$$

From Eq. 4.17,

$$\frac{\bar{H}_d}{\bar{H}_s} = 1.354 \cdot 1.570 \bar{K}_T$$

$$\bar{H}_d = 14413.82 \times (1.354 \cdot 1.570 \times 0.63) = 5259.6 \text{ kJ/m}^2\text{-day}$$

Beam component, can be calculated as,

$$H_b = H_s - H_d = 14413.82 - 5259.6 = 9154.22 \text{ kJ/m}^2\text{-day}$$

### 4.12.3 Monthly Average, Hourly Global Radiation

On the lines similar to prediction of daily radiation discussed in the previous section, correlations are suggested for estimating monthly average, hourly radiation. One such correlation is given below:

$$\frac{\bar{I}_s}{H_o} = (a + b \cos \omega) \frac{\bar{I}_o}{H_o} \quad (4.18)$$

where  $\bar{I}_o$  and  $\bar{H}_o$  are monthly average, hourly and daily extraterrestrial radiation, respectively that would fall at the location on a horizontal surface (in the absence of atmosphere).

$\bar{I}_o$  = monthly average, hourly radiation, on a horizontal surface

The values of  $a$  and  $b$  may be obtained as follows:

$$a = 0.409 + 0.5016 \sin (\omega_i - 60^\circ)$$

$$b = 0.6609 - 0.4767 \sin (\omega_i - 60^\circ)$$

$\omega$  = hour angle at a particular time

It should be noted that  $\bar{I}_o$  is expressed in  $\text{kJ/m}^2\text{-h}$ , which can be calculated by obtaining the instantaneous value (in  $\text{kW/m}^2$ ) at the midpoint of the hour under consideration and multiplying by 3600.



#### 4.12.4 Monthly Average, Hourly Diffused Radiation

There is a close correlation between the values of ratios  $\left(\bar{I}_d / \bar{H}_d\right)$  and  $\left(\bar{I}_o / \bar{H}_o\right)$ . The following correlation is suggested between the two.

$$\frac{\bar{I}_d}{\bar{H}_d} = \left( a' + b' \cos \omega_i \right) \frac{\bar{I}_o}{\bar{H}_o} \quad (4.19)$$

$$\text{where } a' = 0.4922 + \left( \frac{0.27}{\bar{H}_d / \bar{H}_o} \right) \quad \text{for } 0.1 \leq (\bar{H}_d / \bar{H}_o) \leq 0.7$$

$$= 0.76 + \left( \frac{0.113}{\bar{H}_d / \bar{H}_o} \right) \quad \text{for } 0.7 \leq (\bar{H}_d / \bar{H}_o) \leq 0.9$$

$$\text{and } b' = 2 (1 - a') (\sin \omega_i - \omega_i \cos \omega_i) / (\omega_i - 0.5 \sin 2 \omega_i)$$

#### Example

From the data given in Example 4.3 for Agra, calculate the monthly average of the hourly global and hourly diffuse radiations on a horizontal surface during 1100 to 1200 h (LAT).

#### 4.5

##### Solution

Given data:

For Agra,  $\phi = 27.166^\circ$

For the month of January, we shall use the 17th day of the month as the day for which  $H_o$  is equal to  $\bar{H}_o$ .

Thus, the day of the year,  $n = 17$

For the above data, the values calculated in Example 4.3 are

$$\delta = -20.96^\circ$$

$$\begin{aligned} \frac{\omega}{H_o} &= 78.66^\circ \text{ or } 1.7328 \text{ radians} \\ \frac{\omega}{H_o} &= 22863.3 \text{ kJ/m}^2\text{-day} \\ \frac{\omega}{H_s} &= 14413.82 \text{ kJ/m}^2\text{-day} \end{aligned}$$

The hourly extraterrestrial radiation,  $I_o$ , on a horizontal surface at the location at a particular hour may be obtained in  $\text{kJ/m}^2\text{-h}$  by multiplying the instantaneous radiation (in  $\text{kW/m}^2$ ) by 3600. Thus,

$$\begin{aligned} I_o &= 3600 \times I_o \left[ 1.0 + 0.033 \cos \left( \frac{360n}{365} \right) \right] (\cos \phi \cos \delta \cos \omega + \\ &\quad \sin \delta \sin \phi) \end{aligned}$$

The value of  $\omega$  is calculated from Eq. 4.6 at the middle of the hour, i.e., at 11:30.

$$\begin{aligned}\omega &= [\text{Solar Time} - 1200] \text{ (in H)} \\ &= -7.5 \text{ or } -0.1309 \text{ radian}\end{aligned}$$

Now,

$$\begin{aligned}I_o &= 3600 \times 1.367 \times \left[ 1.0 + 0.033 \cos \left( \frac{360 \times 17}{365} \right) \right] (\cos 27.166^\circ) \\ &\quad \cos (-20.96) \cos (-7.5^\circ) + \sin (-20.96) \sin 27.166^\circ\end{aligned}$$

$$= 4921.2 \times [1.031597] \times 0.6604$$

$$I_o = 3352.58 \text{ kJ/m}^2\text{h}$$

$I_o$  may be taken as  $\bar{I}_o$  on January 17.

Now,  $\bar{I}_s$  can be calculated using Eq. 4.18:

$$\frac{\bar{I}_s}{H_s} = (a + b \cos \omega) \frac{\bar{I}_o}{H_o}$$

The values of  $a$  and  $b$  may be obtained as follows:

$$\begin{aligned}a &= 0.409 + 0.5016 \sin (\omega_s - 60^\circ) = 0.409 + 0.5016 \sin (78.66^\circ - 60^\circ) \\ &= 0.5695 \\ b &= 0.6609 - 0.4767 \sin (\omega_s - 60^\circ) = 0.6609 - 0.4767 \sin (78.66^\circ - 60^\circ) \\ &= 0.2093\end{aligned}$$

Substituting these values in Eq. 4.18,

$$\begin{aligned}\bar{I}_s &= 14413.82 \times (0.5695 + 0.2093 \times \cos (-7.5)) \times \frac{3352.58}{22863.3} \\ &= 1642.27 \text{ kJ/m}^2\text{h}\end{aligned}$$

Thus the monthly average of the hourly global radiation on a horizontal surface during 11:00 to 12:00 hours (LAT) at Agra = 1642.27 kJ/m<sup>2</sup>·h

The monthly average of the hourly diffused radiation can be calculated from Eq. 4.19

$$\frac{\bar{I}_d}{H_d} = (a' + b' \cos \omega) \frac{\bar{I}_o}{H_o}$$

As calculated in Example 4.4,  $\bar{H}_d = 5259.6 \text{ kJ/m}^2\text{-day}$

$$\begin{aligned}\frac{\bar{H}_d}{H_d} / \frac{\bar{H}_s}{H_s} &= 5259.6 / 14413.82 = 0.3649 \\ a' &= 0.4922 + \left( \frac{0.27}{H_d / H_s} \right) = 1.2321\end{aligned}$$



$$\begin{aligned}
 b' &= 2(1-d)(\sin \omega_r - \omega_r \cos \omega_r)/(\omega_r - 0.5 \sin 2\omega_r) \\
 &= 2 \times (1-0.2321) \times (\sin 78.66^\circ - 1.7328 \times \cos 78.66^\circ) / \\
 &\quad (1.7328 - 0.5 \times \sin(2 \times 78.66^\circ)) \\
 &= 2 \times (-0.2321) \times 1.3212 / 1.54 = -0.3983
 \end{aligned}$$

Now, from Eq. 4.19,

$$\bar{I}_d = 5259.6 \times \left( 1.2321 - 0.3983 \times \cos(-7.5^\circ) \right) \times \frac{3352.58}{22863.3} \\
 = 645.695 \text{ kJ/m}^2\text{-h}$$

Thus, the monthly average of the hourly diffused radiation on a horizontal surface during 11:00 to 12:00 hours (1 AT) at Agra  
 $= 645.695 \text{ kJ/m}^2\text{-h}$

#### 4.12.5 Daily and Hourly Diffused Radiation on an Individual Day

Normally, global radiation is recorded at many locations whereas diffused radiation is not. Therefore, correlations have been suggested to predict daily and hourly diffused radiation from measured daily and hourly global-radiation data respectively.

##### Correlation for Daily Diffused Radiation

$$\frac{H_d}{H_g} = 0.99 \quad \text{for } K_t \leq 0.17 \\
 = 1.188 - 2.272 K_t + 9.437 K_t^2 - 21.856 K_t^3 + 14.648 K_t^4 \quad \text{for} \\
 0.17 < K_t \leq 0.8 \quad (4.20)$$

where  $K_t = H_g/H_o$ , is the daily clearness index for an individual day.

On the same lines, correlations have also been developed for estimating hourly diffused radiation  $I_d$  from measured value of hourly global radiation.

$$\frac{I_d}{I_g} = a - b K_t \quad (4.21)$$

where  $K_t = I/I_o$ , is the hourly clearness index at an hour of an individual day.

$$\begin{aligned}
 a &= 0.949 + 0.0118 |\phi| \\
 b &= 1.185 + 0.0135 |\phi|
 \end{aligned}$$

and  $\phi$  = latitude in degrees

Equations 4.20 and 4.21 are valid for  $0.35 \leq K_t \leq 0.75$ .



### HOURLY GLOBAL, DIFFUSE AND BEAM RADIATIONS ON HORIZONTAL SURFACE UNDER CLOUDLESS SKIES

The hourly global radiation  $I_g$  on a horizontal surface is the sum of the hourly beam radiation,  $I_b$ , and the hourly diffuse radiation  $I_d$ . Thus:

$$I_g = I_b + I_d$$

Now, if  $I_{\text{in}}$  is the beam radiation on a surface normal to the direction of sun rays, the beam radiation received on a horizontal surface may be given as

$$I_b = I_{\text{in}} \cos \theta_z \quad (4.22)$$

$$\text{Thus, } I_g = I_{\text{in}} \cos \theta_z + I_d$$

$I_{\text{in}}$  and  $I_d$  are estimated as follows:

$$I_{\text{in}} = A \exp(-B/\cos \theta_z) \quad (4.24)$$

$$I_d = C I_{\text{in}}$$

where  $A$ ,  $B$  and  $C$  are constants whose values have been determined monthwise on the basis of measurements carried out in USA. These constants change during the year because of seasonal changes in dust and moisture contents of the atmosphere and also because of change in the sun–earth distance. The values are tabulated in Table 4.2.

**Table 4.2** Constants  $A$ ,  $B$  and  $C$  for predicting hourly solar radiation on clear days [8].

Month	$A (\text{W}/\text{m}^2)$	$B$	$C$
January 21	1202	0.141	0.103
February 21	1187	0.142	0.104
March 21	1164	0.149	0.109
April 21	1130	0.164	0.120
May 21	1106	0.177	0.130
June 21	1092	0.185	0.137
July 21	1093	0.186	0.138
August 21	1107	0.182	0.134
September 21	1136	0.165	0.121
October 21	1136	0.152	0.111
November 21	1190	0.144	0.106
December 21	1204	0.141	0.103

**Example****4.6**

Estimate the hourly global, beam and diffused radiations at New Delhi ( $28^\circ 35' N, 77^\circ 12' E$ ) between 1300 to 1400 hours (LAT) on May 15 and compare these data with measured values given in Tables G1 and G2 in Appendix C.

**Solution**

Given data:

$$\phi = 28.58^\circ$$

For May 15,  $n = 135$

$$\begin{aligned}\delta &= 23.45 \times \sin \left[ \frac{360}{365} (264 + 135) \right] \\ &= 18.79^\circ\end{aligned}$$

We shall consider hour angle  $\omega$  for the middle of the hour, i.e., 1330 hours,

$$\omega = [\text{Solar Time} - 1200] \text{ (in hours)} \times 15 \text{ degrees} = 22.5^\circ$$

From Eq. 4.9,

$$\begin{aligned}\cos \theta_z &= \cos \phi \cos \delta \cos \omega + \sin \delta \sin \phi \\ &= \cos 28.58^\circ \cos 18.79^\circ \cos 22.5^\circ + \sin 18.79^\circ \sin 28.58^\circ \\ &= 0.768 + 0.154 \\ &= 0.922\end{aligned}$$

From Table 4.2, the values of  $A$ ,  $B$  and  $C$  are obtained as

$$A = 1106 \text{ W/m}^2 = 3.6 \times 1106 \text{ kJ/m}^2 \cdot \text{h} = 3981.6 \text{ kJ/m}^2 \cdot \text{h}$$

$$B = 0.177$$

$$C = 0.130$$

From Eq. 4.24,

$$\begin{aligned}I_{\text{in}} &= A \exp(-B/\cos \theta_z) = 3981.6 \times \exp(-0.177/0.922) \\ &= 3285.63 \text{ kJ/m}^2 \cdot \text{h}\end{aligned}$$

From Eq. 4.25, the diffused radiation,

$$I_d = C I_{\text{in}} = 0.130 \times 3285.63 = 427.13 \text{ kJ/m}^2 \cdot \text{h}$$

From Eq. (4.22), the beam radiation,

$$I_b = I_{\text{in}} \cos \theta_z = 3285.63 \times 0.922 = 3029.35 \text{ kJ/m}^2 \cdot \text{h}$$

The global radiation  $I_g = I_b + I_d = 3456.48 \text{ kJ/m}^2 \cdot \text{h}$

**Comparison**

	<i>Estimated</i>	<i>Measured</i>
Diffused radiation	427.13 $\text{kJ/m}^2 \cdot \text{h}$	1108.4 $\text{kJ/m}^2 \cdot \text{h}$
Beam radiation	3029.35 $\text{kJ/m}^2 \cdot \text{h}$	1930 $\text{kJ/m}^2 \cdot \text{h}$ -0.008
Global radiation	3456.48 $\text{kJ/m}^2 \cdot \text{h}$	3038.4 $\text{kJ/m}^2 \cdot \text{h}$



It is seen that the values of  $A$ ,  $B$  and  $C$  obtained on the basis of US data, predict high values of beam radiation and low values for diffused radiation, when used under Indian conditions. However, the two effects tend to balance each other to some extent and therefore, the values for global radiations are predicted to a reasonable degree of accuracy.

#### SOLAR RADIATION ON AN INCLINED PLANE SURFACE

Total radiation incident on an inclined surface consists of three components: (i) beam radiation, (ii) diffused radiation and (iii) radiation reflected from the ground and surroundings. It may be mentioned here that both beam and diffused components of radiation undergo reflection from the ground and surroundings. The total radiation on a surface of arbitrary orientation may be evaluated as:

$$I_t = I_b r_b + I_d r_d + (I_g + I_g') r_t \quad (4.26)$$

where  $r_b$ ,  $r_d$  and  $r_t$  are known as tilt factors for beam, diffuse and reflected components respectively. The expressions for these factors are given below:

$r_g$  It is defined as the ratio of flux of beam radiation incident on an inclined surface ( $I_g'$ ) to that on a horizontal surface ( $I_g$ ).

$$I_g' = I_{bn} \cos \theta$$

$$I_g = I_{bn} \cos \theta_i$$

where  $I_{bn}$  is the beam radiation on a surface normal to the direction of sun rays

$$r_b = \frac{I_g'}{I_g} = \frac{\cos \theta}{\cos \theta_i} \quad (4.27)$$

For a tilted surface facing south,  $\gamma = 0^\circ$ , the expression for  $r_b$  may be written as

$$r_b = \frac{\sin \delta \sin (\phi - \beta) + \cos \delta \cos \omega \cos (\phi - \beta)}{\sin \delta \sin \phi + \cos \delta \cos \omega \cos \phi} \quad (4.28)$$

$r_d$  It is defined as the ratio of flux of diffused radiation falling on an inclined surface to that on the horizontal surface. The value of this tilt factor depends upon the distribution of diffused radiation over the sky and on the portion of the sky dome seen by the tilted surface. Assume that the sky is an isotropic source of diffused radiation; we have for a tilted surface with slope  $\beta$ ,

$$r_d = \frac{1 + \cos \beta}{2} \quad (4.29)$$

$r_t$  The reflected component comes mainly from the ground and surrounding objects. Since  $(1 + \cos \beta)/2$  is the radiation shape factor for a tilted surface with respect to the sky, it follows that  $(1 - \cos \beta)/2$  is the radiation shape factor for the

surface with respect to the surrounding ground. Assume that the reflection of the beam and diffused radiation falling on the ground is diffused and isotropic and the reflectivity is  $\rho$ . The tilt factor for reflected radiation may be written as

$$r_t = \rho \left( \frac{1 - \cos \beta}{2} \right) \quad (4.30)$$

where  $\rho$  is the reflection coefficient of the ground (equal to 0.2 for ordinary grass or concrete and 0.6 for snow-covered ground respectively).

For a vertical surface,  $\beta = 90^\circ$ ,  $r_d = 0.5$  and  $r_r = 0.5\rho$ . This indicates that half of the diffused and half of the total reflected radiation is received by a vertical surface. For a horizontal plane,  $r_d = 1$  and  $r_r = 0$ , which indicates that maximum diffuse radiation is received by the horizontal surface and that a horizontal surface receives no ground reflected radiation. The ratio  $r'$  of total solar energy incident on an inclined surface to that on a horizontal surface is given as

$$r' = \frac{I_T}{I_b + I_d} = \frac{I_T}{I_g} \left( 1 - \frac{I_d}{I_g} \right) r_b + \frac{I_d}{I_g} r_d + r_t \quad (4.31)$$

Equation 4.31 can be used for calculating hourly radiation falling on a tilted surface if the hour angle  $\omega$  is considered at the midpoint of the hour concerned.

The monthly average, hourly value  $\bar{I}_T$  can be obtained by considering the representative day of the month for calculation of  $I_T$ . Eq. 4.32 will then be modified as

$$\frac{\bar{I}_T}{I_g} = \left( 1 - \frac{\bar{I}_d}{I_g} \right) \bar{r}_b + \frac{\bar{I}_d}{I_g} \bar{r}_d + \bar{r}_t \quad (4.32)$$

where  $\bar{r}_b = r_b$  on representative day of the month,

$$\begin{aligned} \bar{r}_d &= r_d \\ \bar{r}_t &= r_t \end{aligned}$$

On similar lines, the ratio of the daily total radiation on tilted surface  $H_t$  to the daily global radiation on a horizontal surface may be written as

$$\frac{H_t}{H_g} = \left( 1 - \frac{H_d}{H_g} \right) R_b + \frac{H_d}{H_g} R_d + R_t \quad (4.33)$$

For a south-facing surface,  $\gamma = 0^\circ$ ,

$$R_b = \frac{\omega_a \sin \delta \sin (\phi - \beta) + \cos \delta \sin \omega_a \cos (\phi - \beta)}{\omega_a \sin \delta \sin \phi + \cos \delta \sin \omega_a \cos \phi} \quad (4.35)$$



where  $\omega_a$  = sunrise hour angle expressed in radians on a tilted surface  
 $\omega_s$  = sunrise hour angle expressed in radians on a horizontal surface

$$\text{And } R_d = r_t = \frac{1 + \cos \beta}{2} \quad (4.36)$$

$$R_t = r_t = \rho \left( \frac{1 - \cos \beta}{2} \right) \quad (4.37)$$

Eq. 4.33 can also be used for calculating monthly average of daily radiation falling on an inclined surface if the required values are calculated for a representative day of the month. Eq. 4.33 may then be written in its revised form,

$$\overline{\overline{H}}_T = \left( 1 - \frac{\overline{H}_d}{\overline{H}_s} \right) \overline{R}_b + \frac{\overline{H}_d}{\overline{H}_s} \overline{R}_{d,t} + \overline{R}_t \quad (4.38)$$

where  $\overline{R}_b = R_b$  on the representative day of the month

$$\overline{R}_d = R_d = \frac{1 + \cos \beta}{2} \quad (4.39)$$

$$\overline{R}_t = R_t = \rho \left( \frac{1 - \cos \beta}{2} \right) \quad (4.40)$$

### Example

Calculate the monthly average, total daily radiation falling on a flat-plate collector facing south ( $\gamma = 0^\circ$ ) and tilted by  $30^\circ$  from the ground, at New Delhi ( $28^\circ 35' N, 77^\circ 12' E$ ) for the month of November. Assume ground reflectivity as 0.2.

## 4.7

### Solution

Given data:

$$\phi = 28.58^\circ$$

$$B = 30^\circ$$

The representative day for the month of November is  $14^{\text{th}}$ .

Therefore, for the day of the year on November 14,  $n = 318$

Monthly average of the daily global radiation for the month of November in New Delhi (from Table C1 in Appendix C),

$$\overline{H}_s = 16282.8 \text{ kJ/m}^2 \cdot \text{day}$$

Monthly average of the daily diffused radiation for the month of November in New Delhi (from Table C2 in Appendix C),

$$\overline{H}_d = 4107.6 \text{ kJ/m}^2 \cdot \text{day}$$

Using Eq. 4.5,  $\delta = -18.91^\circ$

Using Eq. 4.11,  $\omega_s = 79.245^\circ$ , or 1.383 radians



As the day under consideration lies between September 22 and March 21, the hour angle at sunrise will be same as that obtained for a horizontal surface. Thus,

$$\omega_a = \omega_s = 79.245^\circ, \text{ or } 1.383 \text{ radians}$$

Using Eq. 4.35,

$$\begin{aligned} R_h &= \frac{1.383 \times \sin(-18.91) \sin(28.58 - 30) + \cos(-18.91) \sin 79.245 \cos(28.58 - 30)}{1.383 \times \sin 28.58 \sin(-18.91) + \cos(-18.91) \sin 79.24 \cos 28.58} \\ &= 1.56 \end{aligned}$$

Using Eq. 4.39,

$$\bar{R}_d = \frac{1 + \cos 30^\circ}{2} = 0.933$$

Using Eq. (4.40),

$$\bar{R}_t = 0.2 \times \left( \frac{1 - \cos 30^\circ}{2} \right) = 0.0134$$

Now, monthly average total daily radiation,  $\bar{H}_T$  on a tilted surface may be calculated using Eq. 4.38,

$$\frac{\bar{H}_T}{\bar{H}_E} = \left( 1 - \frac{\bar{H}_d}{\bar{H}_g} \right) \bar{R}_b + \frac{\bar{H}_d}{\bar{H}_g} \bar{R}_d + \bar{R}_t$$

$$\begin{aligned} \bar{H}_T &= 1628.8 \times \left[ \left( 1 - \frac{4107.6}{16282.8} \right) \times 1.56 + \frac{4107.6}{16282.8} \times 0.933 + 0.0134 \right] \\ &= 23043.89 \text{ kJ/m}^2\text{-day} \end{aligned}$$

### Review Questions

- What are the disadvantages of solar energy?
- What are the indirect forms of solar energy?
- How is the energy continuously being produced in the sun?
- What do you understand by the earth's albedo?
- At what wavelengths are the radiation emitted from the sun and that reflected from the earth centered?
- Define solar irradiance, solar constant, extraterrestrial and terrestrial radiations. What is the standard value of solar constant?
- Describe the percentage-wise distribution of various components in extraterrestrial radiation.
- Explain the depletion process of solar radiation as it passes through the atmosphere to reach the surface of the earth.
- What is solar time and why it is different from the standard clock time of a country?



10. Define declination angle, hour angle, zenith angle, solar azimuth angle and angle of incidence:
11. Derive an expression for solar day length.
12. Define beam, diffused and global radiation. Derive an expression for total radiation on an inclined surface. Show that a horizontal surface receives no ground-reflected radiation.
13. Explain the construction and principle of operation of a sunshine recorder.
14. How does the collection of solar energy get affected by tilting a flat-plate collector with respect to the ground?
15. How does sun tracking help in energy collection by a flat-plate solar collector?
16. What are the basic features required in an ideal pyranometer?

### Problems

1. Calculate the number of daylight hours (daylength) at Bangalore on 21 June and 21 December in a leap year. The latitude of Bangalore is  $12^{\circ}58'N$ .

(Ans. 12:056 h, 11:944 h)

2. Calculate the angle made by beam radiation with the normal to a flat-plate collector, tilted by  $30^{\circ}$  from the horizontal, pointing due south, located at New Delhi, at 11:00 h (IST), on 1 June. The latitude and longitude of New Delhi are  $28^{\circ}35'N$  and  $77^{\circ}12'E$  respectively. The standard IST longitude is  $81^{\circ}44'E$ .

(Ans. 29.88°)

3. Calculate the angle of incidence on a horizontal plane surface at Kolkata, at 14:00 h (IST) on 21 March in a leap year. The longitude and latitude of Kolkata are  $88^{\circ}20'E$  and  $22^{\circ}32'N$  respectively. The standard longitude of IST is  $81^{\circ}44'E$ .

(Ans. 40.6°)

4. An inclined surface, facing due south, tilted at  $60^{\circ}$  with the horizontal, is located at Aligarh (latitude  $27^{\circ}54'N$ , longitude  $78^{\circ}05'E$ ) on 22 March at 1 p.m. (IST). The reflection coefficient  $\rho$  of the ground is 0.2. Calculate the total radiation received at the surface. Also, calculate the values of  $R_g$ ,  $R_b$ ,  $R_a$  and  $R'$ .

(Ans. 929.77W/sq. m, 0.964, 0.75, 0.05, 0.9877)

5. Calculate the monthly average of the daily global radiation on the horizontal surface at Gulmarg ( $34.05^{\circ}N, 74.38^{\circ}E$ ), during the month of October if the average sunshine hour per day is 5 hours.

(Ans. 13562.859 kJ/m<sup>2</sup>-day)

6. From the data given in Problem 5 for Gulmarg, estimate the monthly average of the daily diffused and beam radiations on a horizontal surface.

(Ans. 7083.35 kJ/m<sup>2</sup>-day, 6479.5 kJ/m<sup>2</sup>-day)

7. From the data given in Problem 5 above for Gulmarg, calculate the monthly average of the hourly global and hourly diffused radiations on a horizontal surface during 13:00 to 14:00 hours (LAT).

(Ans. 1151.284 kJ/m<sup>2</sup>·h, 800 kJ/m<sup>2</sup>·h)



8. The following hourly values are measured between 11:00 to 12:00 hours on a clear day on 20 March at Mumbai ( $19^{\circ} 07' N$ ,  $72^{\circ} 51' E$ ).

Global radiation =  $3196.8 \text{ kJ/m}^2\cdot\text{h}$

Diffuse radiation =  $745.2 \text{ kJ/m}^2\cdot\text{h}$

Using empirical relations, estimate the values of global and diffused radiations and compare with the measured data.

(Ans.  $I_g = 3608 \text{ kJ/m}^2\cdot\text{h}$ ,  $I_d = 387.48 \text{ kJ/m}^2\cdot\text{h}$ )

9. Calculate the monthly average total daily radiation falling on a flat-plate collector facing south ( $\gamma = 0^{\circ}$ ) and tilted by an angle equal to latitude from ground, at Mumbai ( $19^{\circ} 07' N$ ,  $72^{\circ} 51' E$ ) for the month of September. Assume ground reflectivity as 0.15. For the month of September at Mumbai, the daily average data are given as  $H_d = 17560.8 \text{ kJ/m}^2\cdot\text{h}$  and  $H_a = 10296 \text{ kJ/m}^2\cdot\text{h}$ .

(Ans.  $17202.8 \text{ kJ/m}^2\cdot\text{h}$ )

10. Calculate the hour angles at sunrise on 21 June and also on 21 December for a flat-plate solar collector inclined due south (i.e.,  $\gamma = 0^{\circ}$ ) at an angle equal to the latitude of the place. The collector is located at Nagpur ( $21^{\circ} 06' N$ ,  $79^{\circ} 03' E$ )

(Ans.  $90^{\circ}$ ,  $83.36^{\circ}$ )

### Objective-type Questions

- Which process is responsible for production of energy in the sun?  
 (a) Nuclear fission reaction      (b) Nuclear fusion reaction  
 (c) Exothermal chemical reaction      (d) All of the above
- Which one of the following statements is not true for solar energy?  
 (a) It is a dilute form of energy.  
 (b) Its availability is diurnal.  
 (c) Availability at any instant of time is uncertain.  
 (d) Its harnessing at large scale is easy.
- Diffused radiation  
 (a) has no unique direction  
 (b) has a unique direction  
 (c) has short wavelength as compared to beam radiation  
 (d) has larger magnitude as compared to beam radiation
- In extraterrestrial radiation, what is the approximate percentage content of infra-red component?  
 (a) 45.5%      (b) 55.5%      (c) 20%      (d) 80%
- Terrestrial radiation has a wavelength in the range of  
 (a) 0.2  $\mu\text{m}$  to 4  $\mu\text{m}$       (b) 0.2  $\mu\text{m}$  to 0.5  $\mu\text{m}$   
 (c) 0.380  $\mu\text{m}$  to 0.760  $\mu\text{m}$       (d) 0.29  $\mu\text{m}$  to 2.3  $\mu\text{m}$
- What is the standard value of solar constant?  
 (a)  $1 \text{ kW/m}^2$       (b)  $1.367 \text{ kW/m}^2$       (c)  $15 \text{ kW m}^{-2}$       (d)  $5 \text{ kW m}^{-2}$
- When incoming solar radiation passes through the atmosphere of the earth  
 (a) radiation of all wavelengths is absorbed uniformly by different types of molecules  
 (b) different molecules selectively absorb the radiation of different wavelengths

- (c) there is no absorption of radiation in the atmosphere  
(d) there is total absorption of radiation.

8. The percentage of the incoming radiation reflected back to space by the earth is

(a) 10%

(b) 20%

(c) 30%

(d) 40%

9. Air mass ratio is minimum

(a) when the sun is at zenith

(b) at sunrise

(c) at sunset

(d) at 06:00 GMT

10. At the inclination angle of  $30^\circ$ , what will be magnitude of the zenith angle?

(a)  $30^\circ$

(b)  $120^\circ$

(c)  $150^\circ$

(d)  $60^\circ$

11. For 1 degree change in longitude, the change in solar time is

(a) 4 minutes

(b) 4 seconds

(c) 1 minute

(d) 1 hour

12. On 21 September, the declination angle will be

(a) zero

(b)  $+23.45^\circ$

(c)  $-23.45^\circ$

(d)  $+180^\circ$

13. At solar noon, the hour angle is?

(a)  $+90^\circ$

(b)  $-90^\circ$

(c) Zero

(d)  $+180^\circ$

14. On the representative day of each month, the extraterrestrial daily radiation may be taken as equal to

(a) beam radiation at the location

diffused radiation at the location

(c) global radiation at the location

(d) monthly average, daily extraterrestrial radiation at the location

15. A horizontal surface receives

(a) no reflected component of radiation

(b) 50% of the reflected component of radiation

(c) 50% of the diffused component of radiation

(d) 50% of the beam component of radiation

16. A vertical surface receives

(a) no reflected component of radiation

(b) 50% of the reflected component of radiation

(c) 100% of diffused component of radiation

(d) 50% of the beam component of radiation



# Solar Thermal Systems

## Introduction

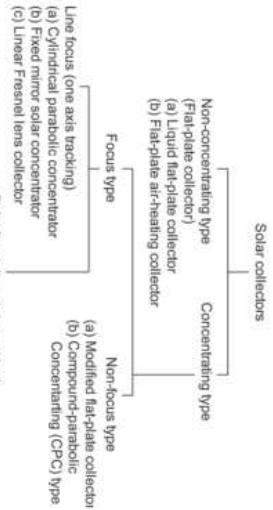
**5** Solar energy can be utilized directly by two technologies, namely, (i) Solar Thermal, and (ii) Solar Photovoltaic. Solar thermal systems provide thermal energy for various processes. In regions of cold climates a large amount of low-grade thermal energy is required to heat air for comfort, and 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.

## SOLAR COLLECTORS

**5.1** 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.

### 5.1.3 Performance Indices

The important performance indices of a solar collector are (i) collector efficiency, (ii) concentration ratio, and (iii) temperature range. The performance of a solar collector is evaluated on the basis of these features.

*Collector efficiency* is defined as the ratio of the energy actually absorbed and transferred to the heat-transport fluid by the collector (useful energy) to the energy incident on the collector.

*Concentration ratio (CR)* is defined as the ratio of the area of aperture of the system to the area of the receiver. The aperture of the system is the projected area of the collector facing (normal) the beam.

*Temperature range* is the range of temperature to which the heat-transport fluid is heated up by the collector.

In flat-plate collectors, no optical system is utilized to concentrate the solar radiation and hence the concentration ratio is only 1. The temperature range is less than 100°C. Line focus collectors have CR up to 100 and a temperature range of the order of 150°C to 300°C. A concentration ratio of the order of thousands and temperature range of 500°C to 1000°C, can be obtained by using point-focus collectors.

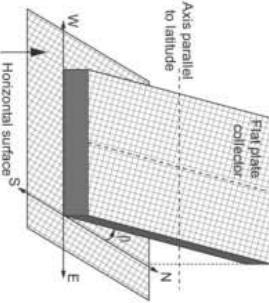
### 5.1.4 Liquid Flat-plate Collector

A flat-plate collector is placed at a location in a position such that its length aligns with the line of longitude and is suitably tilted towards south to have maximum collection. The positioning of the collector is shown in Fig. 5.2. The constructional details of a simple flat-plate collector are shown in Fig. 5.3. The basic elements in a majority of these collectors are:

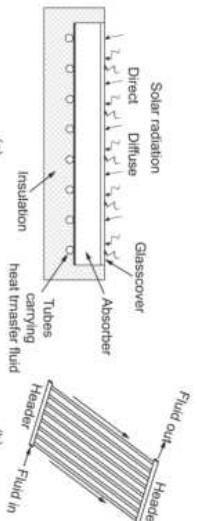
- transparent cover (one or two sheets) of glass or plastic
- blackened absorber plate usually of copper, aluminium or steel
- tubes, channels or passages in

thermal contact with the absorber plate—in some designs, the tubes form an integral part of absorber plate

- weather tight, insulated container to enclose the above components



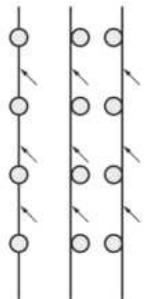
**Fig. 5.2 Positioning of flat-plate collector**



**Fig. 5.3** Construction of flat-plate collector

A liquid, most commonly water, is used as the heat-transport medium from the collector to the next stage of the system. However, sometimes a mixture of water and ethylene glycol (antifreeze mixture) is also used if the ambient temperatures are likely to drop below 0°C during nights. As solar radiation strikes on a specially treated metallic absorber plate, it is absorbed and raises the plates temperature. The absorber plate is usually made from a metal sheet ranging in thickness from 0.2 to 1 mm. The heat is transferred to the heat-transfer liquid circulating in the tube (or channels), beneath the absorber plate and in intimate contact with it. The metallic tubes range in diameter from 1 to 1.5 cm. These are soldered, brazed, welded or pressure bonded to the absorber plate with a pitch ranging from 5 to 12 cm. In some designs, the tubes are bonded to the top or are in line and integral to the absorber plate. Some of these arrangements are shown in Fig. 5.4. Header pipes, which are of slightly larger diameter of typically 2 to 2.5 cm, lead the water in and out of the collector and distribute to tubes. The metal that is most commonly used, both for the absorber plate, the tubes and the header pipes, is copper, but other metals and plastics have also been tried. In the bottom and along the side walls, thermal insulation provided by a 2.5 to 8-cm thick layer of glass wool prevents heat loss from the rear surface and sides of the collector. The glass cover permits the entry of solar radiation as it is transparent for incoming short wavelengths but is largely opaque to the longer infrared radiation reflected from the absorber. As a result, the heat remains trapped in the airspace between the absorber plate and glass cover in a manner similar to a green house. The glass cover also prevents heat loss due to convection by keeping the air stagnant. The glass cover may reflect some 15% of incoming solar radiation, which can be reduced by applying anti-reflective coating on the outer surface of the glass. The usual practice is to have one or two covers with spacing ranging from 1.5 to 3 cm. Plain or toughened glass of 4 to 5-mm thickness is the most favoured material. Transparent plastics may also be used in place of glass but they often offer inferior performance as compared to glass. Most plastics are not as opaque to infrared radiation as glass. Also, their transparency for incoming solar radiation decreases with aging. The life of a plastic material is short when exposed to sunrays as it breaks down and cracks develop over a span of time.

## (5.1) Non-conventional Energy Resources



- Fig. 5.4** Cross-sections through collector plates
- (i) **Pipe-and-fin Type** Here, the liquid flows only in the pipe and hence they have a comparatively low wetted area and liquid capacity.
  - (ii) **Rectangular or Cylindrical Full-sandwich Type** In this, both the wetted area and water capacity are high.
  - (iii) **Roll-bond or Semi-sandwich Type** It is an intermediate between the above two types.

The best choice depends on the particular application. For low-temperature requirements, such as warming of a swimming pool, the plastic, full water-sandwich plate may be the most appropriate. For domestic and industrial applications, high temperatures are required and hence the pipe-and-fin-type plate may be more suitable.

### 5.1.5 Liquid Flat-plate Collector Efficiency

The instantaneous collection efficiency of a flat-plate solar collector is defined as follows:

$$\eta_i = \frac{\text{useful heat gain}}{\text{solar radiation incident on the collector}} = \frac{q_u}{A_p I_r} \quad (5.1)$$

where  $q_u$  = useful heat gain (i.e., rate of heat transfer to the working fluid)

$A_p$  = area of absorbing plate

$I_r$  = instantaneous radiation energy incident on the collector face ( $\text{kW/m}^2$ )

The above expression is also valid for calculating the hourly collecting efficiency. In that case,  $q_u$  will be taken as useful heat gain in one hour and  $I_r$  as the energy incident on the collector face in one hour ( $\text{kJ/m}^2\text{-h}$ ).

An energy balance on the absorber plate yields the following equation:

$$q_u = A_p \delta q_i \quad (5.2)$$

where  $S$  = incident solar flux absorbed in the collector plate

$q_r$  = rate at which energy is lost by (i) convection and re-radiation from the top, and by (ii) conduction and convection from the bottom and sides of the collector

The flux incident on the top cover of the collector is given by

$$I_t = I_b r_b + [I_d r_d + (I_b + I_d) r] \quad (5.3)$$

In order to determine the flux  $S$  absorbed by the absorber plate, each term of the above equation is multiplied by a term called the *transmissivity-absorptivity product* ( $\tau\alpha$ ). Thus,

$$S = I_b r_b (\tau\alpha)_b + [I_d r_d + (I_b + I_d) r] (\tau\alpha)_d \quad (5.4)$$

The term transmissivity  $\tau$  of the glass-cover system is defined as the ratio of the solar radiation coming through after reflection at the glass-air interfaces and absorption in the glass to the radiation incident to the glass-cover system. The term  $\alpha$  is the absorptivity of the absorber plate. The term

$(\tau\alpha)_b$  transmissivity-absorptivity product for beam radiation falling on the collector and

$(\tau\alpha)_d$  transmissivity-absorptivity product for diffused radiation falling on the collector

It is more convenient to express the heat lost from the collector in terms of an overall loss coefficient defined by the equation:

$$q_L = U_{\perp} A_p (T_{\text{pm}} - T) \quad (5.5)$$

where  $U_{\perp}$  = overall loss coefficient

$A_p$  = area of absorber plate

$T_{\text{pm}}$  = mean (or average) temperature of the absorber plate

and  $T_s$  = temperature of the surrounding air

The heat lost from the collector is the sum of the heat lost from the top, the bottom and the sides. Therefore, total heat loss rate of the collector is given by,

$$q_L = q_r + q_b + q_s \quad (5.6)$$

where  $q_r$  = rate at which heat is lost from the top

$q_b$  = rate at which heat is lost from the bottom

$q_s$  = rate at which heat is lost from the sides

Each of these loss components may also be expressed in terms of individual loss coefficients, that is, top loss coefficient, bottom loss coefficient and side loss coefficient respectively, defined by the following equations.

$$q_t = U_t A_p (T_{pm} - T) \quad (5.7)$$

$$q_b = U_b A_p (T_{pm} - T) \quad (5.8)$$

$$q_s = U_s A_p (T_{pm} - T) \quad (5.9)$$

It is to be noted here that in the above three equations, the coefficients are defined on the basis of common area  $A_p$  and also the common temperature difference. This simplifies the analysis and gives a simple additive equation for overall loss component of the collector. Thus:

$$U_i = U_t + U_b + U_s \quad (5.10)$$

These losses can also be depicted in terms of thermal resistances as shown in Fig. 5.5. The typical value of the overall loss coefficient is in the range of 2 to 10 kW/m<sup>2</sup>K.

Equation (5.2) can now be written as

$$q_u = A_p \Sigma U_i A_p (T_{pm} - T) \quad (5.11)$$

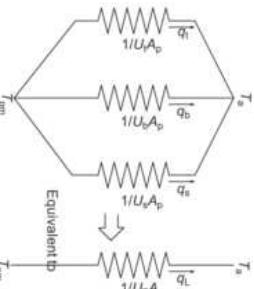
A modified equation in which the plate temperature  $T_{pm}$  is replaced by the local fluid temperature  $T_f$  (temperature of fluid flowing in the tubes) can also be obtained

as follows:

$$q_u = F' [A_p \Sigma U_i A_p (T_f - T)] \quad (5.12)$$

where  $F'$  is known as the *collector efficiency factor* and defined as the ratio of the actual useful heat collection rate to the useful heat-collection rate which would occur if the collector-absorber plate were at the temperature  $T_f$ . Its value ranges from 0.90 to 0.95.

The heat loss from the collector can thus be calculated if either the average plate temperature or local fluid temperature is known. However, these temperatures are generally not known. By considering the heat-removal process due to fluid flow, a modified expression can be obtained in terms of the inlet fluid temperature,  $T_i$ . This is usually a known quantity and hence the expression is more convenient to use. Thus:



**Fig. 5.5** Thermal resistance network showing collector losses



$$q_a = F_k A_p [S - U_L (T_h - T_j)] \quad (5.13)$$

$$\text{where } F_k = \frac{\bar{m} C_p}{U_L A_p} \left[ \frac{F U_L A_p}{\bar{m} C_p} \right] \quad (5.14)$$

The term  $F_k$  is called the collector heat-removal factor. It represents the ratio of the actual useful heat-collection rate to the useful heat-collection rate which would occur if the collector absorber plate were at the temperature  $T_h$  everywhere. The terms  $\bar{m}$ , and  $C_p$  have their usual meanings. Its value ranges from 0 to 1. Equation 5.14 is often referred as the Hottel-Whillier-Bliss equation.

Using the procedure described above, the efficiency of a flat-plate collector may be calculated. For a properly designed flat-plate collector, an instantaneous efficiency of the order of 50–60% may be achieved.

### **Effect of Various Parameters on Performance**

(i) **Selective Surface** Absorber plate surfaces which exhibit characteristics of a high value of absorptivity for incoming solar radiation and low value of emissivity for outgoing re-radiation are called selective surfaces. Such surfaces are desirable because they maximize the net energy collection. Some examples of selective surface layers are copper oxide, nickel black and black chrome.

(ii) **Number of Covers** With increase in the number of covers, the values of both  $(\tau\alpha)_h$  and  $(\tau\alpha)_d$  decrease and thus the flux absorbed by the absorber plate decreases. The value of heat loss from the absorber plate also decreases. However, the amount of decrease is not the same in both cases. Maximum efficiency is obtained with one or two covers.

(iii) **Spacing** Heat loss also varies with spacing between two covers and that between the absorber plate and first cover. The spacing at which minimum loss occurs varies with temperature and also with tilt. Since collectors are designed to operate at different locations with varying tilts and under varying service conditions, an optimum value of spacing is difficult to specify. Spacing in the range from 4 to 8 cm is normally suggested.

(iv) **Collector Tilt** Flat-plate collectors are normally used in a fixed position and do not track the sun. Therefore, the tilt angle at which they are fixed is very important. Optimum tilt depends on the nature of the application. The usual practice is to recommend a value of  $(\phi + 10^\circ)$  or  $(\phi + 15^\circ)$  for winter applications (e.g., water heating, space heating, etc.) and  $(\phi - 10^\circ)$  or  $(\phi - 15^\circ)$  for summer applications (e.g., absorption refrigeration plant etc.).

(v) **Dust on the Top of the Cover** When a collector is deployed in a practical system, dust gets accumulated over it, reducing the transmitted flux through the

cover. This requires continuous cleaning of the cover, which is not possible in a practical situation. Cleaning is generally done once in a few days. For this reason, it is recommended that the incident flux be multiplied by a correction factor which accounts for the reduction in intensity because of accumulation of dust. In general, a correction factor from 0.92 to 0.99 seems to be indicated.

### 5.1.6 Flat-Plate Air-Heating Collector (Solar Air Heater, Solar Air Collector)

A solar air-heating collector is similar to a liquid flat-plate collector with a change in the configuration of the absorber and tube (riser), as shown in Fig. 5.6. The value of the heat-transfer coefficient between the absorber plate and the air is low. For this reason, the surfaces are sometimes roughened or longitudinal fins are provided in the air-flow passage. Corrugated, V-shaped, matrix, etc., are some of the other variations of shapes of the absorber plate. The principal applications of these collectors are drying for agricultural and industrial purposes, and space heating.

It has the following advantages over a liquid flat-plate collector:

- It is compact, simple in construction and requires little maintenance.
  - The need to transfer thermal energy from the working fluid to another fluid is eliminated as air is used directly as the working fluid.
  - Corrosion is completely eliminated.
  - Leakage of air from the duct is less severe.
  - Possibility of freezing of working fluid is also eliminated.
  - The pressure inside the collector does not become very high.
- The major disadvantages of air collectors are the following:
- A large amount of fluid is to be handled due to low density. As a result, the electrical power required to blow the air through the system can be significant if the pressure drop is not kept within prescribed limits.
  - Heat transfer between the absorber plate and air is poor.
  - There is less storage of thermal energy due to low heat capacity.

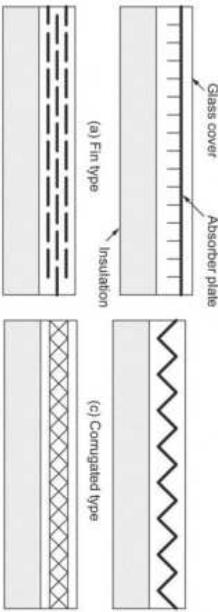


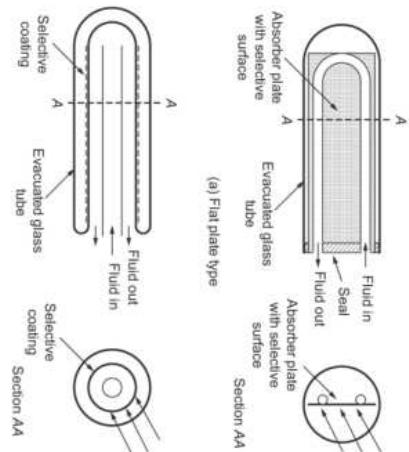
Fig. 5.6 Various types of flat-plate air heating collector

### 5.1.7 Evacuated Tube Collector

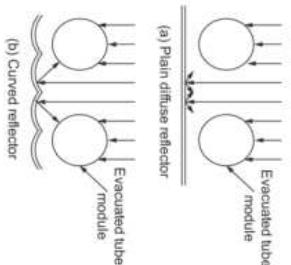
The performance of a flat-plate collector can be improved by suppressing or reducing the heat lost from the collector by convection and conduction. This is done by having vacuum around the absorber. As a consequence, it becomes essential to use a glass tube as the cover because only a tubular surface is able to withstand the stresses introduced by the pressure differences as a result of vacuum. The collector consists of a number of long tubular modules stacked together.

A number of designs have been developed and some of them are commercially available. In the simplest design, each module consists of a metal absorber plate with two fluid tubes housed in an evacuated, cylindrical glass tube as shown in Fig. 5.7(a). The absorber plate has a selective surface coating on it. The two tubes are joined at the other end inside the glass cover and form a "U" path for the fluid, with one tube acting as the inlet tube while the other as the outlet tube. A glass to metal seal is provided between the absorber tubes and the end cover of the vacuum tube. Also, special precaution is required to reduce thermal contact between the absorber tubes and the outer tube through the seal.

In another design shown in Fig. 5.7(b), the metal to glass seal is avoided by using three concentric tubes with the space between the outer two tubes, which are made from glass, being evacuated. The outer surface of the middle tube acts as the absorbing surface and has a selective surface coating on it. The liquid flows in through the innermost tube and flows out through the annulus between this tube and the middle tube.



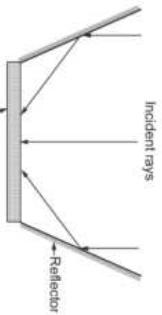
**Fig. 5.7** Various designs of evacuated tube collectors



**Fig. 5.8** Layout of evacuated tube modules with reflectors

reduction of heat loss first occurs because of reduction of the Rayleigh number. When the Rayleigh number is further reduced below the lower threshold of convection, the heat transfer occurs because of conduction only. When the pressure is reduced to  $10^{-3}$  torr, the conduction heat transfer is also completely suppressed. A vacuum of the order of  $10^{-3}$ – $10^{-4}$  torr is easily achievable.

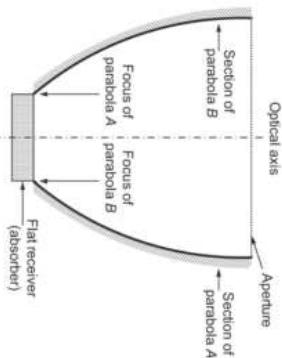
Evacuated tube collectors are very expensive compared to conventional flat-plate collectors. Thus, it is possible to consider them only for high fluid temperatures in a range 100 to 130°C.



**Fig. 5.9** Modified flat-plate collector

By providing plane reflectors at the edges of a flat-plate collector to reflect additional radiation into the receiver, the concentration of solar radiation can be increased. These mirrors are also called booster mirrors. The concentration ratio of these concentrators has a maximum value of 4. Such a design (V-trough) is aligned in the east-west direction and requires periodic tilt adjustment. Different optimum depth to base width ratio and cone angles are possible depending on the frequency of seasonal tilt adjustment. The schematic diagram is shown in Fig. 5.9.

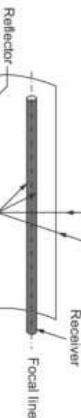
### 5.1.9 Compound Parabolic Concentrator (CPC)



**Fig. 5.10** Compound parabolic concentrator

concentration ratio achieved from this collector is in the range of 3–7.

### 5.1.10 Cylindrical Parabolic Concentrator

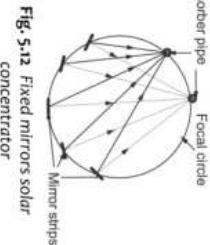


**Fig. 5.11** Cylindrical parabolic concentrator

It consists of a cylindrical parabolic trough reflector and a metal tube receiver at its focal line as shown in Fig. 5.11. The receiver tube is blackened at the outside surface to increase absorption. It is rotated about one axis to track the sun. The heat-transfer fluid flows through the receiver tube, carrying the thermal energy to the next stage of the system. This type of collector may be oriented in any one of the three directions: east-west, north-south or polar. The polar configuration intercepts more solar radiation per unit area as compared to other modes and thus gives the best performance. The concentration ratio in the range of 5–30 may be achieved from these collectors.

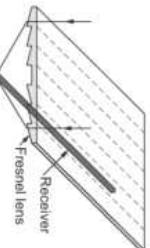
### 5.1.11 Fixed-mirror Solar Concentrator

Due to practical difficulty in manufacturing a large mirror in a single piece in a cylindrical parabolic shape, long narrow mirror strips are used in this concentrator. The concentrator consists of fixed mirror strips arranged on a circular reference cylinder with a tracking receiver tube as shown in Fig. 5.12. The receiver tube is made to rotate about the centre of curvature of the reflector module



**Fig. 5.12** Fixed mirrors solar concentrator

to track the sun. The image width at the absorber is ideally the same as the projected width of a mirror element; the concentration ratio is approximately the same as the number of mirror strips.

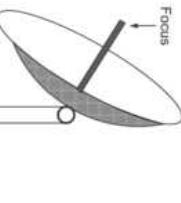


**Fig. 5.13** Linear Fresnel lens collector

which yields temperatures between 150 to 300°C. The construction of this type of collector is shown in Fig. 5.13.

### 5.1.12 Linear Fresnel Lens Collector

In this collector, a Fresnel lens, which consists of fine, linear grooves on the surface of the refracting material (generally optical quality plastic) on one side and flat on the other side, is used. The angle of each groove is designed to make the optical behavior similar to a spherical lens. The beam radiation, which is incident normally, converges on the focal line, where a receiver tube is provided to absorb the radiation. A concentration ratio of 10 to 30 may be realized

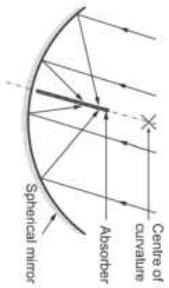


### 5.1.13 Paraboloidal Dish Collector (Scheffler Solar Concentrator)

When a paraboloid is rotated about its optical axis, a paraboloidal shape is produced. Figure 5.14 shows the details of this type of collector. Beam radiation is focused at a point in the paraboloid. This requires two-axis tracking. It can have a concentration ratio ranging from 10 to few thousands and can yield a temperature up to 3000°C. Paraboloidal dish collectors of 6–7 m in diameter are commercially manufactured.

### 5.1.14 Hemispherical Bowl Mirror Concentrator

It consists of a hemispherical fixed mirror, a tracking absorber and a supporting structure as shown in Fig. 5.15. All rays entering the hemisphere after reflection cross the paraxial line at some point between the focus and the mirror surface. Therefore, a linear absorber pivoted about the centre of curvature of the hemisphere intercepts all reflected rays. The absorber is to be moved so that its axis is always aligned with solar rays passing through the centre of the sphere. This requires two-axis tracking. The absorber is either driven around a polar axis at a constant angular speed of 15 degrees/



**Fig. 5.15** Hemispherical mirror concentrator



hour or adjusted periodically during the day. This type of concentrator gives lesser concentration, owing to spherical aberration, than that obtained in paraboloidal concentrator.

### 5.1.15 Circular Fresnel lens Concentrator

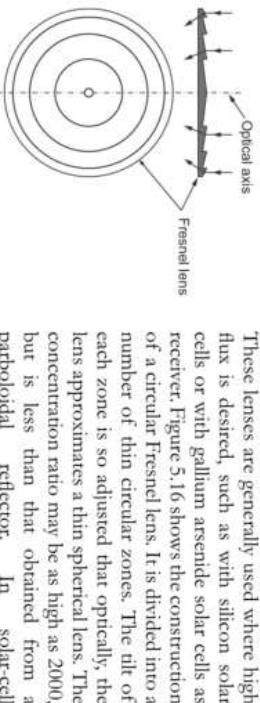
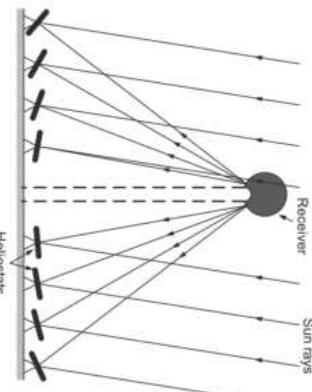


Fig. 5.16 Circular Fresnel lens

These lenses are generally used where high flux is desired, such as with silicon solar cells or with gallium arsenide solar cells as receiver. Figure 5.16 shows the construction of a circular Fresnel lens. It is divided into a number of thin circular zones. The tilt of each zone is so adjusted that optically, the lens approximates a thin spherical lens. The concentration ratio may be as high as 2000, but is less than that obtained from a paraboloidal reflector.

In solar-cell applications, tracking is required to keep the small solar image centered on the receiver.

### 5.1.16 Central Tower Receiver



In a central tower receiver collector, the receiver is located at the top of a tower. Beam radiation is reflected on it from a large number of independently controlled, almost flat mirrors, known as *heliostats*, spread over a large area on the ground, surrounding the tower. Thousands of such heliostats track the sun to direct the beam radiation on the receiver from all sides. The heliostats together act like a dilute paraboloid of very big size.

Concentration ratio of as high a value as 3000 can be obtained. The absorbed energy can be extracted from the receiver and delivered at a temperature and pressure suitable for driving turbines for power generation. The schematic view of a central tower receiver is shown in Fig. 5.17.

Fig. 5.17 Central tower receiver

### SOLAR WATER HEATER

**5.2** 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 immersion 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 110-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.

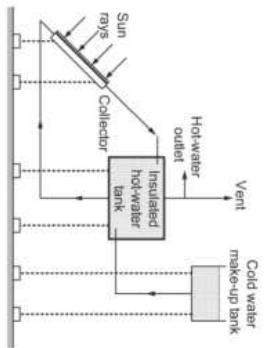


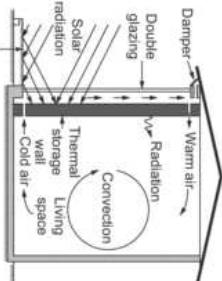
Fig. 5.18 Solar water heater

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.

### SOLAR PASSIVE SPACE-HEATING AND COOLING SYSTEMS

**5.3** 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.

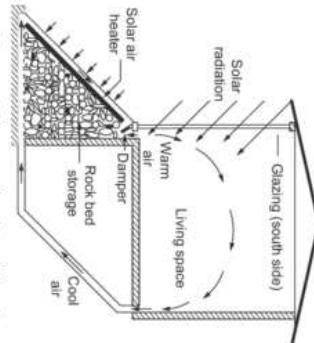
### Solar Thermal Systems



**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.



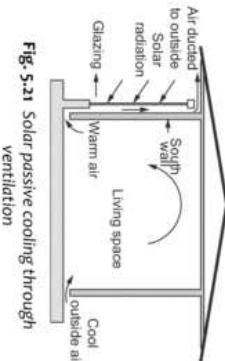
**Fig. 5.20** Solar space heating with rock bed storage

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.

In Fig. 5.20, another variation of a solar space-heating system is shown. Here, a collector cum-rock-bed storage system is integrated with the apartment. During daytime when direct gain through the glaze is sufficient, the hot air from the air heater (collector) is not allowed to enter the room. The available thermal energy is stored in the rock bed to be used later, preferably during night.

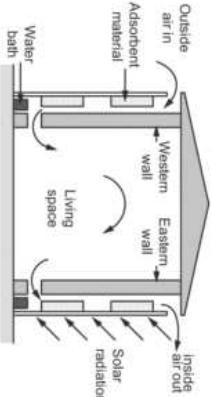
For natural cooling, the first and best approach is to reduce unnecessary thermal loads entering the building. For example, (i) direct sunlight entering the building, which can be reduced by use of sun breakers or shading the windows, walls, roofs, etc., (ii) conduction of heat through building elements, which can be reduced by proper thermal insulation, and (iii) infiltration of outside warm air, which can be reduced by proper sealing. The techniques generally used for passive cooling of the buildings include (i) shading, (ii) ventilation, (iii) evaporation, (iv) radiation, (v) ground coupling and (vi) dehumidification.

The shading method prevents heating from the direct sun light entering the house. In the ventilation method, warm air is driven out and cool outside air is sucked inside by utilizing the chimney effect. The evaporation method is effective in dry regions, where cooling is maintained by utilizing the internal heat to evaporate water. A pond may be used above a thin roof to maintain cooling below it. A desert cooler is another example of evaporative cooling. In radiation cooling, black plastic water bags kept over a metal roof are exposed to the sky at night. Nocturnal radiation cools the water during night. This water absorbs heat from the space below it and keeps it cool. During daytime, the roof is covered by a thermal insulating sheet to prevent heating of water due to solar radiation. A ground coupling system makes use of the fact that in summer the ground temperature is always lower than the air temperature. The lower temperature of the ground can be used for cooling a building by partially sinking it into the ground.



**Fig. 5.21** Solar passive cooling through ventilation

Figure 5.21 shows the scheme for solar passive cooling through ventilation. This scheme utilizes a solar 'chimney effect' and is effective where outside temperatures are moderate. Solar radiation is allowed to heat up the air between the glazing and the interior south wall. The heated air rises up, is ducted outside and the warm air from the room is drawn into this space due to the natural draught thus produced. As a result, cool outside air enters the room from the bottom air vent on the other side of the room.



**Fig. 5.22** Solar passive cooling through dehumidification

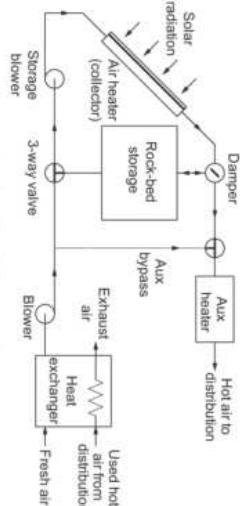
In a dehumidification system, the moisture content of the air in the room is reduced and cooling is maintained by adsorption and evaporation.

The east- and west-facing walls of a specially designed house are provided with solid adsorbent materials and water baths. Air circulation is maintained using a 'chimney effect' as shown in Fig. 5.22. In the morning when the east wall is heated by solar radiation, the air gets heated, rises up and is ducted outside. Due to the natural draught thus produced, air is drawn inside from the west side. The incoming west-side air first gets dried up by a solid adsorbent material, is evaporatively cooled by passing over water baths and then enters the room. The hot air going out through the east-facing wall regenerates the solid adsorbent material. In the evening when the west wall is heated up by the sun, a reversal of air flow occurs and the functions of east and west walls reverse.

## 5.4 SOLAR INDUSTRIAL HEATING SYSTEMS

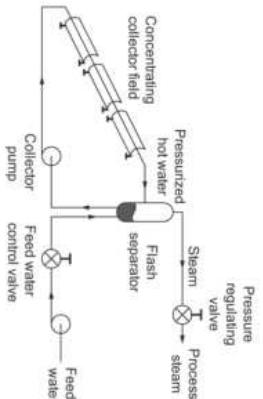
Solar active heating systems are used for several industrial process heat requirements. The process heat in various industries is generally supplied in the form of (i) process hot water, (ii) hot air, and (iii) process steam.

A hot-air solar heating system is shown in Fig. 5.23. Thermal energy is transported from the collector through hot air and is utilized for process heat. The excess heat is stored in a rock-bed thermal storage to be used later when solar radiation is not available. Auxiliary heating augments the supply when the heat supplied by the collector or storage is not sufficient. The used air is passed through a heat exchanger to recover the heat from the exhaust air to raise the initial temperature of fresh air entering the collector.



**Fig. 5.23** Hot-air industrial process heat system

## C134 Non-conventional Energy Resources



**Fig. 5.24** Solar-process steam system

the flash separator is recirculated through the collector field and distributed for use. A pressure regulator valve regulates the pressure.

### SOLAR REFRIGERATION AND AIR-CONDITIONING SYSTEMS

**5.5** Solar energy can also be used in air conditioning (cooling for comfort) and refrigeration (cooling for preserving food). There are several ways of using solar energy for cooling purpose. However, one based on absorption cycle cooling is most widely used at present. The principle of absorption refrigeration was first demonstrated by Faraday in 1825. Thus, this is one of the oldest cycles for producing refrigeration effect, which differs fundamentally from the conventional vapour compression cycle in the method for compressing the refrigerant.

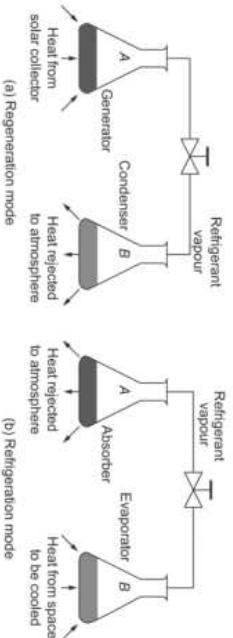
In absorption-cycle cooling systems two working fluids, a refrigerant and an absorbent-refrigerant solution, are used. The absorbent-refrigerant combination is so chosen that the absorbent has a high affinity for the refrigerant and at the same temperature, the vapour pressure of the refrigerant is higher than that of the absorbent. The absorbent cooling is based on the principle that the refrigerant can be bound by a liquid or solid solvent, known as the absorbent to release heat during absorption, while it absorbs heat during evaporation (and thus produces a cooling effect). Though a large number of refrigerant-absorbent combinations is possible, the two most common and commercially tried combinations are LiBr-water (LiBr as absorbent and water as refrigerant) and aqua-ammonia (water as absorbent and ammonia as refrigerant). In the former, the absorbent is a solid (a salt), whereas in the later it is a liquid. The performance of a cooling cycle is judged from its *COP (coefficient of performance)*, which is defined as the ratio of amount of cooling produced to the energy input.

There are four major components in an absorption cycle cooling system: generator, condenser, evaporator and absorber. Cooling can be produced continuously or intermittently. An intermittent refrigerator is compact, simple in operation and is also portable. It has built-in refrigeration storage. Therefore, it is most suited for rural applications using solar energy, which itself is an intermittent source of energy.

Figure 5.24 shows a solar-process steam system. Pressurized water is circulated through a concentrating collector to prevent boiling. The high-pressure heated water is throttled and flash separated in a flash separator. To maintain the necessary liquid level in the flash tank, boiler feed water is injected into the pump suction. The saturated steam obtained from

The basic principle of operation of an intermittent system is demonstrated in Fig. 5.25. Two vessels *A* and *B* containing the absorbent-refrigerant solution and a pure refrigerant respectively are connected through a pipe via a throttle valve. Two modes of operation, regeneration and refrigeration are repeated alternately. In the first mode, Vessel *A* acts as evaporator and Vessel *B* as condenser while in the second mode, Vessel *B* acts as evaporator and Vessel *A* as absorber. In the regeneration mode, a throttle valve is opened and heat is supplied to Vessel *A* through a heat exchanger. The refrigerant vaporizes, moves from *A* to *B* and gets condensed in it. Now, the valve is closed and the contents of *B* are cooled by circulating cold water through a heat exchanger. The system is kept in this state after closing the valve till the time cooling is required. In the refrigeration mode, the valve is opened; the refrigerant evaporates and moves from *B* to *A*. In this mode, it absorbs heat from Vessel *B* and its surroundings and produces a cooling effect.

While in the intermittent type of cooling process, the two operations, regeneration and refrigeration, take place alternately at different times, in continuous-type cooling, the two processes take place simultaneously and a continuous cooling effect is produced. The continuous absorption cycle is more reliable. In most applications, continuous cooling is required.



**Fig. 5.25** Intermittent absorption cooling process

### 5.5.1 Lithium Bromide-Water Absorption Cooling System

A solar energy operated LiBr-water system is shown in Fig. 5.26. In the equilibrium state, the approximate pressures and temperatures maintained in four major components of the system are given in Table 5.1.

**Table 5.1** Temperatures and pressures in various components of LiBr-water system

S.N	Name of component	Pressure (atm.)	Temperature (°C)
1.	Generator	0.1	90
2.	Condenser	0.1	30 to 40
3.	Evaporator	0.008	4
4.	Absorber	0.008	30 to 40

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, (iv) the refrigerant, i.e., water has high latent heat of vaporization, (v) lithium bromide absorbent is non-volatile and therefore, avoids the need of rectifying equipment which is necessary in an ammonia–water cycle, (vi) water–lithium bromide solution is non-toxic, and (vii) 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

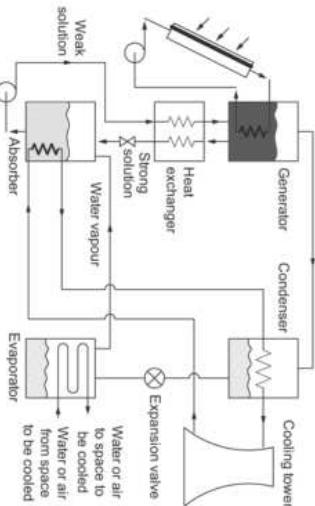
The Aqua-ammonia absorption system is similar to the LiBr–water absorption system explained above. It also has all the basic building blocks as shown for LiBr–water system but the operating pressures and temperatures are quite different. It can produce cooling up to –5°C and therefore, is suitable for 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.



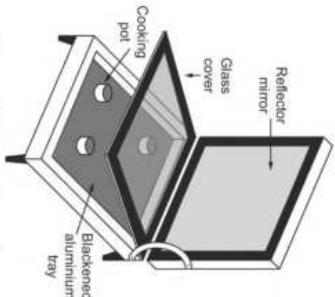
**Fig. 5.26** LIBR- $H_2O$  absorption cooling system

## SOLAR COOKERS

**5.6.1 Box-Type Solar Cooker**

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.

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  $\times$  60 cm  $\times$  20 cm. This cooker is simple in construction and operation. An insulated box of blackened aluminium 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).



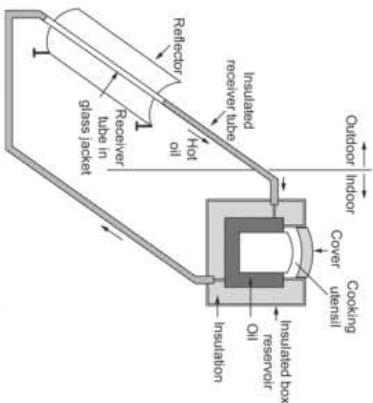
**Fig. 5.28** Paraboloidal dish-type solar cooker Source: MNES Annual Report

### 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  $3 \text{ m} \times 2 \text{ m} \times 0.5 \text{ m}$ , and (ii) an indoor, insulated hot-box reservoir of a size typically  $0.4 \text{ m} \times 0.4 \text{ m} \times 1.2 \text{ m}$ , 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  $150^\circ\text{C}$  and rarely falls below  $100^\circ\text{C}$  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

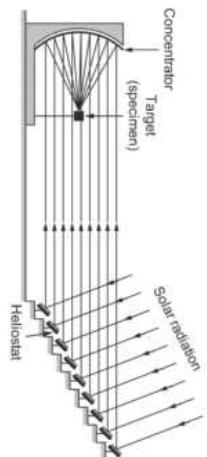
bowl-type collector, use of a heat exchanger to raise steam from heated oil for steam cooking are also possible. Such types of solar cookers are especially useful as large-size community cookers for military camps, temples, ashrams, gurdwaras and hostels.

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 10.6 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<sup>2</sup> 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.

### SOLAR FURNACES

**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 foci.



**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-Romeu, France in 1970. It has 63 heliostats, each 7.5 m × 6 m in size. The paraboloidal 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.

## 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

they all require moderate temperatures and light, adequate quantities of carbon dioxide, oxygen, mineral nutrients, air movement and water as indicated in Table 5.2. Moderate temperatures, light and air movement are energy related needs of plants and are supplied by the greenhouse. A greenhouse designed to use solar energy to meet these requirements is known as solar greenhouse. If natural means are adopted to collect, store and distribute the energy inside, it is known as passive greenhouse. A greenhouse where auxiliary means are used for these functions is known to be an *active* one. Generally, a combination of both active and passive features is employed in solar greenhouses to minimize the need of auxiliary energy.

**Table 5.3** Desirable environmental conditions for growth of a plant.

S.N.	Parameter	Optimum required level
1	Light intensity (about 100,000–150,000 lumen/m <sup>2</sup> available around noon time)	25,000–50,000 lumen/m <sup>2</sup>
2	Night temperature:	
	(i) Air temperature for winter crops	5–15°C
	(ii) Air temperature for summer crops	20–30°C
	(iii) Soil temperature	20–25°C
3	Relative humidity	30–70 per cent
4	Air movement	0.10–0.35 m/s
5	Carbon dioxide	0.03–0.04 per cent
6	Nutrients	Per cent of dry matter
	(i) Carbon, hydrogen, oxygen	90
	(ii) Nitrogen, phosphorous, potassium, calcium, magnesium, sulphur	10
	The availability of these nutrients can be judged from the pH value of the soil.	6.2–6.8 (recommended)
7	Watering	Timing, quantity and frequency should be proper and adequate
		Based on experience

A small greenhouse can also be constructed as an integral part of a house and free exchange of air takes place between the residence and the greenhouse. Such a greenhouse is known as attached greenhouse. A separate independent structure of a greenhouse is known as *free-standing greenhouse*. Some basic design styles of greenhouse frames are shown in Fig. 5.31.

In the lean-to style design, the greenhouse rests on the wall of a building and requires minimum roof support. The single independent style looks like a tent with a sloping or hemispherical roof. Large-sized greenhouses are made in the ridge-and-furrow style, where several greenhouses are connected together, reducing the overall cost. In this design, some arrangements are made to melt and remove the snow collected in the gutter.

### 5.8.1 Regulation of Internal Environment of a Greenhouse

In a greenhouse, visible light,  $\text{CO}_2$  and water are required for the photosynthesis process.

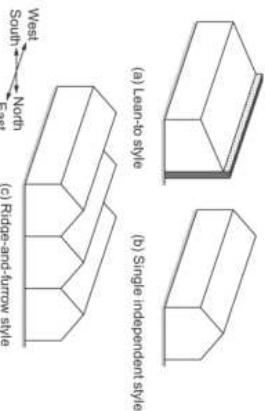


In the respiration process, energy is released which is used by the plant for various functions of growth such as nutrient uptake, protein formation, division of cells, etc.



To make available sufficient light, glazing (glass or plastic sheet) is provided on sufficient area on the surface facing the sun. Nowadays, plastic sheets are preferred to minimize the cost. For proper thermal insulation, two layers of glazing with small air gaps are used. Each layer of glazing cuts about 13% solar radiation; therefore more than two layers are not used. Supplementary lighting may be used to maintain adequate level of light intensity or to increase the duration of light hours. Similarly, curtains can be used to decrease the duration of light hours.

Adequate availability of  $\text{CO}_2$  can be maintained by supplying either outside air or by organic manure or by combustion of sulphur-free fossil fuels or by supplying it directly from a  $\text{CO}_2$  cylinder.



**Fig. 5.31** Basic design styles of greenhouse frames

In cold climates, a greenhouse is designed to maximize the solar energy input by providing a large glazing area with proper orientation. As most heating is required only in winter, the slope is generally decided on the winter basis. The glazing behaves as transparent for incoming short-wavelength visible radiation and permits its entry but becomes largely opaque to long-wavelength infrared

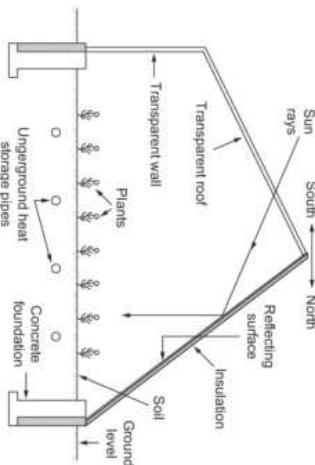
radiation reflected from the ground. Thus, the energy remains trapped and increases the temperature inside. Thermal losses from the greenhouse are reduced by using two layers of glazing with some air gap (typically 5–7 cm), using thermally insulated walls and controlling leakage (or infiltration of ambient air) through cracks. To decrease thermal losses during night through glazing, folding-type insulation cover may be placed over the glazing. The insulation cover may be rolled up again in the morning to permit entry of sunlight.



In places where solar insolation is high, cooling of greenhouse instead of heating is required. Here also thermal insulation is required to prevent entry of heat by conduction through walls, infiltration of warm air through cracks, etc. To maintain a moderate temperature inside, generally evaporative cooling, utilizing fans and wet pads are used. The technique is the same as commonly used in desert coolers for space cooling during summer months in arid zones. The cooling system is based on the principle that heat is absorbed for evaporation of water. If the humidity is low, an evaporative cooler can reduce space temperature by 5–10°C. Some typical greenhouse designs are discussed below.

### 5.8.2 Typical Winter Greenhouse

A typical design of a greenhouse for cold climates is shown in Fig. 5.32. A south-facing wall and roof is provided with double-glazing. A north-facing roof is made of insulating material with reflecting inner lining to reflect solar radiation

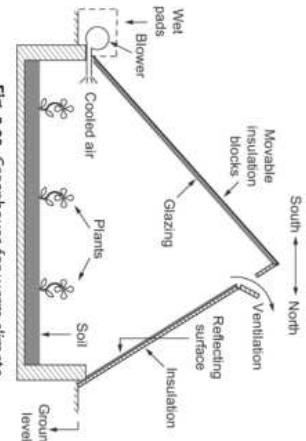


**Fig. 5.32** Greenhouse for cold climate

on the plant canopy. The frame of the entire greenhouse is made of wood. The east- and west-facing walls are provided with a single layer of rigid transparent fiberglass sheets. In some designs, pipes are buried in the soil under the plants to store surplus thermal energy during daytime. Air from the growing area is blown out through these pipes at the time of surplus heat to store the excess heat in the ground. At night the heat is recovered by reversing the direction of air flow through these pipes.

### 5.8.3 Typical Summer Greenhouse

In a summer greenhouse, the most important requirements are maintaining moderate temperature by reducing cooling loads and also to provide adequate solar radiation. A typical summer greenhouse is shown in Fig. 5.33. A south-facing wall is provided with double-glazing, covered with white thick movable insulating



**Fig. 5.33** Greenhouse for warm climate

blocks. These blocks can be selectively moved to admit only absolutely essential solar radiation whenever needed. Sunlight is allowed to enter only in the morning and evening hours. Solar radiation can also be admitted through east and west transparent walls of the greenhouse whenever required by removing plywood sheets covering these walls. The north-facing wall is made of insulating material like plywood etc. with reflective lining on the inner side to reflect solar radiation on the plant canopy. A part of the greenhouse is also sunken in the ground to take advantage of the low and constant ground temperature. Windows on the north and south walls are used for cooling through a natural convection process when the outside temperature is not very high. When the outside temperature becomes very high, south wall windows are closed and evaporative cooling is used by drawing the outside air through wet pads using a powerful blower.

A greenhouse requires certain initial investment to construct and equip it. Greenhouse operation cost includes expenditure on environment control and agricultural inputs. As a result, the cost of production per unit greenhouse area is higher as compared to open field cultivation. However, greenhouse crops yield several times more than those obtained from open-field cultivation. Therefore, the monetary return per unit area is many times higher in case of greenhouse cultivation. Greenhouses are popular for growing high-valued horticultural crops, raising seedlings and plant propagation material. Greenhouses are being used in almost all types of climatic conditions. Intensive greenhouse crop production has been adopted by Israel and Japan due to smaller and marginal land holdings and shorter growing seasons. Israel and Holland are exporters of greenhouse products. Large areas of land are found under greenhouse cultivation in Italy, Turkey, Spain and France. In India, greenhouses are being used only in research and educational institutions.

## 5.9

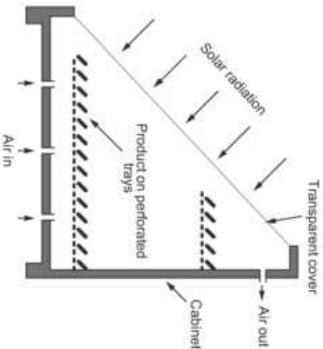
The drying process removes moisture and helps in the preservation of any product. Solar crop drying is perhaps the most ancient and widespread

### SOLAR DRYER

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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 warping 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.

### 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,

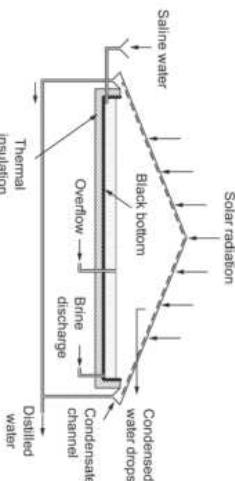
## Solar Thermal Systems



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  $5.3 \text{ l/m}^2 \text{ day}$  (in summer) to  $0.9 \text{ l/m}^2 \text{ day}$  (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.

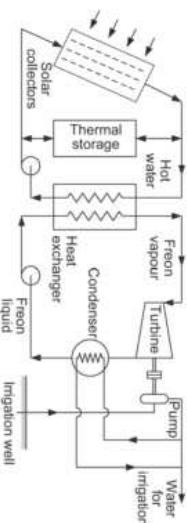
### 5.11.1 Solar Thermal Water Pump

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.

## Solar Thermal Systems

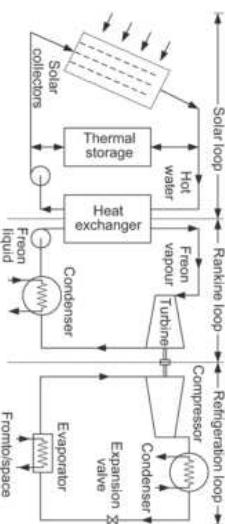
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**Fig. 5.36** Solar thermal water pump

### 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

black bottom serves as an absorber and the layer of still water above it is used as an insulator rather than normal glazing and air space. In a large area pond approximately 1-2 m deep, a vertical gradient of salt concentration is maintained such that most concentrated and dense solutions are at the bottom. The salt concentration varies from 20-30 per cent at the bottom to almost zero at the top. Left to itself, the salt concentration gradient will disappear over a period of time because of upward diffusion of the salt. In order to maintain it, fresh water is added at the top of the pond through a horizontal diffuser, while slightly saline water is run off. At the same time, concentrated brine is added at the bottom of the pond. The amount of salt required for this purpose is about 50 g/m<sup>2</sup>-day, which is a large quantity when considered on an annual basis. For this reason, normally the salt is recycled by evaporating the saline water run-off from the surface in an adjoining evaporation tank.

Because of movement and mixing of the fluid, both at the top and at the bottom, the solar pond is characterized by three zones: (i) a surface convective zone, (ii) a non-convective concentration gradient zone, and (iii) a lower convective zone. The surface convective zone usually has a small thickness, around 10-20 cm. It has a uniform temperature, close to ambient air temperature and low, uniform concentration close to zero. The non-convective zone is much thicker and occupies more than half the depth of the pond. In this zone, both temperature as well as concentration increase with depth. It principally serves as an insulating layer and reduces heat loss in the upward direction. It also serves as part of heat storage as some of the heat collection takes place in this zone also. The lower convective zone is comparable in thickness to the non-convective zone. Both the temperature and concentration are nearly constant in this zone. It serves as the main heat-collection as well as thermal storage medium. This zone is also referred as storage zone.

Solar radiation penetrates through water up to the blackened bottom, where it gets absorbed and increases the temperature near the bottom. In spite of the temperature rise of the bottom layers of the brine, its specific gravity remains higher than that at the top because of the concentration gradient and thus, convection mixing is minimized. The bottom layers of the brine reach 70-85°C while the top remains at 25°C. The hot brine from the bottom is slowly withdrawn in a laminar flow pattern from the pond and used to evaporate an organic working fluid in a heat exchanger and returned to the pond. Alternatively, heat is extracted by water flowing through a heat exchanger coil submerged at the bottom. The organic working fluid produces mechanical power in a Rankine cycle, which in turn generates electrical power using an alternator. The annual collection efficiency generally ranges between 15 to 20 per cent. These values are lower than those obtained for a flat-plate collector. Nevertheless, solar ponds are more cost effective, since their cost per square metre is much less than that for a liquid flat plate collector.

The first experimental solar pond was constructed in Israel to demonstrate its principle of working. So far, more than sixty solar ponds have been built all around the world for a variety of applications. A 2000 sq. m solar pond equipped with a 20 kW turbine has been constructed in Australia. The largest solar pond built so far is a 2,50,000 m<sup>2</sup> pond at Bet Ha Arava in Israel, to generate 5 MW electric power using an organic fluid Rankine cycle. The plant operated till 1988. In India some experimental solar ponds are built for thermal applications.

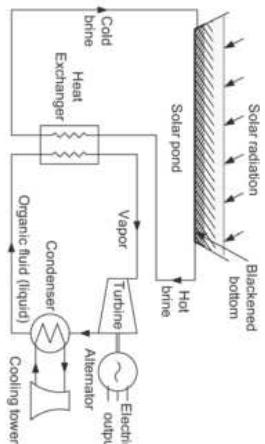


Fig. 5.38 Solar pond electric power plant

#### 5.11.4 Alternative Types of Solar Ponds

A number of other concepts have also been proposed for building a solar pond. Some of these are discussed below:

##### (i) The Solar Gel Pond (Viscosity Stabilized Pond)

In this pond, a thick layer of floating polymer gel acts as a non-convective zone to trap the solar energy in the lower convective zone. The gel has good optical and thermal properties. A small salt gradient in the convective zone is still necessary in order that the gel would float on the top. The main disadvantage of this pond is its high cost due to chemicals required for making gel.

##### (ii) The Partitioned Salt-stabilized Pond

In this pond, a transparent membrane or partition is used to separate the lower convective zone from the non-convective top zone. Thus, the non-convective zone instabilities are suppressed. Other features are similar to the solar gel pond.

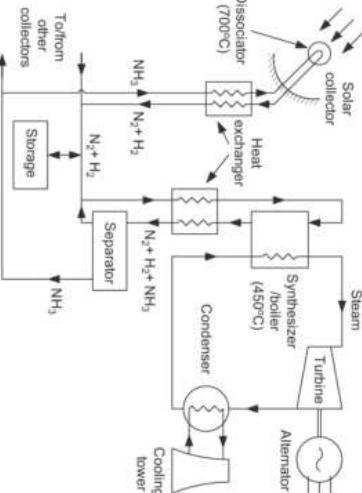
##### (iii) The Equilibrium Solar Pond

It uses a salt whose solubility in water increases strongly with temperature. In this pond, thermal diffusion of salt occurs from lower to higher temperature zones in the fluid. In this pond, the direction of this movement is downward and opposite to that of the mass diffusion occurring in the upward direction due to the concentration gradient. In the equilibrium pond, the two mass fluxes are made to balance each other so that the salt flux is zero. Thus, the requirement of a regular operational procedure for maintaining the salt concentration gradient is eliminated. The concept has been demonstrated experimentally with potassium-nitrate salt solution.

### 5.11.5 Distributed Collector Solar Thermal Electric Power Plant

In a distributed collector system, the solar thermal energy is collected from a large number of sun-tracking solar collectors, cylindrical parabolic trough type or paraboloidal dish type. Each collector transfers heat to a heat-transport fluid. This heat-transport fluid available at high temperature from the collectors is pooled at some central power station. The heat transfer fluid could be water/steam, to be used directly in a steam turbine, or it could be some thermochemical storage medium such as ammonia. The advantage of a later scheme is that thermal energy is stored as chemical energy at ambient temperature and no heat is lost in its transmission over a long distance or in storing it overnight for continuous power generation.

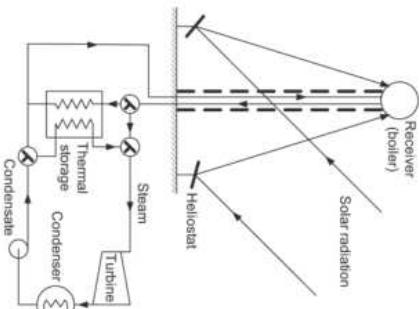
The schematic diagram of a typical distributed collector power generation plant is shown in Fig. 5.39. The heat collected in collectors is used to dissociate ammonia into nitrogen and hydrogen at high pressure (approx. 300 atm). The heat of reaction, 46 kJ/mole (of  $\text{NH}_3$ ) is provided by the solar energy. This nitrogen–hydrogen mixture is transported to the central plant where  $\text{N}_2$  and  $\text{H}_2$  are recombined in a synthesizer, using a catalyst. The heat released during the reaction is utilized in a heat engine to generate electric power through an alternator. In the synthesizer only a part of nitrogen and hydrogen recombine to produce ammonia. The products of the synthesizer are cooled to liquefy ammonia, separate it out and send it to the collector system. The mixture of nitrogen and hydrogen that remains in gaseous state is fed back to the synthesizer.



**Fig. 5.39** Distributed collector solar thermal electric-power plant

The first commercial solar electric-generating system was constructed in 1984 at Daggett, California, using parabolic trough collectors with an electric output of 13.8 MW. Subsequently, several other plants based on parabolic trough collectors were installed in the range of 30 MW and 80 MW.

### 5.11.6 Central Tower Receiver Power Plant

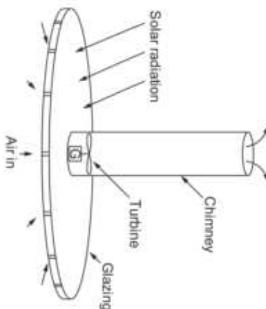


**Fig. 5.40** Central tower receiver power plant

A central-tower power plant of 1 MW capacity has been in operation in Catania, Sicily, Italy, since 1981. It has 182 heliostats in total, with a total mirror area of 6202 sq. m. Also, the Southern California Edison Company has installed a 10-MW, central power plant with 1818 heliostats.

### 5.11.7 Solar Chimney Plant

A solar chimney is much simpler but works with much lower efficiency as compared to a central tower receiver powerplant. The circular field of heliostats is replaced by a circular area of land covered with glazing, i.e., a circular greenhouse. The central receiver tower is replaced by a tall chimney that houses a wind turbine at the base of the chimney as shown in Fig. 5.41. Sunlight passing through the transparent cover causes the air trapped in the greenhouse to heat up. A convection system is set up in which the air drawn up through the chimney drives the turbine coupled with a generator.



**Fig. 5.41** Solar chimney power plant

The hot air is continuously replenished by fresh air drawn in the periphery of the greenhouse. A 50-kW prototype had been built in Spain and worked uninterrupted from 1986 to 1989. It had a 200-m high chimney with a constant diameter of 10.3 m. The solar collector area extended to a radius of 126 m from the chimney with glazing being 2 m above the ground. Further progress in this direction is hampered due to the exorbitant cost involved.

### **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.
  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 2003–04)
12. Classify different types of solar thermal collectors and show the constructional details of a flat-plate collector. What are its main advantages?
- (UPTU Lucknow 2007–08)
13. Write the advantages and disadvantages of concentrating collectors over flat-plate types of solar collectors.
- (UPTU Lucknow 2005–06)
14. With the help of a schematic diagram explain the working of solar water heating.
  15. What is a solar house?
  16. What is the basic difference between an active and passive solar heating system?
  17. With the help of schematic diagram explain a solar passive-space cooling system through ventilation.
  18. With the help of schematic diagram explain solar-process steam system.
  19. Compare the relative merits and elements of LIBR-water and aqua-ammonia vapour absorption cooling systems.
  20. What is the main advantage of using a glass cover in a box-type cooker?
  21. What is the maximum temperature obtained in a solar furnace?
  22. What are the main advantages and disadvantages of a solar furnace?
  23. What is a greenhouse?
  24. How is adequate supply of  $\text{CO}_2$  maintained in a greenhouse?
  25. What is the purpose of double layer of glazing in a greenhouse?
  26. What is the average output of a solar still during summer in Indian climate?
  27. What is a solar still? Draw its diagram and explain its working in detail.
- (UPTU Lucknow 2005–06)



28. What are the major limitations of thermo-mechanical systems?
29. What features of solar energy make it attractive for use in irrigation water pumps?
30. With the help of schematic diagram explain the working of solar thermal water pump.
31. Draw a schematic diagram of solar pond based electric-power plant with cooling tower and explain its working.
- (UPTU Lucknow 2005–06)
32. With the help of schematic diagram explain the working of distributed collector solar thermal electric power plant.
33. How can solar energy be converted into electrical energy? Give a diagram showing the elements of such a plant.
34. Give a neat diagram of a central tower receiver power plant and explain its operation. Give the details of an operational plant if such a plant exists anywhere in the world.
- 
- ### Objective-type Questions
1. A solar thermal collector
    - (a) collects the solar energy and reflects it back
    - (b) absorbs the solar radiation and dissipates it to the ambient
    - (c) collects and converts the solar energy into electrical energy
    - (d) collects and converts the solar energy into thermal energy and delivers it to the next stage of the system
  2. The concentration-type solar collector
    - (a) first absorbs the radiation and then increases its concentration
    - (b) increases the density of solar radiation before absorbing it
    - (c) dilutes the density of solar radiation before absorbing it
    - (d) increases the intensity of solar radiation and then reflects it back
  3. Read the following statements about flat-plate collectors and answer the questions.
    - (i) These are simple in construction.
    - (ii) They have high efficiency.
    - (iii) They do not track the sun.
    - (iv) They make use of both beam as well as diffused radiation.
    - (a) (i) and (ii) are correct.
    - (b) (i), (ii) and (iii) are correct.
    - (c) only (ii) is correct.
    - (d) (i), (iii) and (iv) are correct.
  4. The value of concentration ratio of a flat-plate collector is
    - (a) 1
    - (b) 10
    - (c) 100
    - (d) 1000
  5. Selective surface has the characteristics of
    - (a) selective absorption of long-wavelength radiation
    - (b) selective absorption of short-wavelength radiation
    - (c) high value of absorptivity for incoming solar radiation and low value of emissivity for outgoing re-radiation
    - (d) low value of absorptivity for incoming solar radiation and high value of emissivity for outgoing re-radiation
  6. The value of heat removal factor  $F_n$  of a flat-plate collector lies in the range:
    - (a) 0 to 0.1
    - (b) 0 to 1
    - (c) 0.9 to 0.95
    - (d) 0.5 to 0.6



7. For optimal gain in heating applications during winter in the northern hemisphere, the collector tilt angle must be fixed at

- (a)  $\phi$
- (b)  $(\phi - 10^\circ)$  or  $(\phi - 15^\circ)$
- (c)  $(\phi + 10^\circ)$  or  $(\phi + 15^\circ)$
- (d)  $+10^\circ$  or  $+15^\circ$

8. In evacuated tube collectors

- (a) both conduction well as convection losses are suppressed
- (b) only conduction losses are suppressed
- (c) only convection losses are suppressed
- (d) only radiation losses are suppressed

9. Use of booster mirrors with a flat-plate collector

- (a) increases the reflection to the atmosphere
- (b) decreases the reflection to the atmosphere
- (c) increases the diffused radiation component on the absorber
- (d) increases the beam radiation component on the absorber

10. A cylindrical parabolic concentrator requires

- (a) 2-axes tracking
- (b) 1-axis tracking
- (c) no tracking
- (d) seasonal adjustment only

11. A Scheffler solar concentrator has:

- (a) 2- axes tracking
- (b) 1-axis tracking
- (c) no tracking
- (d) seasonal adjustment only

12. The payback period of an ordinary passive solar water heater is

- (a) 20–60 years
- (b) 1 year
- (c) 2–6 years
- (d) 6–10 years

13. What is the typical cooking time of a paraboloidal dish cooker?

- (a) 2–3 hours
- (b) 20–30 minutes
- (c) 20–30 seconds
- (d) 6–12 hours

14. The most important advantage of a solar furnace is

- (a) heating available throughout the day
- (b) cheap low-grade heating
- (c) availability of both heat and light
- (d) heating without contamination or electromagnetic field

15. The main advantage in storing solar thermal energy by dissociation of  $\text{NH}_3$  is

- (a) the process is easy to implement
- (b) thermal energy is stored and transported at high temperature
- (c) thermal energy is stored and transported at room temperature
- (d) this type of thermal energy store is more compact

16. A solar thermal water pump

- (a) uses solar thermal energy to evaporate water
- (b) uses solar thermal energy to circulate hot water
- (c) uses electric powered pump to circulate water heated by solar energy
- (d) uses solar thermal energy for production of power to drive the pump

17. The main concern in a solar pond is

- (a) maintenance of salt gradient
- (b) extraction of heat
- (c) replenishment of lost water
- (d) handling of hot brine

18. Which one of the following statements is not true about the solar chimney plant?

- (a) It requires large land area.
- (b) It is simple in operating principle.
- (c) It has affordable cost.
- (d) It requires a big air turbine

19. In a central-tower-type solar collector, the heliostats

- (a) have 1-axis tracking facility  
 (b) have 2-axes tracking facility  
 (c) are fixed  
 (d) are adjusted seasonally

(a) uses solar energy  
(b) provides enhanced

- (c) prevents fresh air to come into contact with plants  
 (d) uses solar thermal pump for irrigation

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# Solar Photovoltaic Systems

## Introduction

**6** 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 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

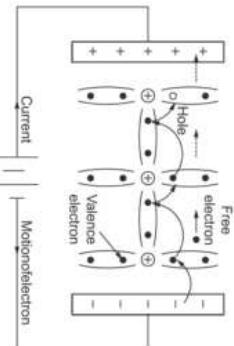
#### 6.1.1 Semiconductors

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 . 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.

## 160 Non-conventional Energy Resources



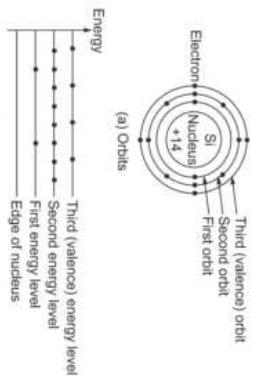
**Fig. 6.1** Free electron-hole flow through a semiconductor

This causes the valence electron to move into the hole creating a new hole at this new location. This effect is same as moving the original hole to the right. The process continues and the valence electron moves across the crystal from the negative to positive plate or the hole moves in a direction opposite to this. Thus, free electrons and holes continuously move in opposite directions inside a semiconductor and constitute electrical current. These are called *charge carriers* because they carry charge from one place to another.

One way to increase the conductivity of a semiconductor is by adding impurity atoms to intrinsic semiconductor. This process is known as *doping*. The doped semiconductor is called *extrinsic* semiconductor. When the doping atom is pentavalent such as arsenic, antimony and phosphorus, one extra electron will be left unattached to any atom after sharing four electrons with the neighbouring four silicon atoms in the crystal. Thus each pentavalent atom donates one free electron and therefore is known as *donor* and the doped semiconductor material is known as *n-type* silicon. In the same manner, when the doping atom is trivalent such as aluminum, boron and gallium, one electron vacancy (hole) will remain after sharing its three electrons with the neighbouring four silicon atoms in the crystal. Therefore, trivalent doping elements are also known as *acceptors* and the doped semiconductor material is known as *p-type* silicon. In *n*-type Si, free electrons are in majority while in *p*-type Si, holes are in majority. By regulating the level of doping, the electrical properties of the doped material are controlled. A lightly doped semiconductor has high resistance, whereas a heavily doped semiconductor has low resistance.

The behaviour of a semiconductor can be best explained with the help of quantum theory. To a good approximation, we can identify the total energy of an electron with the size of its orbit. That is, we can think of each radius of an orbit as equivalent to an energy level. Since an electron is attracted by the nucleus, extra energy is needed to lift an electron into a larger orbit. Some of the external energy sources that can lift the electron to higher energy levels are heat and light.

A silicon crystal is *intrinsic* if every atom in the crystal is a silicon atom. There are equal number of free electrons and holes in an intrinsic semiconductor. When a potential is applied across such a crystal, a free electron moves away from a negatively charged plate until it reaches a positively charged plate and completes the path through external circuit as shown in Fig. 6.1. A hole near a positively charged plate attracts a valence electron on the other side.



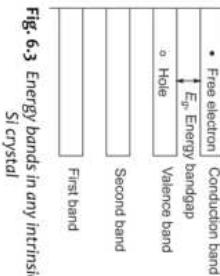
**Fig. 6.2** Orbita and energy levels

In an isolated silicon atom, the orbit of an electron is influenced only by the charges of the atom. Fig. 6.2 shows different energy levels of various electrons by respective lines. When silicon atoms are in a crystal, the orbit of each electron is also influenced by charges of many other silicon atoms around it. Since each atom has a unique position inside the crystal, no two electrons at the same orbital level but belonging to different atoms see exactly the same pattern of surrounding charges. Therefore, for silicon atoms of the whole crystal, the radius of each electron of the same orbit is slightly different and hence the energy levels of corresponding orbits are different. For every orbit, there are billions of slightly different energy levels that form a cluster or band of energy levels corresponding to each orbit. These energy bands are shown in Fig. 6.3. When an electron in a valence band receives sufficient energy to overcome energy gap  $E_g$ , it jumps to the next higher band known as *conduction band* leaving behind a hole in the *valence band*. In an intrinsic Si crystal, there are equal number of free electrons and holes. On application of voltage across such a crystal, the free electrons move in the conduction band while holes move in the valence band. No conduction is possible if all states within an energy band are occupied or when all states are empty.

At this point, it is worthwhile to define a few basic terms.

**Doping** The process of addition of an impurity in an intrinsic semiconductor material in order to alter its electrical characteristics is known as doping.

**Fermi Level ( $E_F$ )** Fermi level, or characteristic energy (in eV) for a crystal, represents the energy state with a 50% probability of its being filled by charge carriers.



**Fig. 6.3** Energy bands in any intrinsic Si crystal

In an intrinsic semiconductor material, the Fermi level lies in the centre of the forbidden energy band as shown in Fig. 6.4, indicating equal concentration of free electrons and holes (in conduction and valence bands). If a donor-type impurity is added to the crystal, assuming all donor atoms are ionized, the Fermi level  $E_F$  moves closer to the conduction band, which indicates that many of the

energy states in that band are filled by the donor electrons, and fewer holes exist in the valence band. The same kind of argument leads to the conclusion that  $E_{\text{F}}$  must move from the centre of the forbidden gap closure to the valence band for a *p*-type material.  $E_{\text{D}}$  and  $E_{\text{A}}$  are the energy levels of donor and acceptor ions respectively. Now, if the temperature of an *n*-type or *p*-type material is increased, the Fermi level moves towards the centre of the energy gap. The Fermi level for an *n*-type material is given by

$$E_{\text{F}} = E_{\text{C}} - kT \ln \frac{N_{\text{C}}}{N_{\text{D}}} \quad (6.1)$$

where  
 $E_{\text{C}}$  = conduction band energy  
 $N_{\text{C}}$  = effective density of states in conduction band  
 $N_{\text{D}}$  = donor concentration (donor density)  
 $k$  = Boltzmann constant (in eV per degree Kelvin)  
 $T$  = absolute temperature in °K

The Fermi level for a *p*-type material is given by

$$E_{\text{F}} = E_{\text{V}} + kT \ln \frac{N_{\text{V}}}{N_{\text{A}}} \quad (6.2)$$

where  
 $E_{\text{V}}$  = valence band energy  
 $N_{\text{V}}$  = effective density of states in valence band  
 $N_{\text{A}}$  = acceptor concentration (acceptor density)

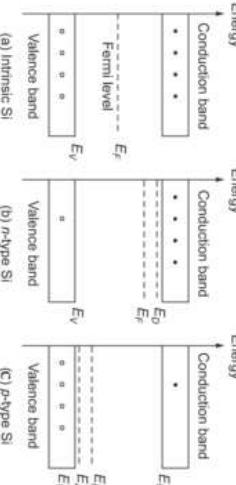


Fig. 6.4 Position of Fermi level in intrinsic, *n*-type and *p*-type Si

**Example**  
**6.1**  
 A *p*-type silicon has effective density of states in the valence band as  $1 \times 10^{23}$   $\text{cm}^{-3}\text{eV}^{-1}$ . An impurity from the 3rd group with concentration of  $1 \times 10^{19}$  per  $\text{cm}^{-3}$  is added. If the band gap for silicon is 1.1 eV, find the closeness of the Fermi level with valence band at the temperature of 27 K.

**Solution**

Given:

$$T = 27 + 273 = 300^\circ\text{C}$$

$$N_V = 1 \times 10^{22} \text{ per cm}^3$$

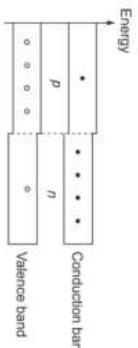
$$N_A = 1 \times 10^{19} \text{ per cm}^3$$

Closeness of Fermi level with valence band:

$$E_F - E_V = kT \ln \frac{N_V}{N_A} = (8.629112 \times 10^{-5} \text{ eV}) \times 300 \times \ln \frac{1 \times 10^{22}}{1 \times 10^{19}}$$

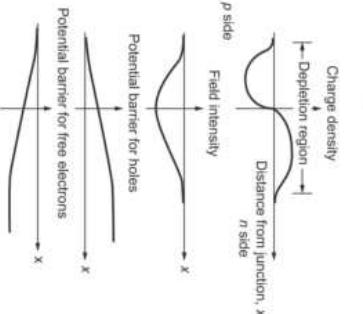
$$= 0.1788 \text{ eV}$$

### 6.1.2 A *pn* Junction



**Fig. 6.5** Energy bands of an abrupt junction before diffusion

An abrupt junction is an idealization because the *p* side cannot suddenly end where the *n* side begins. In a more realistic *pn* junction there is a gradual change from one type of material to another. Such a junction is known as *graded junction*.



**Fig. 6.6** Charge density, electric field intensity and potential barrier in depletion region of a *pn* junction

When a junction between a *p* and *n* type material is formed, the carriers (free electrons and holes) diffuse from a higher-concentration side to a lower-concentration side. Soon after crossing the junction, these carriers recombine with the other types of carriers found in majority on the other side. We see that the holes, which neutralized the acceptor ions near the junction in the *p*-type side disappeared as a result of recombination with free electrons, which have diffused from across the junction. Similarly, free electrons near the junction in the *n*-type side have recombined with holes, which have crossed the junction from the *p* side. The unneutralized ions (also known as uncovered charges) in the

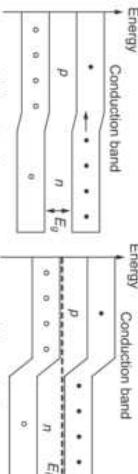
Fig. 6.5 shows the energy bands of an *abrupt pn junction* (or step-graded junction), where the material changes suddenly from *p* to *n* before the diffusion process. The *p* bands are slightly higher than the *n* bands because the *p*-type atoms have slightly larger orbits than that of *n*-type atoms. The reason is that a pentavalent atom with a core charge of +5 attracts an electron more than a trivalent atom with a core charge of +3 does.

Fig. 6.5 shows the energy bands of an *abrupt pn junction* (or step-graded junction), where the material changes suddenly from *p* to *n* before the diffusion process. The *p* bands are slightly higher than the *n* bands because the *p*-type atoms have slightly larger orbits than that of *n*-type atoms. The reason is that a pentavalent atom with a core charge of +5 attracts an electron more than a trivalent atom with a core charge of +3 does.



neighbourhood of the junction result in a charge density. Since this region is depleted of mobile charges, it is called *depletion region*, the space charge region or transition region. Mobile charge carriers exist only outside the depletion region. The charge distribution, which is zero at the junction, constitutes an electric dipole; that is, it is positive on one side and negative on the other side. This electrostatic potential variation causes an electric field in the depletion region. This voltage variation constitutes a potential energy barrier against further diffusion of free electrons and holes to the other side of the junction. This is known as contact potential, *barrier voltage* or potential energy hill (due to its shape). Fig. 6.6 shows charge density, electric field intensity, and barrier voltage for free electrons and holes. The shapes of the curves depend on how a junction is graded and the doping level.

Fig. 6.7 shows energy bands for a graded junction before and after formation of a depletion layer.



**Fig. 6.7** Energy levels in a graded junction before and after the depletion layer is formed

### 6.1.3 Generation of Electron-Hole Pair by Photon Absorption

The energy available in a photon is given by

$$E = h\nu = \frac{hc}{\lambda} \quad (\text{Joules}) \quad (6.3)$$

where  $h$  is Planck's constant ( $h = 6.63 \times 10^{-34}$  joules-second),  $\nu$  is the speed of light ( $2.988 \times 10^8$  m/s),  $\nu$  is frequency of photons in Hz and  $\lambda$  is the wavelength of photons in metres. Expressing  $\lambda$  in  $\mu\text{m}$ , and energy in eV (1 eV =  $1.6 \times 10^{-19}$  joules), the expression becomes:

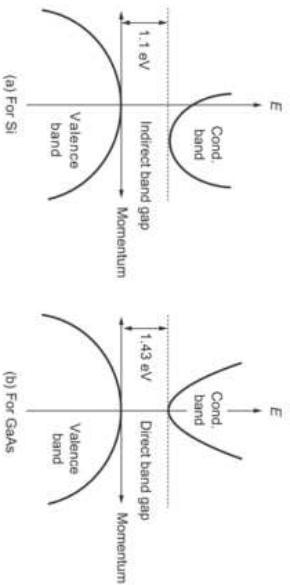
$$E = \frac{1.24}{\lambda} \quad (\text{eV}) \quad (6.4)$$

The energy in a photon must exceed the semiconductor band-gap energy  $E_g$  in order to get absorbed and generate an electron-hole pair. For energies less than the band gap energy, no absorption takes place. The material appears transparent to these low-energy photons. If a photon has energy much greater than the band gap, it still produces a single electron-hole pair. The remainder of the photon energy is lost to the material as heat. Therefore, it is desirable that



the semiconductors used for photo-absorption have band-gap energy such that the maximum percentage of solar spectrum is efficiently absorbed. Maximum theoretical efficiency of around 31% is estimated for a material having band gap of 1.51 eV with a standard spectral density of solar radiation. For silicon, which has band gap of 1.1 eV, photons of  $\lambda = 1.1 \mu\text{m}$  or less are required to produce electron-hole pair.

The nature of the band gap also affects the efficiency of absorption in a material. The allowed energy level of a particle in valence or conduction band also depends on the momentum of the particle in these bands. The shapes of these bands for Si and GaAs, considering energy as well as momentum, are shown in Fig. 6.8. Note that for Si, the bottom of the conduction band is displaced in the momentum direction from the peak of the valence band. Such materials are known as *indirect band-gap materials*. In the *direct band-gap materials* (such as gallium arsenide, GaAs, cadmium telluride, CdTe, copper indium diselenide, CIS and amorphous silicon), these bands are not displaced in the direction of momentum. Now, since photons do not have momentum, it turns out that direct band-gap materials absorb photons much more readily than do the indirect band-gap materials such as crystalline silicon, where it has to travel more distance before getting absorbed. Thus, a silicon cell must be sufficiently thick to absorb the incident light. In some cases, the path length is increased by causing multiple reflection of the incident light internally from the back surface and front surface while inside the material until it is absorbed.



**Fig. 6.8** Direct and indirect band-gap materials

### Example

Calculate the optimum wavelength of light for photovoltaic generation in a CdS cell. The band gap for CdS is 2.42 eV.

## 6.2

**Solution** Given:  $E = 2.42$

From Eq.(6.4):

$$E = \frac{1.24}{\lambda} \text{ eV}$$

$$\lambda = \frac{1.24}{2.42} \mu\text{m} = 0.512 \mu\text{m}$$

### 6.1.4 Photoconduction

Once an electron-hole pair is generated within the junction (depletion layer), both carriers will be acted upon by the built-in electric field. Since the field is directed from  $n$  to  $p$  side, it will cause the holes to be swept quickly towards the  $p$  side and the electrons to be swept quickly towards the  $n$  side. Once out of the junction region, these carriers become a part of the majority carriers in the respective regions and diffuse away from the junction region as their concentration near the junction has increased. This addition of excess majority charge carriers on each side of the junction results in a voltage across external terminals of the junction. If a load is connected across these terminals, the photon-generated current will flow through this external circuit. This current will be proportional to the number of electron-hole pairs generated, which in turn, depends on the intensity of illumination. Thus, an illuminated  $p/n$  junction becomes a photovoltaic cell with a positive terminal on  $p$  side.

If an electron-hole pair is generated near the junction (but not within it) then depending on how far it is from the junction, it may or may not contribute to the photocurrent. Suppose, for example, that an electron-hole pair is generated near the junction on the  $n$  side. If the generated hole which is a minority carrier in the  $n$  region, manages to reach the junction before it gets recombined, it will be swept across the junction on the  $p$  side and contribute to photocurrent. If it gets recombined before reaching the junction, it is lost from the conduction process. Similarly, if the electron-hole pair is generated near the junction on the  $p$  side, the generated electron must reach the junction before getting recombined in order to contribute in photocurrent. Thus, the minority carriers, generated outside the junction region due to optically generated electron-hole pair, must reach the junction in a time less than the respective minority carrier lifetime to be able to contribute in the photocurrent.

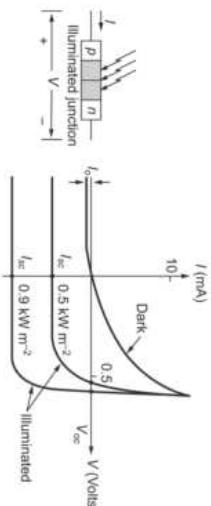
## SOLAR CELL CHARACTERISTICS

### 6.2.1 I-V Characteristic

The well-known characteristic of an ordinary silicon  $p/n$  junction is shown in Fig. 6.9 as a dark characteristic with the junction not illuminated. Mathematically, this is given by

$$I = I_s \{ \exp(V/V_T) - 1 \} \quad (6.5)$$

where  $I_o$  is the reverse saturation current,  $V_T$  is known as the voltage equivalent of temperature and at room temperature ( $20^\circ\text{C}$ ), its approximate value is 26 mV.



**Fig. 6.9**  $I$ - $V$  characteristic of dark and illuminated  $pn$  junction

$$V_T = \frac{kT}{q}; \quad \text{where } k \text{ is Boltzmann's constant, } T \text{ is temperature in } {}^\circ\text{K and } q \text{ is charge of an electron}$$

When the  $pn$  junction is illuminated, the characteristic gets modified in shape and shifts downwards as the photon-generated component is added with reverse leakage current as shown in Fig. 6.9. The above diode Eq. 6.5 is modified as

$$I = -I_{sc} + I_o \left\{ \exp(V/V_T) - 1 \right\} \quad (6.6)$$

When the junction is short-circuited at its terminals,  $V$  becomes zero and a finite current  $I = -I_{sc}$  flows through the external path emerging from the  $p$  side.  $I_{sc}$  is known as *short-circuit current* and its magnitude will depend on solar insulation. Now, a voltage source is inserted in the external path with positive polarity on the  $p$  side. As the magnitude of this external voltage is increased from zero, the current starts decreasing. The value  $V_{oc}$  of this voltage at which the current becomes zero is known as *open-circuit voltage*.

$$\text{Thus, } V_{oc} = V_T \ln \left\{ \left( I_{sc}/I_o \right) + 1 \right\} \quad (6.7)$$

Typically for  $I_{sc} = 2 \text{ A}$ ,  $I_o = 1 \text{ nA}$  and at room temperature,  $V_{oc}$  is found to be 0.55 V. Thus, an illuminated  $pn$  junction can be considered as an energy source, (a photovoltaic cell) with open circuit voltage  $V_{oc}$  and short-circuit current  $I_{sc}$ . However, for an energy source, by convention, the current coming out of the positive terminal is considered as positive. The schematic symbol of a solar PV cell with standard sign convention for voltage and current is shown in Fig. 6.10(a). Adopting the standard sign convention for a solar PV cell, the characteristic of Fig. 6.9 will be redrawn as shown in Fig. 6.10(b). Mathematically, the  $I$ - $V$  characteristic of a solar cell may be written (as per standard sign convention) as:

$$I = I_{sc} - I_o \left\{ \exp(V/V_T) - 1 \right\} \quad (6.8)$$

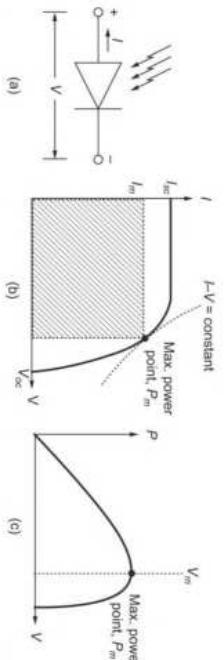
In order to obtain as much energy as possible from the rather costly PV cell, it is desirable to operate the cell to produce maximum power. The maximum

power ( $P_m$ ) point can be obtained by plotting the hyperbola defined by  $V \times I = \text{constant}$ , such that it is tangential to the  $I-V$  characteristic. The voltage and current corresponding to this point are peak-point voltage,  $V_m$  and peak point current  $I_m$  respectively. Thus, there is only one point on the characteristic at which it will produce the maximum electrical power under the incident illumination level. Operating at other than the maximum power point will mean that the cell will produce a lesser electrical power and more thermal power. The maximum power point is also readily found by simply plotting cell power versus cell voltage as shown in Fig. 6.10(c). If a rectangle of maximum possible area is inscribed in the area defined by the  $I-V$  characteristics and  $I-V$  axes, it meets the characteristics at the peak point as shown in Fig. 6.10(a). Closeness of the characteristics to the rectangular shape is a measure of the quality of the cell. An ideal cell would have a perfect rectangular characteristic. Therefore, the 'fill factor',  $FF$  which indicates the quality of a cell, is defined as the ratio of the peak power to the product of open-circuit voltage and short-circuit current, i. e.,

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \quad (6.9)$$

An ideal cell will have a fill factor of unity. In order to maximize the fill factor, the ratio of the photocurrent to reverse saturation current should be maximized while minimizing internal series resistance and maximizing the shunt resistance. Typically, its value for a commercial silicon cell is in the range of 0.5 to 0.83. The conversion efficiency,  $\eta$ , of a solar cell is given by

$$\eta = \frac{V_m I_m}{\text{Solar power}} = \frac{FF V_{oc} I_{sc}}{\text{Solar power}} \quad (6.10)$$



**Fig. 6.10** (a) Schematic symbol of a photovoltaic cell (b)  $I-V$  characteristic, maximum power point (c)  $P-V$  characteristic

### 6.2.2 Equivalent Circuit

The  $I-V$  characteristic given in Eq. (6.8) is derived for ideal condition, considering the internal series resistance of the cell as zero and shunt resistance as infinite. In actual practice, however, both have finite values, which would alter the characteristic.

The ideal and practical equivalent circuits of the solar cell are shown in Fig. 6.11. In practical cells,  $I_{sc}$  is no longer equal to the light generated current  $I_l$ , but is less by shunt current through  $R_{sh}$ . Further, an internal voltage drop of  $IR_i$  is also included in the terminal voltage. Thus, for a practical cell, the characteristic is modified as

$$I = I_l - I_0 \left[ \exp\left\{ (V + IR_i) / V_T \right\} - 1 \right] \cdot (V + IR_i) / R_{sh} \quad (6.11)$$

For a typical, high-quality, one square inch silicon cell,  $R_i = 0.05$  to  $0.10$  ohms and  $R_{sh} = 200$  to  $300$  ohms.

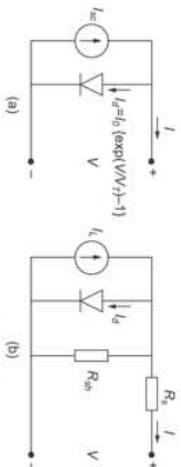


Fig. 6.11 Equivalent circuit of solar cell: (a) ideal (b) practical

### 6.2.3 Effect of Variation of Insolation and Temperature

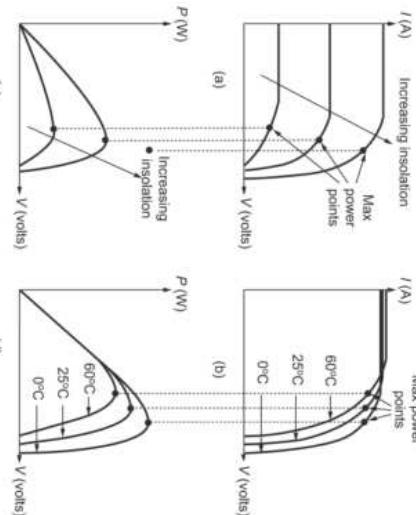
As the insolation keeps on varying throughout the day, it is important to observe its effects on PV characteristics. If the spectral content of the radiation remains unaltered, and temperature and all other factors remain same, both  $I_{sc}$  and  $V_{oc}$  increase with increasing the intensity of radiation. The photo-generated current depends directly on insolation. Therefore, the short-circuit current depends linearly while the open-circuit voltage depends logarithmically on the insolation. This is shown in Fig. 6.12(a, c).

If  $I_{sc}$  is known under standard test conditions, i.e., radiation of  $G_o = 1 \text{ kW/m}^2$  at AM 1.5, then the short circuit current  $I'_{sc}$  at any other insolation level  $G$  can be calculated to a very good approximation, as

$$I'_{sc} = \frac{G}{G_o} \times I_{sc} \quad (6.12)$$

An illuminated PV cell converts only a small fraction (approx. less than 20%) of irradiance into electrical energy. The balance is converted into heat, resulting into heating of the cell. As a result, the cell can be expected to operate above the ambient temperature. Keeping insolation level as constant, if the temperature is increased, there is a marginal increase in the cell current but a marked reduction in the cell voltage. An increase in temperature causes reduction in the band gap. This, in turn, causes some increase in photo-generation rate and thus a marginal increase in current. However, the reverse saturation current increases rapidly with temperature. Due to this, the cell voltage decreases by approximately 2.2 mV per °C rise in its operating temperature, depending on the resistivity of the silicon

used—higher the silicon resistivity, more marked is the temperature effect. Also, the fill factor decreases slightly with temperature. This is shown in Fig. 6.12(b, d).



**Fig. 6.12** Effect of variation of (a) and (c) insulation and (b) and (d) temperature on the characteristic of solar cell

The  $I-V$  characteristic is generally provided by the manufacturer for standard test conditions. The internationally accepted Standard Test Conditions (STC) refer to an incident AM1.5 irradiance of  $1 \text{ kW/m}^2$ , with operating temperature of  $25^\circ\text{C}$  and wind speed of  $1 \text{ m/s}$ .

#### 6.2.4 Energy Losses and Efficiency

The conversion efficiency of a solar cell is the ratio of electrical power output to incident solar power. In laboratory studies, the highest reported conversion efficiency of a single crystal silicon solar cell is about 24%. Conversion efficiencies of commercially produced single crystal solar cells are in the range 12–15%.

Various loss mechanisms limit the conversion efficiency of the cell. Some of these losses are due to the inherent nature of internal physical processes and available input. These cannot be influenced by external means. The other category of losses can be influenced by suitable selection of material, processing technology and other parameters of the cell.

The energy distribution of the incident photons depends on various factors beyond anybody's control. A significant fraction of these photons do not contribute to photocurrent generation as they have energy lower than the silicon band gap energy of  $1.1 \text{ eV}$ . These low-energy photons have wavelengths more

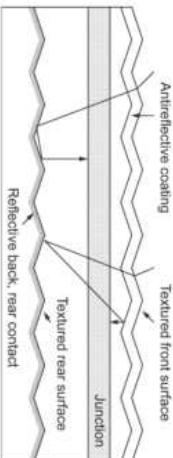


than the maximum required value of  $1.1\text{ }\mu\text{m}$ . The energy associated with these unutilized low-energy photons can be from 15% to 25% of the total incident photon energy depending on the air mass (AM). On the other hand, incident photons having energy higher than the band gap would lose their excess energy as heat. This loss may be 5% to 20% of the total incident photon energy. Thus, due to the nature of spectral distribution, as much as 20% to 45% of the incident radiation may not be utilized for photocurrent generation.

The second-most significant loss mechanism arises due to inherent material properties and the physical principle on which a solar cell operates. The separation of photon-generated electron-hole pairs by the junction depends on the movement of the minority carriers to a region where they have minimum potential energy. This process results in loss of energy. The magnitude of this loss is a function of barrier height and may be as high as 30% to 40% of the energy contained in the photo-generated carriers.

Thus, the spectral distribution of solar radiation and the inherent properties of silicon  $p/n$  junction together result in a total energy loss close to 65% of the incident energy. Therefore, for an ideal  $p/n$  junction, photo-generated carriers after separation across the junction are likely to have energy about 35% of the incident solar energy. However, there are other losses, which further reduce the overall efficiency of the cell. During the carrier-collection process, some minority carriers are lost due to recombination. There are losses due to reflection from the active surface of the cell. As a result, a fraction of incident photons will not enter the bulk material. To minimize these losses, the active surface must be properly treated, by suitable anti-reflection coating and/or by having a pyramidal or textured structure.

As discussed earlier, silicon is an indirect band-gap material. Photons of adequate energy require travelling some distance in bulk material in order to get absorbed. If the thickness of the cell is not sufficient (approx. 10 microns), some photons will pass through the full thickness of the material without ever getting absorbed. In order to utilize these photons, a reflecting-back ohmic contact should be used on the rear, to enhance photon absorption in thinner cells as shown in Fig. 6.13.



**Fig. 6.13** Antireflective coated, textured front surface and reflective coated, textured rear surface

### 6.2.5 Maximizing the Performances

Desirable features of a solar cell are— maximum values of  $V_{oc}$  and  $I_{sc}$ , low series resistance that will lead to high fill factor and high shunt resistance.  $I_{sc}$  is related to photocurrent and  $V_{oc}$  depends on the ratio of  $I_{sc}$  to  $I_o$ . Shunt resistance is maximized by ensuring that no leakage occurs at the perimeter of the cell. This is done by passivating the surface. Reduction of series resistance requires high doping of semiconductor. But high doping will also decrease the width of depletion layer, which in turn decreases the photocurrent. Therefore, both  $V_{oc}$  and  $I_{sc}$  are affected. Therefore, trade-off is made in choosing the level of doping to get optimal performance.

### 6.2.6 Cell Size

Terrestrial application demands the use of large-sized solar cells. As silicon is a brittle material, this fact tends to limit the area of commercially produced silicon solar cells due to handling difficulty. Also, as the area of solar cell increases, it becomes difficult to maintain homogeneity of all relevant material parameters across the cell surface area and the bulk. This affects the performance of the cell. Although some companies still produce small diameter cells for specific applications, the current industry standards on the size of bulk silicon solar cells can be divided into four groups:

- (a) 100 mm (4 inch) diameter, round single crystalline
- (b) 100 cm<sup>2</sup> off square single crystalline
- (c) 100 mm × 100 mm (~ 4 inch × 4 inch) square multicrystalline
- (d) 125 mm × 125 mm (~ 5 inch × 5 inch) square multicrystalline

The current industry standard of the thickness of bulk silicon wafer appears to have settled in the range from 200 microns to 400 microns.

### 6.2.7 Energy Payback Period (EPP)

The length of time during which a solar cell generates the same amount of energy that it has consumed during its production is known as *energy payback period*. As the production process of a solar cell is highly energy intensive, energy economy can only be achieved if EPP is low. Typically, the EPP of a single crystal bulk silicon solar cell under the existing state-of-the-art technology is between 3.5 to 5 years. In other words, a single crystal bulk silicon solar cell would have to continuously generate electrical energy for about 5 years before it starts providing energy in excess of what it has originally consumed during its manufacture.

## SOLAR CELL CLASSIFICATION

**6.3** Solar cells may be classified on the basis of (i) thickness of active material, (ii) type of junction structure, and (iii) the type of active material used in its fabrication.

### 6.3.1 On the Basis of Thickness of Active Material

Depending on the thickness of the active material, they are classified as (i) bulk-material cell, and (ii) thin-film cell. In bulk-material cells, the base material (starting material in fabrication process) is itself an active material. In thin-film cells, a thin film (a fraction of a micron) deposition of active material is carried out on the back support sheet, known as a *substrate*. Thin-film solar cells have the major advantage of significantly low active material consumption and the possibility of continuous sequence of production processes. This is unlike batch processing of bulk material solar cells. However, some technological difficulties of thin-film cells are yet to be solved. The cell area larger than about  $25\text{ cm}^2$  appears to be difficult with state-of-the-art technology. Small area cells have disadvantage of cell mismatch. There are problems in texturization of the surface. In the past, thin-film single crystal and multicrystalline cells have been tried but could not succeed commercially. The amorphous-silicon and compound semiconductor cells are being developed using thin-film technology, but most of them degrade their performance when exposed to outdoor radiation. Some of them are very unstable. Therefore, at present, bulk-material single crystal and multicrystalline cells are most successful for terrestrial applications.

### 6.3.2 On the Basis of Junction Structure

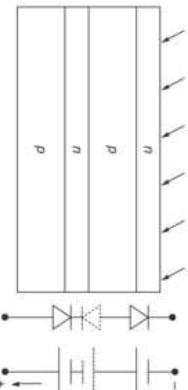
On the basis of the type of junction structure, they are classified as (i)  $p-n$  homojunction cell, and (ii)  $p-n$  heterojunction cell, (iii)  $p-p$  multijunction cell, (iv) metal-semiconductor (Schottky) junction, and (v)  $p-i-n$  ( $p$ -type-intrinsic- $n$  type) semiconductor junction.

In a homogeneous  $p-n$  junction, the semiconductor material on both sides of the junction is same, only doping materials are different. Thus, the band gap remains the same throughout the cell material. Most of the electron hole pairs generated in the top layer are lost to recombination when they are created more than a diffusion length from the junction. On the other hand, in a heterogeneous  $p-n$  junction, two dissimilar semiconductor materials, such as group III-V or group II-VI compound semiconductors with closely matching crystal lattice are used to form the junction. The band gap of the top material exposed to sunlight is wider than the band gap of the material below the junction. As a result, the higher band-gap region will appear transparent to photons with lower energies, so they can penetrate to the junction where the band gap is less than the incident photon energy. Thus, electron-hole pairs are generated in the junction region, where they are collected before they recombine. Common heterogeneous solar-cell structures include gallium arsenide-gallium aluminium arsenide (GaAs-GaAlAs), cadmium sulphide-copper sulphide ( $\text{CdS-Cu}_2\text{S}$ ), cadmium sulphide-copper indium diselenide ( $\text{CdS-CuInSe}_2$ ) or cadmium telluride.

When a contact is made between a metal and semiconductor, either an ohmic contact (permitting bi-directional current) or a rectifying contact (permitting only



unidirectional current) is formed depending on the work functions of metal and semiconductor. The rectifying contact is known as Schottky junction. The Schottky junction has depletion layer and a built-in electric field on the semiconductor side of the junction. This electric field is responsible for sweeping of the minority charge carriers on the other side of the junction. The Schottky barrier junction is relatively straightforward to fabricate, but is not very efficient as a PV cell since it has a relatively smaller open circuit voltage than a conventional  $p/n$  junction.



**Fig. 6.14** Two junctions in tandem, showing an opposing  $p/n$  junction

in tandem (series). High-energy photons will be absorbed at the top junction followed by absorption of lower energy photons at subsequent junctions. A multijunction structure is shown in Fig. 6.14. Although the idea looks logical at the outset, a problem is encountered due to the presence of unwanted reverse biased  $p/n$  junction (shown with dotted line) in series opposition between the two junctions, which leads to power dissipation. This unwanted reverse biased junction is eliminated by incorporating a  $p^+ n^-$  tunnel junction in its place. A  $p-i-n$  type ( $p$ -type-intrinsic- $n$ -type) junction structure, where intrinsic silicon is interposed between the  $n$  and  $p$  layers is used in tandem in amorphous-silicon solar cells.

### 6.3.3 On the Basis of Type of Active Material

Depending on the type of material used for fabrication of a junction, they are classified as (i) single crystal silicon cell, (ii) multicrystalline silicon cell, (iii) amorphous silicon (a-Si), (iv) gallium arsenide cell (GaAs), (v) copper indium (gallium) diselenide cell (CIS), (vi) cadmium telluride cell (CdTe), and (vii) organic PV cell. At present, only single crystal, multicrystalline and to some extent a-Si cells are being produced commercially.

**(i) Single Crystal Silicon Solar Cell** The first silicon PV cells were of the single crystal variety. Single crystal silicon cells are the most efficient and most robust of the silicon PV family. Their main drawbacks are: (i) they are most energy intensive in their production, and (ii) the unit consumption of silicon to produce one unit of PV electricity is also quite high. Other variations of PV cells are being developed to overcome mainly these two drawbacks. Let us have a brief overview of the main steps involved in their production.

As a photon is most efficiently absorbed when its energy is close to the band gap, a clever way to absorb more photon energy is to stack junctions of different band gaps, what is known as *multijunction structure*. The top junction has a relatively wider band gap followed by one or two more junctions in decreasing order of band gaps,

absorbed at the top junction followed by absorption of lower energy photons at subsequent junctions. A

multijunction structure is shown in Fig. 6.14. Although the idea looks logical at the outset, a problem is encountered due to the presence of unwanted reverse biased  $p/n$  junction (shown with dotted line) in series opposition between the two junctions, which leads to power dissipation. This unwanted reverse biased junction is eliminated by incorporating a  $p^+ n^-$  tunnel junction in its place. A  $p-i-n$  type ( $p$ -type-intrinsic- $n$ -type) junction structure, where intrinsic silicon is interposed between the  $n$  and  $p$  layers is used in tandem in amorphous-silicon solar cells.



The first step is the production of metallurgical grade (99% pure) silicon,  $MgSi$  from its ore,  $SiO_2$ , by reduction reaction with carbon in an arc furnace. The energy cost of this step is 50 kWh/kg of silicon. Also, in this process  $CO_2$  is produced as a byproduct, which is a greenhouse gas. Electronic grade pure (an impurity of about 1 part in  $10^7$ ) polysilicon (or polycrystalline silicon) is then obtained by refining it further through various complex operations at an energy cost of 200 kWh/kg of silicon. These two steps are highly energy intensive.

The polysilicon is then melted and the IIIrd group impurity (generally boron) in a desired quantity is introduced in the melt to get a  $p$ -type base material. The bulk resistivity of this material is chosen appropriately by controlled doping. Low doping or high resistivity should result in a wider depletion layer and increased short-circuit current. But this would also result into lower open-circuit voltage and a large series resistance leading to reduction of fill factor. On the other hand, too low resistivity, or a high doping leads to lower photocurrent due to larger carrier recombination. Such considerations have lead to selection of resistivity in the range 1 to 3 ohm-cm as an optimum value for bulk silicon solar cells. The molten mass is recrystallised into a single crystal ingot as large as 4 to 6 inches in diameter and 3 to 5 feet long, using a silicon seed crystal. Special saws are then used to cut the ingots into wafers of thickness between 200 to 400 microns. Again, this crystal growth and wafering processes are quite energy intensive. Also about 40–50% of this expensive material is lost in this slicing operation. Efforts are on to fabricate a thin ribbon-shaped crystal to avoid the need of wafering. The edges of the wafers are then trimmed to make it closer to a square so as to increase the packing density, as circular wafers mounted on a module would leave a large amount of space between them. After preparation of the surface, on each wafer a Vth group impurity (usually phosphorus) is diffused to get a thin (fraction of a micron) layer of  $n$ -type material and thus a  $p/n$  junction is formed. Low-resistance ohmic contacts are made on both sides for external connection.

The most common commercially produced silicon cell has an  $n$ -on- $p$  structure, where the base material is  $p$ -type, which has a thin diffused  $n$  layer on top of it. Since the diffused layer is relatively heavily doped, it is likely to have a large number of unwanted recombination centres. Therefore, the diffusion length of minority carriers in this region is quite small and they are not expected to contribute significantly to photocurrent. The major contribution would normally come from the base region. The minority carrier diffusion length for electron is about twice that of a hole in silicon. Therefore, a  $p$ -type silicon base material, which has electrons as its minority carriers are preferred for making single crystalline bulk silicon solar cell.

**(ii) Multicrystalline Silicon Solar Cell** Multicrystalline silicon cells are less energy intensive in their production and less costly as compared to single-crystal silicon cells. But they are less efficient. Commercial multicrystalline solar cells have efficiencies in the range 10% to 14%. Impurity segregation in grain boundaries,



which act as recombination centres, has limited the achievable maximum conversion efficiency.

The first two steps of manufacturing, up to the production of polysilicon are the same as explained above for the case of single crystalline cell. The polysilicon thus obtained is melted and after proper doping, an ingot of multicrystalline silicon is produced by controlled cooling without seeding. While a single crystalline silicon cannot be grown in a square shape and, therefore, is physically trimmed into it, large square shaped solids can be obtained in multicrystalline silicon leading to economy in material consumption by reducing the kerf loss. It is also possible to reduce the unit energy consumption in the growth of multicrystalline ingot and the growth may be made much faster. Slicing into wafers and all further steps are similar to that for the case of single crystal silicon cell explained above.

**(iii) Amorphous Silicon (a-Si) Solar Cell** Amorphous silicon cells are recently developed using thin-film technology. These are cheaper alternatives to single or multicrystalline cells. Their main drawbacks are that they have low efficiency (a commercial a-Si cell has efficiency in the range of 4% to 8%) and they degrade in outdoor applications. They perform best when used indoors with diffused or indoor lights. Thus, they are ideally suited in applications such as pocket calculators, electronic watches, small radio receivers and low power hand-held electronic instruments.

Amorphous silicon has no predictable crystal structure. Due to randomness of atoms, many covalent bonds are incomplete. These incomplete bands cause a large number of equivalent impurity states in the band gap. The impurity states result in trapping of mobile carriers. Non-crystalline nature of material also results in very low mobility of carriers. This renders amorphous silicon as a rather poor semiconductor material.

The properties of a-Si are considerably improved when alloyed with hydrogen, to get a-Si:H material. Much of the unwanted gap states are removed by passivation with hydrogen and electronic properties are improved. By incorporating an intrinsic layer between  $p$  and  $n$  layers, a reasonable electron-hole pair generation region can be created. Another positive feature of a-Si:H is that it has a direct band gap close to 1.75 eV, which makes it a potential candidate for thin-film cells. Efficiency can be improved by stacking a number of carefully tailored  $p$ -i- $n$  junctions. This also reduces the degradation.

**(iv) Gallium Arsenide Cell** GaAs has a direct band gap of 1.43 eV, which makes it an attractive pV material. Simple GaAs cells have thin films of  $n$  type and  $p$  type GaAs, grown on a suitable substrate. Other structures have cascading of many layers of  $p$  and  $n$  materials formed using impurities from III-V elements. These are high-performance extraterrestrial quality cells. Fill factor in excess of 80% has been achieved. Single-cell open circuit voltage generally varies from 0.8 V



to 0.9 V. The efficiencies in excess of 20% are common and can even be enhanced on more expensive GaAs substrates. However, high production cost has limited their use only in extraterrestrial and other special purpose applications.

**(v) Copper Indium (Gallium) Diselenide (CIS) Cell** CIS has a direct band gap of 1.0 eV. Incorporation of Ga into the CIS mixture increases the band gap beyond 1.1 eV. A heterogeneous junction with  $n$ -type CdS and  $p$ -type CIS is fabricated using thin-film technology. Its main attraction is inexpensive preparation. It is more stable as compared to a-Si cell in outdoor applications and has efficiency of around 10%. However, exposure to elevated temperatures results in loss of efficiency, but light soaking (starving) restores it to original efficiency level.

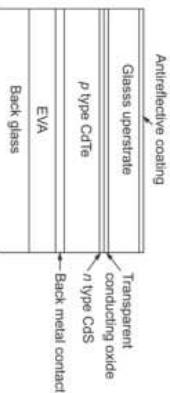


Fig. 6.15 Basic structure of CdTe cell

**(vi) Cadmium Telluride Cell** CdTe has a favorable direct band gap of 1.44 eV. Thin film heterogeneous junction with  $n$ -type CdS and  $p$ -type CdTe is fabricated as shown in Fig. 6.15. Here, a transparent conducting oxide layer is used instead of metallic contact at the top on the  $n$  side. EVA (ethylene vinyl acetate) is used for encapsulation. No instability problem has been reported in a trial of few years of outdoor application. Its efficiency is about 10% and open-circuit cell voltage is around 0.8 V. Commercial production requires more R and D efforts.

#### (vii) Organic PV Cell

Currently, organic PV cells, fabricated out of carbon based dyes and polymers (often referred as solar plastics) are under the development stage. Their principal advantage is that they are flexible and can bend without breaking, unlike Si, which is brittle. They are also very light and cheap. They may be folded or cut into required sizes and can still be used. However, at present, their efficiency is very low (about 3.5%).

## 6.4 SOLAR CELL, MODULE, PANEL AND ARRAY CONSTRUCTION

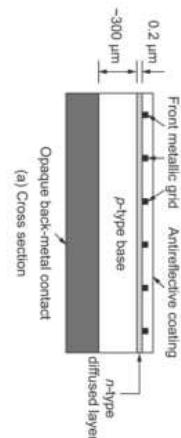
### 6.4.1 Solar Cell

The basic cell structure of a typical  $n$ -on- $p$ , bulk silicon cell is shown in Fig. 6.16. The bulk material is  $p$ -type silicon with a thickness of 100 to 350 microns, depending on the technology used. A thin layer of  $n$ -type silicon is formed at the top surface by diffusing an impurity from the Vth group (phosphorus being the most common) to get a  $p/n$  junction. The top active surface of the  $n$  layer has an ohmic contact with metallic grid structure to collect the current produced by impinging photons. The metallic grid covers minimum possible top surface area (less than 10% of the total area) to leave enough uncovered surface area for incoming photons. Similarly, the bottom inactive surface has an ohmic metallic contact over the entire area. These

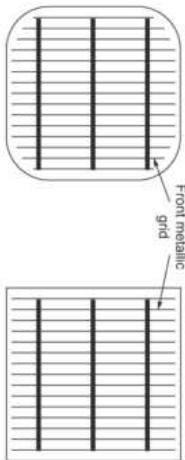
two metallic contacts on *p* and *n* layers respectively form the positive and negative terminals of the solar cell. In addition to basic elements, several enhancement features are also included in the construction. For example, providing antireflective coating, textured finish of the top surface and reflective, textured rear surface, to capture maximum photons and direct them toward the junction.

### 6.4.2 Solar PV Module

A bare single cell cannot be used for outdoor energy generation by itself. It is because (i) the output of a single cell is very small, and (ii) it requires protection (encapsulation) against dust, moisture, mechanical shocks and outdoor harsh conditions. Workable voltage and reasonable power is obtained by interconnecting an appropriate number of cells. The unit is fixed on a durable back cover of several square feet, with a transparent cover on the top and hermetically sealed to make it suitable for outdoor applications. This assembly is known as solar module—a basic building block of a PV system. The most common commercial modules have a series connection of 32 or 36 silicon cells to make it capable of charging a 12-V storage battery. However, larger and smaller capacity modules are also available in the international market.



(a) Cross section



**Fig. 6.16** Construction of bulk silicon cell

**Cell Mismatch in a Module** In a module, a number of cells are interconnected, and it is very important that these cells should match as closely as possible. That means,  $V_{oc^*} I_{sc^*} V_m$  and  $I_m$  (or fill factor) for all cells must be exactly same. Any mismatch in the characteristics of these cells leads to additional mismatch loss. Therefore, peak power of the combination is always less than the sum of individual peak power of the cells. Only under an ideal case when all cells are

exactly identical, the resultant peak power would be equal to the arithmetic sum of its constituents. This is elaborated as follows.

When two cells with mismatched characteristics are connected in series and a load is applied, both cells are bound to carry same current. The composite characteristics of the combination can be obtained by adding the individual output voltage of the cell corresponding to a common current, for all operating points, as shown in Fig. 6.17. At a particular operating point, while one cell may be operating at peak power, the other may not. Thus, peak power of the combination is always less than the sum of individual peak power of each cell. This is also clear from the shape of composite characteristics, which has a lower fill factor. Also, if such a combination is short-circuited, equal and opposite voltages  $V'_1$  and  $V'_2$  are produced by individual cells and therefore, one cell will be generating power while the other will be dissipating it. Had the two cells been perfectly matched, no power would be generated or dissipated.

A similar conclusion may be drawn by considering a parallel combination of two mismatched cells. Here, the voltages of the cells are bound to be equal, but the currents will be different and hence, so will be the maximum power points. The conclusion may be generalized for more than two cells connected in series or in parallel. It can also be shown that larger the number of cells in a module, more would be the possibility and quantum of mismatch loss.

To reduce mismatch losses, modules are fabricated from cells belonging to same batch. Also, *cell sorting* is carried out to categorize cells having matched parameters with specified tolerance.

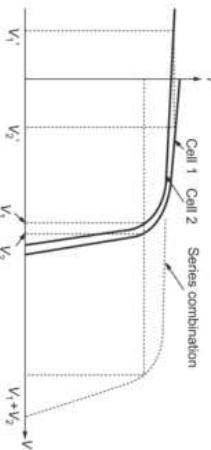


Fig. 6.17 Composite characteristic of two cells in series

#### **Effect of Shadowing**

Partial shadowing may have serious consequences and may completely damage a module due to creation of a hot spot. Let us examine the operation of a module under the conditions of (i) partial shadowing of a cell in an open-circuited series string of cells, and (ii) complete shadowing of one cell in a short-circuited, series string of cells.

When a cell is partially shadowed, the shadowed portion will not produce any power but the remaining portion will remain active and produce power. The generated voltage by illuminated portion will forward-bias the parallel rectifier corresponding to the shadowed portion, as shown in Fig. 6.18. If the shadowed area is relatively small, the large circulating current through it will result in excessive heating of the shadowed portion. The phenomenon is known as *hot-spot effect* and may completely damage the module for prolonged partial shadowing.

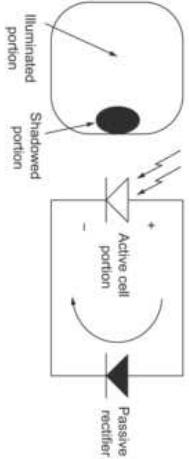


Fig. 6.18 Partial shadowing of a cell

A short-circuited, series string of  $(n + 1)$  cells with one cell completely shadowed is shown in Fig. 6.19. Here, the voltages produced by  $n$  illuminated cells add up and appear as reverse bias voltage of  $nV$  across the shadowed cell. As long as peak inverse voltage (PIV) of the shadowed cell is more than the reverse bias, no current will flow. If, however, the PIV is less than the total reverse voltage appearing across the shadowed cell, current will flow through the string, dissipating large power in the shadowed cell, thus leading to possible damage of the module. The chances of damage to the shadowed cell due to excessive heating increase with the number of cells in the string. If the string supplies a load instead of being short-circuited, the chances of damage still persist through to a lesser extent. The damage due to shadowing can be avoided by connecting a bypass diode across the affected cell as shown in Fig. 6.19. This bypass diode would allow an alternative path for the load current. During healthy operation, the bypass diode has no role as the cell voltage would keep it reverse biased. Even so, its use would result some loss because of finite reverse leakage current through it. It is neither practical, nor required to incorporate a bypass diode across each cell in a module. It has been the international practice to provide a bypass diode for every 18 crystalline silicon solar cells in a series string. Thus, the internationally standard module with 34–36 cells would contain two bypass diodes placed inside its terminal box.

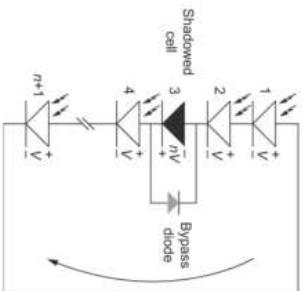
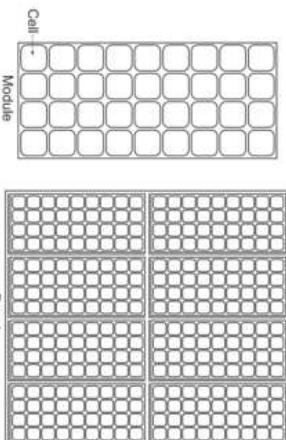


Fig. 6.19 Shadowed cell and bypass diode connection

### 6.4.3 Solar PV Panel

Several solar modules are connected in series/parallel to increase the voltage/current ratings. When modules are connected in series, it is desirable to have each module's maximum power production occur at the same current. When modules are connected in parallel, it is desirable to have each module's maximum power production occur at the same voltage. Thus while interconnecting the modules, the installer should have this information available for each module. Solar panel is a group of several modules connected in a series-parallel combination in a frame that can be mounted on a structure. Fig. 6.20 shows the construction of module and panel.



**Fig. 6.20** Cell, module and panel

Figure 6.21 shows a series-parallel connection of modules in a panel. In a parallel connection, blocking diodes are connected in series with each series string of modules, so that if any string should fail, the power output of the remaining series strings will not be absorbed by the failed string. Also, bypass diodes are installed across each module, so that if one module should fail, the output of the remaining modules in a string will bypass the failed module. Some modern PV modules come with such internally embedded bypass diodes.

### 6.4.4 Solar PV Array

In general, a large number of interconnected solar panels, known as solar PV array, are installed in an array field. These panels may be installed as stationary or with sun tracking mechanism. It is important to ensure that an installed panel



does not cast its shadow on the surface of its neighbouring panels during a whole year. The layout and mechanical design of the array such as tilt angle of panels, height of panels, clearance among the panels, etc., are carried out taking into consideration the local climatic conditions, ease of maintenance, etc.

### Example

A PV system feeds a dc motor to produce 1 hp power at the shaft. The motor efficiency is 85%. Each module has 36 multicrystalline silicon solar cells arranged in a  $9 \times 4$  matrix. The cell size is 125 mm  $\times$  125 mm and the cell efficiency is 12%. Calculate the number of modules required in the PV array. Assume global radiation incident normally to the panel as  $1 \text{ kW/m}^2$ .

### Solution

$$\text{Motor output power} = 1 \text{ hp} = 735 \text{ W}$$

$$\text{Electrical power required by the motor} = 735 / 0.85 = 864.7 \text{ W}$$

$$\text{Cell area in one module} = 9 \times 4 \times 125 \times 125 \times 10^{-6} = 0.5625 \text{ m}^2$$

$$\text{Let } N \text{ number of modules be required.}$$

$$\text{Solar radiation incident on panel} = 1 \text{ kW/m}^2 = 1000 \text{ kW/m}^2$$

$$\text{Cell efficiency} = 0.12$$

$$\text{Output of solar array} = 1000 \times 0.5625 \times N \times 0.12 = 67.5 \times N$$

$$\text{The output of solar array is the input to the motor;}$$

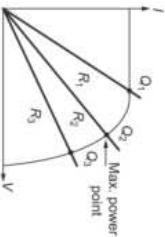
$$67.5 \times N = 864.7$$

$$N = 12.8 \approx 13$$

Therefore, 13 modules are required in the panel.

## 6.5 MAXIMIZING THE SOLAR PV OUTPUT AND LOAD MATCHING

To make best use of the solar PV system, the output is maximized in two ways. The first is mechanically tracking the sun and always orienting the panel in such a direction as to receive maximum solar radiation under changing positions of the sun. The second is electrically tracking the operating point by manipulating the load to maximize the power output under changing conditions of insulation and temperature.

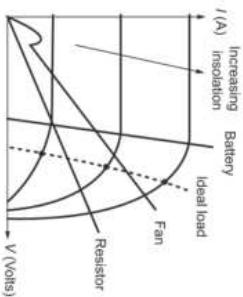


**Fig. 6.22** Load matching with resistive load  
available from the PV system for a load resistance of  $R_L$ . Such load matching is required for extracting maximum power from a PV system.

The operating point of an electrical system is determined by the intersection of source characteristics (source line) and load characteristics (load line). The operation for a solar PV system connected to a resistive load is shown in Fig. 6.22. For a low value of resistance,  $R_L$ , the system operates at  $Q_1$ . As the resistance is increased to  $R_2$  and then to  $R_3$ , the operating point moves respectively to  $Q_2$  and  $Q_3$ . Maximum power is

**MAXIMUM POWER POINT TRACKER (MPPT)**

**6.6** When a solar PV system is deployed for practical applications, the  $I-V$  characteristic keeps on changing with insulation and temperature. In order to receive maximum power, the load must adjust itself accordingly to track the maximum power point. The  $I-V$  characteristics of PV system along with some common loads are shown in Fig. 6.23. An ideal load is one that tracks the maximum power point.

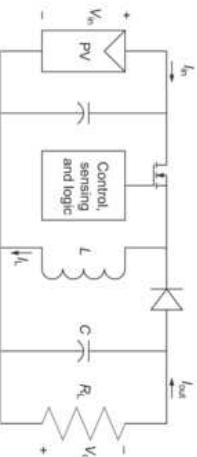


**Fig. 6.23** Characteristic fo PV and some loads

switching times. Basic elements of a buck-boost converter that may be used in an MPPT are shown in Fig. 6.24. The output voltage of the buck-boost converter is given by

$$V_{out} = \frac{D}{1-D} V_m \quad (6.13)$$

where  $D$  is the duty cycle of the MOSFET, expressed as fraction ( $0 < D < 1$ ). Details of operation and design of the converter may be found in any standard book of power electronics.



**Fig. 6.24** Maximum point tracker using buck-boost converter

The power output of a PV system is given by

$$P = V' \cdot I \quad (6.14)$$

With incremental change in current and voltage, the modified power is given by

$$\Delta P = (I + \Delta I) \cdot (V' + \Delta V') \quad (6.15)$$

which, after ignoring small terms simplifies to

$$\Delta P = \Delta V' \cdot I + \Delta I \cdot V' \quad (6.16)$$

$\Delta P$  must be zero at peak point. Therefore, at peak point the above expression in the limit becomes

$$\frac{dV'}{dI} = -\frac{V'}{I} \quad (6.17)$$

It may be noted here that  $\frac{dV'}{dI}$  is the dynamic impedance of the source, which is required to be equal to negative of static impedance,  $\frac{V'}{I}$ .

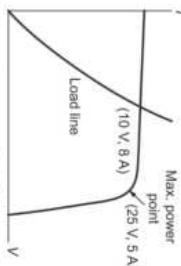
There are three possible strategies for operation of an MPPT:

(i) **By Monitoring Dynamic and Static Impedances** A small signal current is periodically injected into the array bus and the dynamic as well as static bus impedances ( $Z_d$  and  $Z_s$  respectively) are measured. The operating voltage is then adjusted until the condition  $Z_d = -Z_s$  is achieved.

(ii) **By Fixing the Output Voltage as a Fraction of  $V_{oc}$**  This method makes use of the fact that for most PV cells, the ratio of the voltage at maximum power point to the open circuit voltage, is approximately constant (say  $k$ ). This is also evident from Fig. 6.12. For high-quality crystalline silicon cell,  $k = 0.72$ . An additional identical unloaded cell is installed on the array to face same environment as the module in use and its open-circuit voltage  $V'_{oc}$  is continuously measured. The operating voltage of the array is then set at  $k \cdot V'_{oc}$ . The implementation of this scheme is simplest among all the available schemes.

**Example**

A PV source having IV characteristics as shown in Fig. 6.25 is supplying power to a load whose load line intersects the characteristics at (10 V, 5 A). Determine the additional power gained if an MPPT is interposed between the source and the load. If the cost of the MPPT is Rs. 4000.00, for how long does the system need to operate in order to recover the cost of MPPT? The cost of electricity may be assumed as Rs 3.00 per kWh.

**6.4**

**Fig. 6.25** PV system – load characteristics

**Solution**

Power produced without MPPT =  $10 \times 8 = 80$  W

Maximum power-production capability of the PV module

$$= 25 \times 5 = 125 \text{ W}$$

As the efficiency of the MPPT is 95%, actual power produced with MPPT =  $125 \times 0.95 = 118.75$  W

Surplus power produced by use of MPPT =  $118.75 - 80$

$$= 38.75 \text{ W}$$

$$\text{Surplus energy produce in } t \text{ hours} = \frac{38.75 \times t}{1000}$$

$$= 0.03875 \times t \text{ kWh}$$

Cost of surplus energy =  $3 \times 0.03875 \times t$

Cost of MPPT = 4000

Time (in hours) required to recover the cost of MPPT

$$= \frac{4000}{0.03875} = 34408.6 \text{ hours}$$

**BALANCE OF SYSTEM COMPONENTS****6.7**

The balance of system (BOS) components include mounting materials for the module, wire and all wiring components (including distribution panel, junction box and miscellaneous connectors), lightning protectors, grounding connections, battery fuses, battery cables and battery containers. In some cases, the connected loads are also considered to be part of BOS, for example, when the system is installed to operate a specific load.

Certain BOS components are regulated by codes or standards. Array mounts, for example, must meet wind-loading requirements of applicable building codes. Battery compartments are covered in the NEC (National Electrical Code). Also, BOS components may need to be appropriate for environmental considerations.

## 6.8

### SOLAR PV SYSTEMS

#### 6.8.1 Classification

Solar PV systems are broadly classified as follows:

(i) **Central Power Station System** Central PV power stations are conceptually similar to any other conventional central power station. They feed power to grid. These are being proposed in few MW range to meet daytime peak loads only. Central PV power stations of up to 6 MW<sup>p</sup> (peak MW) capacities have already been demonstrated within USA and Europe. While the concept has been demonstrated through such experimental plants, the capital costs are currently somewhat high for their commercial exploitation.

(ii) **Distributed System** Distributed form of energy use is unique and much more successful with solar and most other renewable energy sources. These systems can be further divided into three groups:

(a) **Stand-alone System** It is located at the load centre and dedicated to meet all the electrical loads of a village/community or a specific set of loads. Energy storage is generally essential. It is most relevant and successful in remote and rural areas having no access to grid supply. Indicative capacity of such a system is 10 kW<sup>p</sup>–100 kW<sup>p</sup>.

(b) **Grid-interactive System** This system is connected to the utility grid with two-way metering system. It may be a small rooftop system owned and operated by the house owner or a relatively bigger system meant for the whole village or a community. It meets daytime requirements of the house owner without any battery backup and surplus power is fed to the grid. During peak hours and during nights, the energy shortage may be met from grid.

(c) **Small System for Consumer Applications** These systems are meant for low energy consumer devices requiring power in the range of microwatts to 10 W<sup>p</sup> and mostly designed for indoor applications, e.g., calculators, watches, electronic games, etc.

#### 6.8.2 Stand-Alone Solar PV System

The main components of a general stand-alone solar PV system are shown in Fig. 6.26. The MPPT senses the voltage and current outputs of the array and

adjusts the operating point to extract maximum power under the given climatic conditions. The output of the array after converting to ac is fed to loads. The array output in excess of load requirement is used to charge the battery. If excess power is still available after fully charging the battery, it may be shunted to dump heaters. When the sun is not available, the battery supplies the load through an inverter. The battery discharge diode  $D_b$  prevents the battery from being overcharged after the charger is opened. The array diode  $D_a$  is to isolate the array from the battery to prevent battery discharge through array during nights. A mode controller is a central controller for the entire system. It collects the system signals and keeps track of charge/discharge state of the battery, matches the generated power and load and commands the charger and dump heater on-off operation.

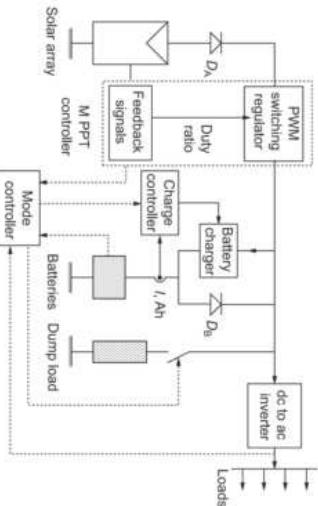


Fig. 6.26 A general stand-alone solar PV system

### 6.8.3 Grid-Interactive Solar PV System

In a grid-interactive system, all excess power is fed to a grid and dump heaters are not required. Also, during absence or inadequate sunshine, supply of power is maintained from the grid, and thus battery is eliminated. The mechanism for synchronized operation is incorporated. The dc power is first converted to ac by inverter, harmonics are filtered and then only the filtered power is fed into the grid after adjusting the voltage level. Recently, PV modules are being made with inverters as an integral component in the junction box of the module, what is known as *ac-PV modules*. It provides utility grade 60 Hz power directly from the module junction box. This greatly simplifies the design of a PV system. The schematic diagram of a general grid-interactive solar PV system is given in Fig. 6.27.

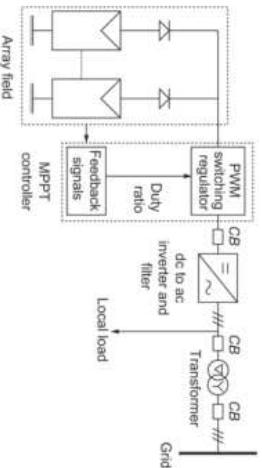


Fig. 6.27 A general grid-interactive solar PV system

#### 6.8.4 Hybrid Solar PV System

Sometimes, it is not economical or practical to provide all energy from a PV system. In such cases, it may be more economical to provide some of the system energy needs by other means, such as diesel/gasoline generators or any other non-conventional source like wind or fuel cells. Such a system is called a *hybrid system*. The best cost-effectiveness is generally obtained when none of the PV-generated energy is wasted.

### SOLAR PV APPLICATIONS

#### 6.9.1 Grid-Interactive PV Power Generation

The first large sized ( $1 \text{ MW}_p$ ) grid-interactive PV plant was installed in Lago, in California, USA. The second and largest ( $6.5 \text{ MW}_p$ ) plant was installed in Carissa Plains, California, USA. Also, some other large sized plants are operating in various countries and many others are proposed in Italy, Switzerland, Germany, Austria, Spain and Japan. Several small-capacity systems in the range of  $25 \text{ kW}_p$ – $200 \text{ kW}_p$  are being experimentally tried out in Africa, Asia and Latin America. In India,  $33 \text{-SPV}$ , grid-connected plants with a total installed capacity of  $2.54 \text{ MW}_p$  have been installed so far and another  $550 \text{ kW}_p$  aggregate installed capacity plants are undergoing installation process. A  $200 \text{-kW}_p$  grid-interactive SPV plant, installed recently at village Khatkarla, Dr. Nawanshahar of Punjab is shown in Fig. 6.28. This is the biggest operating SPV plant at present in the country. Also, a large number of small rooftop grid interactive systems are successfully being operated at various parts of the world. A total of  $1791 \text{ kW}_p$  stand-alone SPV systems have been installed so far in the country.



**Fig. 6.28** A 200-kW<sub>p</sub> grid-interactive SPV plant at Village KhatkarKalan, Dt. Nawanshahr Punjab Source: MNES Annual report

### 6.9.2 Water Pumping

Pumping of water for the purpose of drinking or for minor irrigation during sunshine hours is a very successful application of a standalone PV system without storage. Water pumping appears to be most suited for solar PV applications as water demand increases during dry days when plenty of sunshine is available. There would be less need of water during the rainy season when the availability of solar energy is also low. SPV water-pumping systems have been successfully used in many parts of the world in the range of few hundred W<sub>p</sub> to 5 kW<sub>p</sub>. An SPV water-pumping system is expected to deliver a minimum of 15,000 litres per day for a 200-W<sub>p</sub> panel and 1,70,000 litres per day for 2,250 W<sub>p</sub> panel from a suction of 7 metres and/or a total head of 10 metres on a clear sunny day. Three types of motors have generally been used: (i) permanent magnet dc motor, (in low-capacity pumping systems), (ii) brushless dc motors, and (iii) variable voltage and variable frequency ac motors, with appropriate electronic control and conversion system. An SPV water-pumping system for a fishing farm is shown in Fig. 6.29.



**Fig. 6.29** An SPV water-pumping system for fishing. Source: MNES Annual Report



### 6.9.3 Lighting

Next to water pumping, lighting is the secondmost important and extensive application of a standalone solar PV system. As lighting is required when the sun is not available, battery storage is essential. Energy-efficient compact fluorescent lamps (CFL) or low-pressure sodium vapour lamps (LPSVL) are used at 25–35 kHz frequencies, as SPV is an expensive power source. Pole mounted outdoor lighting, shown in Fig. 6.30, is designed for 3–6 hours an evening. A typical system has two 35 W modules connected in parallel, an 11-W (900 lumens) CFL, a 90 or 120 Ah, 12-V storage battery and associated electronics including inverter, battery charger and timer to switch on and off the light. The approximate cost of one pole-mounted streetlight is Rs 30,000.

A portable SPV lantern, shown in Fig. 6.31, is usually designed to operate for 2–6 hours. A typical system consists of a 10 W<sub>p</sub> module, a 5–7 W CFL, a 7-Ah, 12-V battery and associated electronics and hardware. The cost of a portable solar lantern varies from Rs 4000 to Rs 5000.



Fig. 6.30 Pole-mounted SPV lighting

Source: MNES Annual Report

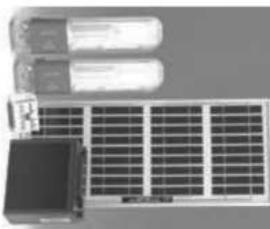


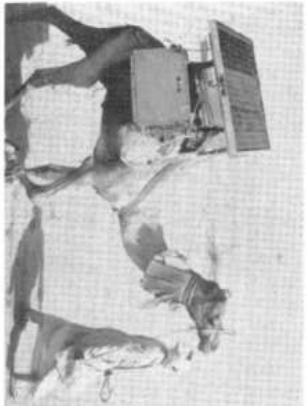
Fig. 6.31 Solar lantern Source:

Tata BP Solar Products

### 6.9.4 Medical Refrigeration

Many life-saving medical supplies, particularly vaccines, require refrigeration during storage and transportation in order to remain effective. For life-saving vaccines, the World Health Organization (WHO) has laid down ground rules to maintain the cold chain from the point of their manufacture to their application. In many developing countries, where such life-saving vaccines are in great demand, electricity is not available to operate conventional refrigerators. WHO has specified technical details for PV-based refrigerators using solar energy for such applications. This has resulted in success of WHO-sponsored immunization programmes in these countries. The volume of a refrigerator chamber varies from 20–100 litres with the freezer volume ranging from 10–35 litres. The PV module size ranges from 100 W<sub>p</sub> to over 600 W<sub>p</sub> with a 12 V/24 V battery, of 150 to over 600 Ah

capacities. An SPV powered portable medical refrigerator is shown in Fig. 6.32.



**Fig. 6.32** An SPV powered portable medical refrigerator

### 6.9.5 Village Power

Solar PV power can be used to meet low energy demands of many remote, small, isolated and generally unapproachable villages in most developing countries. Two approaches have generally been used:

- (i) Individual SPV system for every household.
- (ii) A centralized SPV plant to meet combined load demand of the whole village.

Both approaches have been extensively tried out in most parts of the world, particularly in developing countries. Whereas a centralized village PV power system requires large scale integrated planning and execution, individual village household systems may be available off-the-shelf. In many Asian and African countries, PV kits are available to cater to the needs of the latter types.

### 6.9.6 Telecommunication and Signaling

Solar PV power is ideally suited for telecommunication applications such as local telephone exchange, radio and TV broadcasting, microwave and other forms of electronic communication links. This is because, in most telecommunication applications, storage batteries are already in use and the electrical systems are basically dc.

Radio and TV signals may not reach in hilly and mountainous terrain as they get blocked or reflected back due to the undulating terrain. At these locations, either low-power transmitters (LPT) or very low-power transmitters (VLPT) are installed to receive and retransmit the signals for the local population. As these locations are generally remote and normal grid supply is not available, these are



powered by solar photovoltaic electricity. Each VLPT is designed to operate completely unattended. It consists of a 10-W transmitter with a daily mean energy consumption of less than 4 kWh. Usually, a 1.7-kW<sub>p</sub> SPV system with battery storage, enough to last for 6 days in cloudy season is provided.

On highways, SPV power is being used for lighted road signs and highway telephone booths even in many industrialized nations. Indian Railways is now using stand-alone SPV system for applications such as semaphore signaling and automatic radio-controlled level-crossing audio-visual alarms. These applications are highly cost effective in comparison to kerosene lamps used earlier.

## Review Questions

1. Which is the most expensive component in a solar PV system?
2. What are major advantages and disadvantages of a solar PV system?
3. What are the advantages and disadvantages of direct energy conversion system over the conventional power generation system?  
(UPTU Lucknow 2003-04)
4. Describe the principle of solar photovoltaic energy conversion.  
(UPTU Lucknow 2003-04)
5. What are direct and indirect gap materials?
6. Explain the mechanism of photoconduction in a PV cell.
7. Explain the I-V characteristics of a solar cell and define fill factor. What is the significance of fill factor?
8. Explain how the variation of insulation and temperature affects the I-V characteristics of a solar cell.
9. Explain the various factors contributing to losses and hence reduction of efficiency of a solar cell.
10. What do you understand by energy payback period?
11. Explain the various types of solar cells based on material thickness and the type of junction structure.
12. Explain the main features of different types of solar cells based on the active material used in their fabrication.
13. What do you understand by cell mismatch in a solar module and what are its implications?
14. What is the effect of partial or complete shadowing of a cell in a module?
15. Illustrate the concept of load mismatch in an SPV-load system.
16. What is the importance of MPP in an SPV system? Explain various strategies used for operation of an MPPT.
17. With the help of block diagrams explain the operations of standalone and grid interactive SPV systems.
18. Distinguish between an abrupt and graded pn junction.
19. Explain depletion region and barrier voltage.
20. How are electron-hole pairs generated when solar radiation is directed on a semiconductor material?

21. Draw and explain an equivalent circuit of a practical solar PV cell.  
 22. Describe the classification of solar cells based on the type of active material used.  
 23. Explain with suitable diagrams, the working of various types of solar photovoltaic power plant.

(UPTU Lucknow 2007-08)

### *Problems*

1. In an n-type silicon, the effective density of states in a conduction band is  $1 \times 10^{21}$  cm<sup>-3</sup>. What level of donor concentration is required to move the Fermi level close to conduction band by 0.2 eV? Assume room temperature as 0°C.  
**(Ans.  $2.056 \times 10^{19}$  cm<sup>-3</sup>)**
2. The band gap for GaAs is 1.43 eV. Calculate the optimum wavelength of light for photovoltaic generation in a GaAs cell.  
**(Ans. 0.867 μm)**
3. Calculate the open-circuit voltage of a silicon solar cell at 47°C if short circuit and reverse saturation currents are given as 2 A and 10 nA respectively.  
**(Ans. 0.5275 V)**
4. Solve the problem given in Example 6.4 by considering a load that intersects the PV characteristics at (26V, 2A), other data remaining the same.  
**(Ans. 20,000 hours)**

5. A photovoltaic system is installed for supplying water for minor irrigation needs at a remote place in a developing country. The water is pumped through a borewell from a depth of 25 m. The PV array consists of 24 modules. Each module has 36 multicrystalline silicon solar cells arranged in 9 × 4 matrix. The cell size is 125 mm × 125 mm and the cell efficiency is 12%. The combined motor and pump efficiency is 50%. Calculate the water discharge rate at noon when global radiation incident normally to the panel is 800 W/m<sup>2</sup>. Assume density of fresh water as 996 kg/m<sup>3</sup>.

**(Ans. 2,653 litres/s)**

### *Objective-type Questions*

1. A solar cell is basically
  - (a) a voltage source, controlled by flux of radiation
  - (b) a current source, controlled by flux of radiation
  - (c) an uncontrolled current source
  - (d) an uncontrolled voltage source
2. The efficiency of a commercial solar cell lies in the range
  - (a) 0–10%
  - (b) 10–20%
  - (c) 20–30%
  - (d) 50–60%
3. A typical open-circuit voltage of a solar cell is
  - (a) 12 V
  - (b) 6 V
  - (c) 3 V
  - (d) 0.5 V

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4. Which of the following statements is not true about solar cells?  
(a) It has no moving parts.  
(b) It is reliable and almost maintenance-free.  
(c) It is modular in design.  
(d) It is cheap and efficient.

5. The charge carrier available in a semiconductor material has  
(a) free electrons and holes      (b) only electrons  
(c) only holes      (d) positively charged ions

6. The Fermi level in an intrinsic type semiconductor material is  
(a) close to the conduction band and away from the valence band  
(b) close to the valence band and away from the conduction band  
(c) lies in the middle of the energy gap  
(d) lies within the valence band

7. The energy level of donor ions are  
(a) very close to the conduction band      (b) very close to valence band  
(c) lies in the middle of the energy gap      (d) lies within the conduction band

8. The energy associated with a photon is  
(a) directly proportional to the wavelength  
(b) inversely proportional to the frequency  
(c) directly proportional to the intensity of radiation  
(d) inversely proportional to the wavelength

9. What is responsible for movement of carriers after creation of an electron-hole pair due to radiation?  
(a) Diffusion process      (b) Drift process  
(c) Built-in electric field across the junction      (d) External voltage

10. The short-circuit current of a solar cell is  
(a) inversely proportional to the radiation intensity  
(b) directly proportional to the radiation intensity  
(c) constant and not affected by radiation  
(d) changes logarithmically with radiation

11. At maximum powerpoint of the solar cell,  
(a) current is maximum  
(b) voltage is maximum  
(c) both voltage and current are maximum  
(d) the product of voltage and current is maximum

12. The photons having energy less than the energy gap  
(a) are absorbed and converted to heat  
(b) are not absorbed by the semiconductor material as it behaves transparent to them  
(c) work jointly to produce an electron-hole pair  
(d) are reflected from the semiconductor material surface

13. The energy payback period of a single crystal silicon cell is  
(a) 6 months to 1 year      (b) 1 to 2 years  
(c) 10 to 20 years      (d) 3 to 5 years

14. In a homogeneous p-n junction  
(a) the width of p and n layers are equal and constant throughout  
(b) the impurity levels on both sides of the junction are same

- (c) the same semiconductor material is used on both sides of the junction  
(d) different semiconductor materials are used on both sides of the junction but the same level of doping is used

15. In a series string of mismatched solar cells,

- (a) full voltage and current capability can be attained and losses are less  
(b) losses are less  
(c) full current capability cannot be attained and losses are more  
(d) full voltage capability cannot be attained and losses are more

16. If no load is connected to a solar PV system,

- (a) it will stop absorbing light  
(b) it will dissipate energy in the panel and increase its temperature  
(c) its voltage will go on increasing till its breakdown  
(d) it will start reflecting the light.

17. An MPPT is basically

- (a) a dc-dc switching regulator  
(b) an ac-dc converter  
(c) a dc-ac inverter  
(d) an amplifier

18. A grid-interactive solar system:

- (a) always supplies power to the grid  
(b) supplies power to as well as receives power from the grid as required  
(c) always receives power from the grid  
(d) works only when the grid fails



# 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

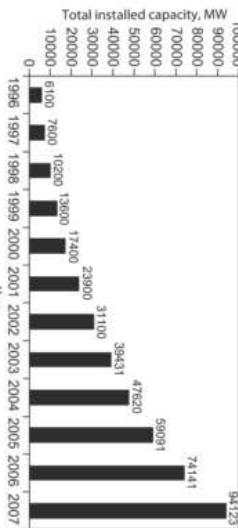
energy can be available continuously throughout a 24-hour day for much longer periods, though it can vary a great extent, including no wind periods. It is a clean, cheap, and eco-friendly renewable source. The main disadvantages are that it is dispersed, erratic and location-specific source. Wind energy 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 favorable 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 ( $1 \text{ TW} = 10^{12} \text{ W}$ ). It is also estimated that favorable 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 also 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<sup>[44]</sup>.



**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<sup>[44]</sup>. India ranks fourth in respect of installed capacity.

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

S. No.	Country	Installed Capacity (MW)	%age
1.	Germany	22,247	23.6
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
Total top ten		94,123	(86.2%)



S. No.	Country	Installed Capacity (MW)	%age
9.	UK	2,389	2.5
10.	Portugal	2,150	2.3
11.	Rest of the world	13,019	13.8
Total		94,123	100

Major factors that have led to an accelerated development of wind power are as follows:

- (i) Availability of high strength fibre composites for constructing large low-cost rotor blades
- (ii) Falling prices of power electronics
- (iii) Variable speed operation of electrical generators to capture maximum energy
- (iv) Improved plant operation, pushing the availability up to 95 per cent
- (v) Economy of scale, as the turbines and plants are getting larger in size
- (vi) Accumulated field experience (the learning curve effect) improving the capacity factor
- (vii) Short energy payback (or energy recovery) period of about one year

## ORIGIN OF WINDS

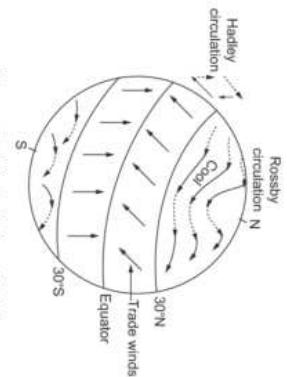
**7.1** The origin of winds may be traced basically to uneven heating of the earth's surface due to the sun. This may lead to circulation of widespread winds on a global basis, producing planetary winds or may have a limited influence in a smaller area to cause local winds.

### 7.1.1 Global (or Planetary) Winds

Two major forces determine the speed and direction of wind on a global basis.

- (i) The primary force for global winds is developed due to differential heating of the earth at equatorial and polar regions. In the tropical regions, there is a net gain of heat due to solar radiation, whereas in the polar regions there is net loss of heat. This means that the earth's atmosphere has to circulate to transport heat from tropics towards the poles. On a global scale, these atmospheric currents work as an immense energy-transfer medium. Ocean currents act similarly, and are responsible for about 30% of this global heat transfer.
- (ii) Spinning of the earth about its axis produces a coriolis force, which is responsible for deviation of air currents towards the west.

Between 30°N and 30°S, heated air at the equator rises and is replaced by cooler air coming from the north and south. This is known as *Hadley circulation*. Due to coriolis force, these winds deviate towards the west. These air currents are also known as trade winds because of their use in sailing ships for trades in the past.



**Fig. 7.2** Global circulation of wind

There is little wind near the equator ( $\pm 5^\circ$  around it), as the air slowly rises upwards rather than moving westward. Between  $30^\circ\text{N}(\text{S})$  and  $70^\circ\text{N}(\text{S})$  predominantly western winds are found. These winds form a wavelike circulation, transferring cold air southward and warm air northward (in the northern hemisphere and vice versa in the southern hemisphere). This pattern is called Rossby circulation. This is shown in Fig. 7.2.

### 7.1.2 Local Winds

Localized uneven heating is responsible for local winds. Local winds are produced due to two mechanisms:

- (i) The first is differential heating of land surface and water bodies due to solar radiation. During the day, solar energy is readily converted to sensible thermal energy on the land surface and this quickly increases its temperature. Whereas, on water bodies it is partly consumed in evaporating water and only partly absorbed to cause an increase in temperature. The land mass thus becomes hotter than water, which causes differential heating of air above them. As a result, cool, heavier air blows from the water towards land. At night, the direction of wind is reversed as the land mass cools to sky more rapidly than the water. This is the mechanism of shore breeze.
- (ii) The second mechanism of local winds is differential heating of slopes on the hillsides and that of low lands. The slope heats up during the day and cools down during night more rapidly than the low land. This causes the heated air to rise along the slope during the day and relatively cool air to flow down at night.

### 7.1.3 Factors Affecting the Distribution of Wind Energy on the Surface of the Earth

Several factors are responsible for distribution of wind energy on the surface of the earth. Some factors work globally while others have limited local influence. Both global and local factors influence the availability of wind energy at a particular site. The extent of influence of each factor varies from site to site.

- (i) On the planetary level, great mountain masses influence the circulation of air currents.



- (ii) Surface roughness or friction, owing to the resistance that different elements of the earth's surface offer to air circulation affects the nature of wind. Hills, trees, buildings and similar obstructions impair streamline air flow. Turbulence results and the wind velocity in a horizontal direction gets markedly reduced. Frictional effect is less on smooth areas such as seas or large open areas and more in rough urban areas with tall buildings or trees. Therefore, wind speed is quite high near the sea shore.
- (iii) Climatic disturbances such as down draught from thunderclouds and precipitation also affect the local winds.
- (iv) Wind speed also increases while passing through narrow mountain gaps, where it gets channelled.

## 7.2

**NATURE OF WINDS** To be able to understand and predict the performance of wind turbines it is essential to have some knowledge of the behaviour and structure of wind. This is also required for proper design of a supporting structure to carry the imposed load safely and at an economically viable cost. The behaviour and structure of the wind varies from site to site depending on the general climate of the region, the physical geometry of the locality, the surface condition of the terrain around the site and various other factors.

Rapid fluctuations in the wind velocity over a wide range of frequencies and amplitudes, due to turbulence caused by mechanical mixing of lower layers of atmosphere by surface roughness, are commonly known as *gusts*.

The Beaufort scale, a wind-speed classification, gives a description of the effect of the wind. It was initially designed for sailors and described the sea state, but has been modified to include wind effects on land. It is a useful guide to wind speed. The description of wind based on Beaufort numbers is given in Table 7.2.

**Table 7.2** Description of wind based on the Beaufort scale

Beaufort number	Wind speed m/s	Wind speed km/h	Observable effects	Wind description
0	0.0-0.4	0.0-1.6	Smoke rises vertically	Calm
1	0.4-1.8	1.6-6	Smoke drifts but vane unaffected	Light
2	1.8-3.6	6-13	Leaves move slightly but vane unaffected	Light
3	3.6-5.8	13-21	Leaves in motion, flags begin to extend	Light
4	5.8-8.5	21-31	Small branches move, dust raised, pages of book loosen	Moderate
5	8.5-11	31-40	Small trees sway, wind noticeable	Fresh
6	11-14	40-51	Large branches sway, telephone lines whistle	Strong
7	14-17	51-63	Whole tree in motion	Very Strong

Beaufort number	Wind speed m/s km/h	Observable effects	Wind Description
8	17–21	63–76 Twigs break off, walking difficult	Gale
9	21–25	76–88 Slight structural (e.g., chimneys) damage	Grave
10	25–29	88–103 Trees uprooted, much structural damage	Strong gale
11	29–34	103–121 Widespread damage	Hurricane
12	>34	>121 Disastrous conditions, countryside devastated, only occurs in tropical cyclones	

### 7.2.1 Wind Data

All countries have national meteorological services that record and publish weather-related data including wind speed and direction. Wind speed is measured by an anemometer and wind direction is measured by a wind vane attached to a direction indicator. Anemometers work on one of the following principles.

- (i) The oldest and simplest anemometer is a swinging plate hung vertically and hinged along its top edge. Wind speed is indicated by the angle of deflection of the plate with respect to the vertical.
- (ii) A cup anemometer consists of three or four cups mounted symmetrically about a vertical axis. The speed of rotation indicates wind speed.
- (iii) Wind speed can also be recorded by measuring the wind pressure on a flat plate.
- (iv) A hot-wire anemometer measures the wind speed by recording cooling effect of the wind on a hot wire. The heat is produced by passing an electric current through the wire.
- (v) An anemometer can also be based on sonic effect. Sound travels through still air at a known speed. However, if the air is moving, the speed decreases or increases accordingly.
- (vi) The other more novel techniques include the laser anemometer, the ultrasonic anemometer and the SODAR Doppler anemometer.

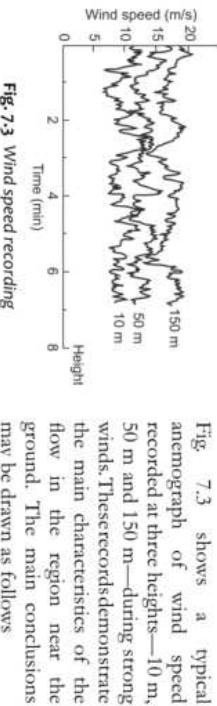


Fig. 7.3 Wind speed recording

- (i) Wind speed increases with height.
- (ii) Wind speed is fluctuating with time, i.e., turbulences are present at the site.
- (iii) The turbulence is spread over a broad range of frequencies.



As per the World Meteorological Organization (WMO) recommendation, wind speed measurement should be made at an effective height of 10 m above the ground. The frequency of measurement depends on the purpose for which the data is going to be used. For some applications, such as the estimation of the highest probable gust or the evaluation of turbulence intensity at a site, measurements at few seconds interval are required as wind speed varies on a time scale of seconds or less. For the purpose of energy studies, mean wind speed is used, which is generally based on different averaging periods from 10 min to 1 h in different countries. An elegant method of describing average wind speed, duration and direction on a single graph is shown in Fig. 7.4. It is known as *wind rose*. It depicts the compass bearing from which the wind comes (all 16 directions) along with average wind speed and duration in a year. The lengths of bars represent the percentage of duration. It is also possible to present the same information by another wind rose shown in Fig. 7.5. Here, the concentric circles represent duration in a 100-h interval and the solid lines the wind speed contours.

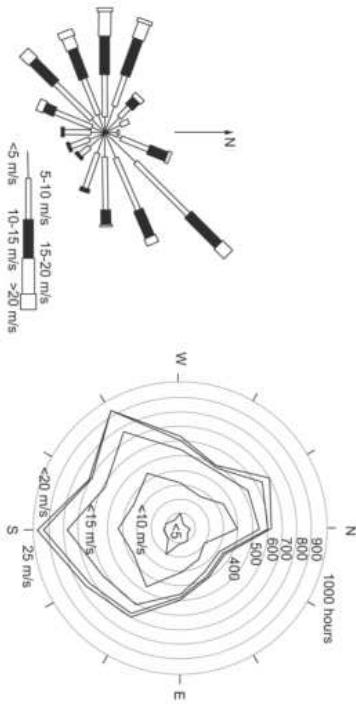


Fig. 7.4 A typical wind rose

## 7.2.2 Variation of Wind Speed With Height

At the earth's surface, wind speed is always zero. It increases with height above the ground. The wind near the earth's surface is retarded by surface roughness. The rate of change of wind speed with height is called *wind shear*. The lower layers of the air retard those above them, resulting in change in mean wind speed with height, until the shear forces are reduced to zero. This height is called the *gradient height* and is typically of about 2000 m. Above the gradient height, known as *free atmosphere*, changes in wind speed are not affected by ground conditions. The layer of air from ground to gradient height is known as *planetary boundary layer*. The planetary boundary layer mainly consists of (i) *surface layer*, which extends from the height of local obstructions to a height of approximately 100 m, and (ii) *Ekman layer*, which

Fig. 7.5 Alternative presentation of wind rose

starts from 100 m and extends up to gradient height as shown in Fig. 7.6. In the surface layer, the variation of shear stress can be neglected and mean wind speed with height can be represented by the Prandtl logarithmic law model:

$$u_z = V' \ln \left( \frac{z - d}{z_0} \right) \quad (7.1)$$

where,  $V'$  is characteristic speed,  $d$  is zero plane displacement, its magnitude is a little less than the height of local obstructions,  $z_0$  is roughness length,  $(z_0 + d)$  is the height of local obstructions.

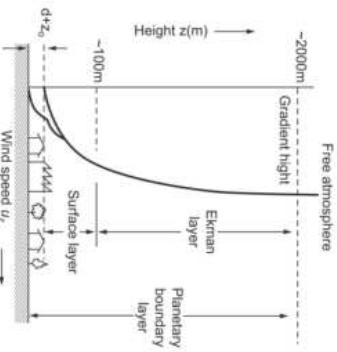


Fig. 7.6 Wind speed variation with height

As seen in the diagram, near the line of local obstructions, the average wind speed does not follow Eq. 7.1, (i.e., the dotted line), but deviates from it and becomes highly erratic.

It is very important then to place the wind turbine well above the height of local obstructions so that the turbine disk receives a strong uniform wind flux across its area without erratic fluctuations.

As stated earlier, the standard wind speed measurements are often taken at a height of 10 m from the ground but wind turbines often operate at a height above this. A simple empirical power law model can be used to estimate wind speed  $u_z$  at a height  $z$  relative to that available at standard reference height  $H$ .

$$u_z = u_{10} \left( \frac{z}{H} \right)^\alpha \quad (7.2)$$

where  $u_{10}$  is the mean wind speed at reference height  $H$  (usually 10 m),  $\alpha$  depends on surface roughness and the range of height being covered. The value of  $\alpha$  is often taken as 0.14 for open sites. It varies with season and the time of the day. Great care should be taken in using this formula, especially for  $z > 50$  m. Good sites should have low values of  $\alpha$ .

### 7.2.2 Variation of Wind Speed with Time

As wind speed fluctuates with time, it is more important to know about the continuity of supply than the total amount of energy available in a year. For electric-power generation, the minimum average wind speed required is 5 m/s. A site is not considered favorable for wind-power generation if average wind speed remains less than this for prolonged periods, as there will be no generation during



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).

### WIND TURBINE SITING

**7.3** 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.

### MAJOR APPLICATIONS OF WIND POWER

**7.4** 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,  $u_0$**  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).



**Incident Wind Velocity,  $u_i$**  Velocity of air passing through the rotor, i.e., the velocity at which the wind strikes the blade. It is slightly less than  $\bar{u}_i$ .

**Blade Element Linear Velocity,  $v$**  Linear circumferential velocity of the blade element due to rotation of blade.

**Relative Wind Velocity,  $v_r$**  Velocity of air relative to the blade element as the both the air and blade element move.

**Angular Speed,  $\omega$**  Angular speed of rotor in rad/s.

**Angle of Attack (or angle of incidence),  $\alpha$**  Angle between central line of the blade element and relative wind velocity  $v_r$  as shown in Fig. 7.7 (c).

**Blade Setting Angle (or pitch angle),  $\gamma$**  Angle between central line of the blade element and direction of linear motion of the blade element or angle between relative wind velocity  $v_r$  and normal to the plane of blade.

**Drag Force,  $\Delta F_D$**  Incremental force acting on the blade element in the direction of relative velocity of wind.

**Lift Force,  $\Delta F_L$**  Incremental force acting on the blade element in a direction perpendicular to the relative velocity of wind.

**Axial Force,  $\Delta F_A$**  Incremental force acting on the blade element along the axis of rotation of the blade.

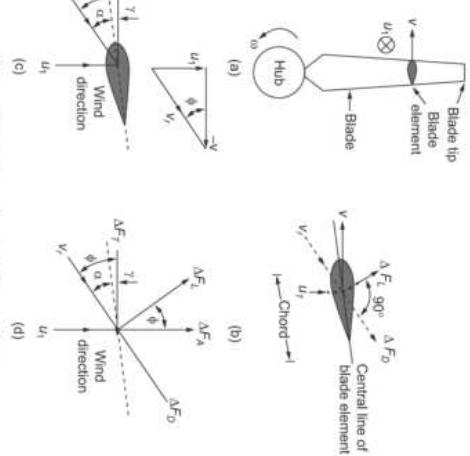
**Tangential Force,  $\Delta F_T$**  Incremental force acting on the blade element tangential to a circular path of rotation.

**Solidity** Solidity is defined as the ratio of the projected area of the rotor blades on the rotor plane to the swept area of the rotor.

Details and the relative positions of the above quantities are illustrated in Fig. 7.7. The incremental axial and tangential forces acting on the blade element are given by:

$$\Delta F_T = \Delta F_L \cos \phi + \Delta F_D \sin \phi$$

$$\Delta F_T = \Delta F_L \sin \phi - \Delta F_D \cos \phi \quad \text{where, } \phi = \alpha + \gamma$$



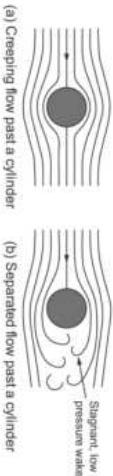
**Fig. 7.7** Blade element velocities and forces

### 7.5.2 Elementary Fluid Flow Concepts

The nature of flow around a body at a given velocity depends upon the relative magnitudes of the inertia and the viscous forces. The ratio of these forces is known as the *Reynolds number*.

In a very slow-moving (creeping) fluid, there is no relative motion at the body wall, and the drag on the body may be directly attributed to viscous, frictional shear stresses set up in the fluid. The flow remains attached to the surface of the body as shown in Fig. 7.8 (a).

In practical situations, when the viscosity is low and the velocity is relatively high, the drag force that exists is due primarily to an unsymmetrical pressure distribution, *fore* and *aft*. This is caused by the fact that the fluid does not follow the boundary of the body, but separates from it leaving a low pressure, stagnant fluid in the wake as shown in Fig. 7.8 (b). On the upstream side, where the flow remains attached, the pressure is high, because the flow has been slowed down and pushed aside by the body obstructing its path.



**Fig. 7.8** Attached and separated flow past a cylinder



An airfoil is a streamlined body tapered gently in the aft region and has a sharp trailing edge. For an airfoil, the flow remains attached to the body throughout. Because the trailing edge is sharp, the separation leaves no low-pressure wake. The drag is very low, largely due to skin friction only, rather than the pressure difference. The drag does not depend on the frontal area but on the surface area and surface finish. This situation is shown in Fig. 7.9 (a).

Consider an airfoil at a small angle of incidence  $\alpha$  to oncoming flow as shown in Fig. 7.9 (b). The flow remains attached and the drag is small. The particles above the airfoil travel faster causing static pressure there to reduce, whereas, those beneath it move slowly causing the static pressure to increase in this region. This produces a normal force on the airfoil, known as *lift force*.

When the incidence angle  $\alpha$  is increased beyond a certain critical value (10 to 16° depending on the Reynolds number), the separation of the boundary layer on the upper surface takes place as shown in Fig. 7.9 (c). This causes a wake to form above the airfoil, reducing the lift and increasing the drag substantially. This is known as *stalled state* of the airfoil. A well-rounded leading edge and proper thickness of the airfoil improves stalling behaviour of the airfoil.



**Fig. 7.9** Fluid flow around an airfoil

## 7.6

### WIND TURBINE AERODYNAMICS

#### 7.6.1 Energy Estimation of Wind

If  $u_0$  is the speed of free wind in unperturbed state, the volume of air column passing through an area  $A$  per unit time is given by  $A u_0$ . If  $\rho$  is the density of air, the air-mass flow rate, through area  $A$ , is given as,  $\rho A u_0$ . Power ( $P_o$ ) available in wind, is equal to kinetic energy associated with the mass of moving air; i.e.,

$$P_o = \frac{1}{2} (\rho A u_0) u_0^2$$

$$\text{or } P_o = \frac{1}{2} (\rho A) u_0^3 \quad (7.3)$$

Power available in wind per unit area is

$$\frac{P_o}{A} = \frac{1}{2} \rho u_0^3 \quad (7.4)$$

## Wind Energy

This indicates that power available in wind is proportional to the cube of wind speed. Assuming a typical value of wind density,  $\rho$  at 15°C, and at sea level to be 1.2 kg/m<sup>3</sup>, power available in moderate wind of 10 m/s is 600 W/m<sup>2</sup>.

### 7.6.2 Power Extraction from Wind

A wind turbine is used to harness useful mechanical power from wind. The rotor of the turbine collects energy from the whole area swept by the rotor. For the purpose of simple analysis, a smooth laminar flow with no perturbations is assumed. A horizontal axis wind turbine, which is most commonly used, is considered. The rotor may be considered as an actuator disk across which there is reduction of pressure as energy is extracted. As air mass flow rate must be same everywhere within the stream tube, the speed must decrease as air expands. The stream tube model, also known as *Betz model* of expanding air stream tube is shown in Fig. 7.10. The stream tube area of constant air mass is  $A_0$  upstream, which expands to  $A_1$  while passing through the rotor and becomes  $A_2$  downstream. The wind speed is  $u_0$  upstream, which reduces to  $u_1$  while passing through the rotor and becomes  $u_2$  downstream. The air-mass flow rate remains same throughout the stream tube. Therefore,

$$\dot{m} = \rho A_0 u_0 = \rho A_1 u_1 = \rho A_2 u_2 \quad (7.5)$$



(a) Unperturbed wind stream tube in absence of turbine

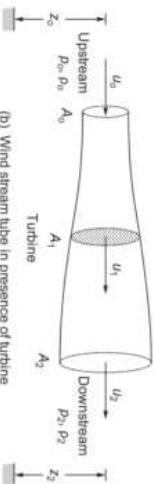


Fig. 7.10 Betz model of expanding air-stream tube

If  $u_0$  and  $u_2$  are wind speeds upstream and downstream respectively; the force or thrust on the rotor is equal to the reduction in momentum per unit time from the air mass flow rate  $\dot{m}$ :

$$F = \dot{m} u_0 - \dot{m} u_2 \quad (7.6)$$

This force is applied by the air at uniform air-flow speed of  $u_1$ , passing through the actuator disk (turbine). The power extracted by the turbine is

$$P_t = F u_1 = \dot{m} (u_0 - u_2) u_1 \quad (7.7)$$

The power extracted from wind is also equal to loss in KE per unit time. Thus,

$$P_w = \frac{1}{2} \dot{m} \left( u_o^2 - u_2^2 \right) \quad (7.8)$$

Equating 7.7 and 7.8, we have

$$u_1 = \frac{u_o + u_2}{2} \quad (7.9)$$

As an extreme case, considering  $u_2$  to be zero (which is not practical as downstream air must have some kinetic energy to leave the turbine region),  $u_1 = u_o/2$ . Thus, according to this linear momentum theory, the air speed through the actuator disk cannot be less than half the speed of upstream air.

An *interference factor*,  $a$  is defined as fractional wind speed decrease at the turbine thus:

$$a = (u_o - u_1)/u_o \quad (7.10)$$

$$\text{or } u_1 = (1-a) u_o \quad (7.11)$$

$$\text{or } a = (u_o - u_1)/(2u_o) \quad (7.11)$$

$a$  is also known as the *induction* or *perturbation* factor.

Using Eqs 7.5, 7.7, 7.9 and 7.10, power extracted by the turbine may be written as:

$$P_t = 4 a (1-a)^2 \left( \frac{1}{2} \rho A_1 u_o^3 \right) \quad (7.12)$$

Comparing with Eq 7.4:

$$P_t = C_p P_o \quad (7.13)$$

where  $C_p$  is the fraction of available power in the wind that can be extracted and is known as *power coefficient*.  $C_p$  is given as:

$$C_p = 4 a (1-a)^2 \quad (7.14)$$

The variation of the power coefficient  $C_p$  with the interference factor  $a$  is shown graphically in Fig 7.11. The physical significance of the curve is discussed below:

When no load is coupled to the turbine, the blades just freewheel. There is no reduction of wind speed at the turbine, therefore,  $u_1 = u_o$  and the value of  $a$  is zero. The turbine does not generate any power and  $C_p = 0$ . The air just passes through the turbine without any reduction of speed.

Now as load is applied, power is extracted, so  $C_p$  increases as  $u_1'$  decreases. Maximum value of  $C_p$  (i.e.,  $C_{p\max} = 16/27 = 0.593$ ) occurs at  $a = 1/3$ . At this condition,

$$u_1' = \frac{2}{3} u_o \quad \text{and} \quad u_2' = \frac{1}{3} u_o$$

That means, at maximum power extraction condition, the upstream wind speed is reduced to two-third at the turbine and further reduced to one third downstream. The criterion for maximum power extraction, i.e.,  $C_{p\max} = 16/27$  is called the *Betz criterion*. This applies to an ideal case. For a commercial wind turbine, however, maximum power coefficient is less than ideal value.

When  $u_1' = 0$ ,  $a = 0.5$  and the simple model breaks down as no wind is predicted to be leaving downstream. In practice, this is equivalent to the onset of a turbulence downstream. Power extraction decreases due to mismatch of rotational frequency and wind speed and partial stalling begins. The turbine blades will still be turning, causing extensive turbulence in the air stream, leading to more losses. When the wind speed at the turbine is reduced to zero (i.e.,  $u_1' = 0$ ),  $a$  becomes unity and no power is extracted. This state is known as (complete) *stall state* of blades.

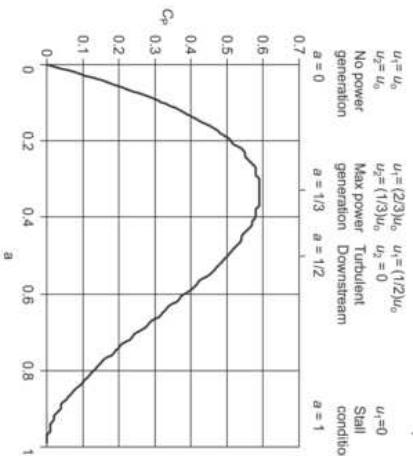
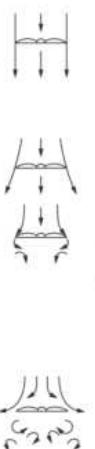


Fig. 7.11  $C_p$  versus  $a$

**Betz Criterion** In practice, all of the kinetic energy in the wind cannot be converted to shaft power since the air must be able to flow away from the rotor area. The Betz criterion, derived using the principles of conservation of

momentum and conservation of energy, suggests a maximum possible turbine efficiency, (or power coefficient) of 59%. In practice, power coefficients of 20–30 % are more common.

### 7.6.3 Axial Thrust on Turbine, $F_A$

With no energy extraction, Bernoulli's equation for upstream and downstream, (refer Fig. 7.10) may be written as

$$\rho_o u_o^2 / \rho_2 + g z_o + u_2^2 / 2 = \rho_2 u_2^2 / \rho_2 + g z_2 + u_2^2 / 2$$

As  $z_o = z_2$  and variation in air density is negligible compared to other terms, considering  $\rho$  as average air density, the static pressure difference across the turbine may be written as

$$\Delta p = \rho_o u_2^2 - \rho_2 u_2^2 = \left( u_o^2 - u_2^2 \right) \rho / 2$$

The maximum value of static pressure difference occurs when  $u_2$  approaches zero (which will be the situation for a solid disk). Thus,

$$\Delta p_{\max} = \rho u_o^2 / 2 \quad \text{and maximum thrust on the disk is}$$

$$F_{A\max} = A_1 \rho u_o^2 / 2 \quad (7.15)$$

On a horizontal machine, this thrust acts along the turbine axis and therefore is known as axial thrust  $F_A$ .

This axial thrust must be equal to loss of momentum of the air stream as given in Eq. 7.6, i.e.,

$$F_A = \dot{m} u_o - \dot{m} u_2$$

Using Eqs. 7.3, 7.9 and 7.10, we can write

$$F_A = 4 \sigma (1-\sigma) (A_1) \rho u_o^2 / 2 \quad (7.16)$$

$$\text{or } F_A = C_p F_{A\max} \quad (7.17)$$

$$\text{where } C_p = 4\sigma (1-\sigma) \quad (7.18)$$

Maximum axial thrust occurs when  $C_p = 1$ , which is achieved when  $\sigma = 0.5$ , equivalent to  $u_2 = 0$ . Maximum power extraction by the Betz criterion occurs when  $\sigma = 1/3$ , corresponding to  $C_p = 8/9$ .

### 7.6.4 Torque Developed by the Turbine, $T$

The maximum conceivable torque  $T_M$  on an ideal turbine rotor would occur if maximum circumferential force acts at the tip of the blade with radius R. Thus,

$$T_M = F_{A\max} R \quad (7.19)$$



$$T_M = \frac{P_o}{\mu_o} R \quad (7.20)$$

Now, if the tip-speed ratio  $\lambda$  is defined as

$$\lambda = \frac{\text{speed of tip of the rotor blade}}{\text{speed of oncoming air}} = \frac{R\omega}{\mu_o} \quad (7.21)$$

then,  $T_M$  can be written as

$$T_M = \frac{P_o \lambda}{\mu_o} \quad (7.22)$$

For a practical machine, where circumferential force is not concentrated at the tip but spread throughout the length of the blade, less shaft torque will be produced than what is given by Eq. 7.22. Thus, the shaft torque,  $T_{sh}$  is given as

$$T_{sh} = C_T T_M \quad (7.23)$$

where,  $C_T$  is known as torque coefficient.

As the product of shaft torque and angular speed equals power developed by the turbine,

$$T_{sh} \omega = P_T$$

$$\text{or } C_T T_M \omega = C_p P_o$$

Substituting for  $T_M$  from Eq. 7.22, we get,

$$C_T P_o \lambda = C_p P_o \quad (7.24)$$

$$\text{or } C_T = \frac{C_p}{\lambda}$$

Both  $C_T$  and  $C_p$  are functions of tip-speed ratio,  $\lambda$ . As per Betz criterion, the maximum value of  $C_p$  can be 0.593, therefore,

$$C_{T_{max}} = \frac{C_{p_{max}}}{\lambda} \quad (7.25)$$

Thus, machines with higher speeds have low value of  $C_{T_{MAX}}$  or low starting torque.

### 7.6.5 Dynamic Matching for Maximum Power Extraction

As per the Betz criterion, a turbine can theoretically extract a maximum of 59% of the available power in wind. However, this criterion tells nothing about dynamic rotational state of the turbine required to reach this maximum power condition. This aspect will be explored here.



**(a) Tip Speed Ratio** For constant wind speed, the power extraction by a turbine will decrease if

- the blades are so close together, or rotating so rapidly that a blade moves into the turbulence created by a preceding blade; or
- the blades are so far apart or rotating so slowly that much of the air passes through the cross section of the device without interacting with the blades.

Thus, for a particular wind speed, there exists an optimum turbine speed to produce maximum output. Therefore, to obtain optimum efficiency, it is important to match the rotational frequency of the turbine to the corresponding wind speed.

Let  $t_b$  be time taken by a blade to move into the position previously occupied by the preceding blade and  $t_w$  be the time for the disturbed wind moving past that position and normal air stream becoming re-established. For an  $n$  bladed turbine rotating at angular velocity of  $\omega$ ,

$$t_b = \frac{2\pi}{n\omega}$$

A disturbance at the turbine disk created by a blade into which the following blade moves will last for a time

$$t_w = d/u_0$$

where,  $d$  is the length of the wind strongly perturbed by the rotating blades.

The maximum power extraction occurs when  $t_w \approx t_b$  at the blade tips, where the blades sweep maximum incremental area. Thus

$$\frac{d}{u_0} \approx \frac{2\pi}{n\omega}$$

Multiplying both sides by  $R$ , the radius of the rotor disk and rearranging the terms,

$$\frac{R\omega}{u_0} \approx \frac{2\pi R}{nd} \quad (7.26)$$

The term on LHS of this equation has earlier been defined as tip-speed ratio, as per Eq. 7.21. Thus, the tip-speed ratio at optimum power extraction is

$$\lambda_o \approx \frac{2\pi}{n} \left( \frac{R}{d} \right) \quad (7.27)$$

Practical observations indicate that  $d \approx (l_z) R$  and therefore,

$$\lambda_o \approx \frac{4\pi}{n} \quad (7.28)$$

Thus, for a two-bladed turbine, the maximum power extraction ( $C_{p\max}$ ) occurs at  $\lambda_o \approx 2\pi$  and that for a four-bladed turbine at  $\lambda_o \approx \pi$ .

The relationship between  $C_p$  and  $\lambda$  for various types of rotors (types to be discussed in Section 7.7) is shown graphically in Fig. 7.12. The maximum practically obtainable value of the power coefficient is approximately 0.5. A wind turbine, achieving a value of power coefficient as 0.4 or above is considered to have good performance.

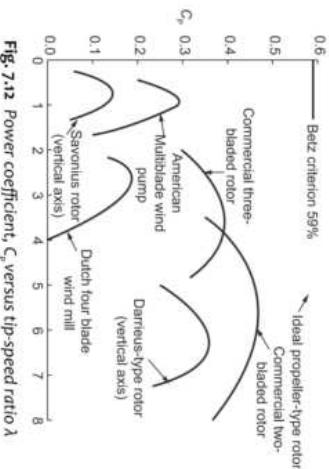


Fig. 7.12 Power coefficient,  $C_p$ , versus tip-speed ratio  $\lambda$

### (b) Blade-Setting Angle, $\gamma$ (or Blade Pitch Angle)

The output of a turbine is also greatly influenced by the blade pitch angle,  $\gamma$ . The effect of blade pitch on  $C_p-\lambda$  characteristics is illustrated in Fig. 7.13. Blade pitch control is a very effective way of controlling the output power, speed or torque.

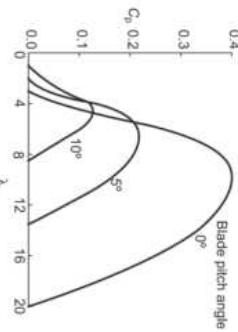


Fig. 7.13  $C_p-\lambda$  curves for different pitch angle settings

**Example**

A propeller-type wind turbine has the following data:  
Speed of free wind at a height of 10 m = 12 m/s  
Air density = 1.226 kg/m<sup>3</sup>  
 $\alpha = 0.14$

**7.1**

- Height of tower = 100 m  
Diameter of rotor = 80 m  
Wind velocity at the turbine reduces by 20%  
Generator efficiency = 85%  
Find  
 (i) total power available in wind  
 (ii) power extracted by the turbine  
 (iii) electrical power generated  
 (iv) axial thrust on the turbine  
 (v) maximum axial thrust on the turbine

**Solution**

From given data,

$$\begin{aligned} u_H &= 12 \text{ m/s}, & H &= 10 \text{ m}, & z &= 100 \text{ m} \\ \rho &= 1.226 \text{ kg/m}^3, & \alpha &= 0.14 & A_1 &= 5026.55 \text{ m}^2 \\ D &= 80 \text{ m} & & & \eta_{\text{Gen}} &= 0.85 \end{aligned}$$

$$\begin{aligned} u_1 &= 0.8 u_H, \\ \text{From Eq. 7.2, } u_r &= 16.565 \text{ m/s } u_1 \text{ and } u_1 &= 0.8 \times 16.565 \\ &= 13.252 \text{ m/s} \end{aligned}$$

- (i) From Eq. 7.4,  $P_o = 14 \text{ MW}$   
 (ii) From Eq. 7.10, the interference factor,  $\alpha = 0.2$

From Eq. 7.14, the power coefficient  $C_p = 0.512$

From Eq. 7.13, power extracted by the turbine  $P_T = 7.168 \text{ MW}$

- (iii) Electrical power generated =  $0.85 \times 7.168 = 6.09 \text{ MW}$   
 (iv) From Eq. 7.16, axial thrust on the turbine,  $F_A = 5.4 \times 10^5 \text{ N}$   
 (v) Maximum axial thrust occurs when  $\alpha = 0.5$  and  $C_p = 1$

$$F_{A_{\max}} = (A_1 \rho u_r^2 / 2) = 8.455 \times 10^5 \text{ N}$$

**Example**

The following data were measured for a HAWT:  
Speed of wind = 20 m/s at 1 atm and 27°C

Diameter of rotor = 80 m  
Speed of rotor = 40 rpm

Calculate the torque produced at the shaft for maximum output of the turbine.

**Solution**

Given:  $u_o = 20 \text{ m/s}$ ,  $P = 1 \text{ atm} = 1.01325 \times 10^5 \text{ Pa}$ ,

$$T = 273 + 27 = 300$$

$$\text{Radius of rotor R} = 40 \text{ m}$$

**7.2**



Speed of rotor  $\omega = 40 \text{ rpm} = (2\pi) \times (40/60) = 4.1888 \text{ rad/s}$

$$\rho = P/(RT) = 1.01325 \times 10^3 / (287 \times 300) = 1.177 \text{ kg/m}^3$$

Area of rotor  $A = \pi R^2 = 5026.548 \text{ m}^2$

For maximum output  $\sigma = 1/3$ ,  $C_{p,\max} = 0.593$

Tip-speed ratio  $\lambda = 40 \times 4.1888/20 = 8.378$

$$\text{From Eq. (7.3), } P_o = \frac{1}{2} (\rho A) \lambda^3 = 23.665 \text{ MW}$$

$$T_M = \frac{P_o}{\omega} R = 23.665 \times 40/20 = 47.33 \text{ N}$$

$$C_{T,\max} = \frac{C_{p,\max}}{\lambda} = 0.593/8.378 = 0.07078$$

Torque produced at the shaft at maximum output,  
 $T_{th,\max} = 47.33 \times 0.07078 = 3.35 \text{ N}$

### Example

A HAWT is installed at a location having free wind velocity of 15 m/s. The 80-m diameter rotor has three blades attached to the hub. Find the rotational speed of the turbine for optimal energy extraction.

## 7.3

Given:

Solution  
Rotor diameter = 80 m,  $R = 40 \text{ m}$

$$\frac{R}{h_o} = 15 \text{ m/s}, n = 3$$

From Eq. 7.28, tip-speed ratio for optimum output,

$$\lambda_o \approx \frac{4\pi}{n} = 4.188$$

From Eq. 7.21, tip-speed ratio is given by  $\lambda_o = \frac{R\omega}{h_o}$

$$4.188 = \frac{40 \times \omega}{15}$$

$$\omega = 1.57$$

If  $N$  is rotor speed in rpm,

$$\omega = 2\pi N/60$$

$$N = 15 \text{ rpm}$$

Therefore, for optimum energy extraction, rotor speed should be maintained at 15 rpm.

## WIND TURBINE TYPES AND THEIR CONSTRUCTION

**7.7** Wind turbines are broadly classified into two categories. When the axis of rotation is parallel to the air stream (i.e., horizontal), the turbine is said to be a Horizontal Axis Wind Turbine (HAWT), and when it is perpendicular to the air stream (i.e., vertical), it is said to be a Vertical Axis Wind Turbine (VAWT). The size of the rotor and its speed depends on rating of the turbine. Some of the features of HAWT estimated at wind speed of 12 m/s and  $C_p = 30\%$  are given in Table 7.3.

**Table 7.3** Typical wind turbine characteristics

Feature	Small			Medium			Large			Very Large		
	1.	2.	3.	1.	2.	3.	1.	2.	3.	1.	2.	3.
Rated power, kW	10	25	50	100	150	250	500	1000	2000	3000	4000	
Rotor diameter, m	6.4	10	14	20	25	32	49	64	90	110	130	
RPM	200	150	100	67	55	43	29	19	15	13	11	

### 7.7.1 Horizontal Axis Wind Turbine (HAWT)

HAWTs have emerged as the most successful type of turbines. These are being used for commercial energy generation in many parts of the world. Their theoretical basis is well researched and sufficient field experience is available with them.

#### A. Main Components

The constructional details of the most common, three-blade rotor, horizontal axis wind turbine is shown in Fig. 7.14. The main parts are as follows:

**Turbine Blades** Turbine blades are made of high-density wood or glass fibre and epoxy composites. They have an airfoil type of cross section. The blades are slightly twisted from the outer tip to the root to reduce the tendency to stall. In addition to centrifugal force and fatigue due to continuous vibrations, there are many extraneous forces arising from wind turbulence, gust, gravitational forces and directional changes in the wind. All these factors are to be taken care off at the designing stage. The diameter of a typical, MW range, modern rotor may be of the order of 100 m.

Modern wind turbines have two or three blades. Two/three blade rotor HAWT are also known as *propeller-type* wind turbines owing to their similarity with propellers of old aeroplanes. However, the rotor rpm in case of a wind turbine is

very low as compared to that for propellers. The relative merits and demerits of two-and three-blade rotors are as follows:

- (i) Compared to the two-blade design, the three-blade machine has smoother power output and balanced gyroscopic force.
- (ii) There is no need to teeter (to be discussed later in this section) the rotor, allowing the use of a simple rigid hub. The blades may be cross-linked for greater rigidity.
- (iii) Adding a third blade increases the power output by about 5% only, while the weight and cost of a rotor increases by 50%, thus giving a diminished rate of return for additional 50% weight and cost.
- (iv) The two-blade rotor is also simpler to erect, since it can be assembled on the ground and lifted to the shaft without complicated maneuvers during the lift.

Three blades are more common in Europe and other developing countries including India. The American practice, however, is in favour of two blades.

**Hub** The central solid portion of the rotor wheel is known as hub. All blades are attached to the hub. The mechanism for pitch angle control is also provided inside the hub.

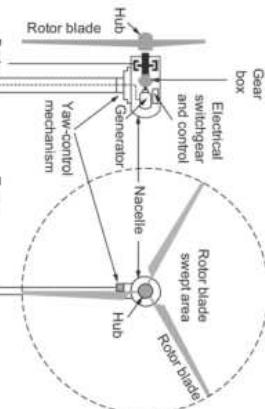


Fig. 7.14 Horizontal axis wind turbine

**Nacelle** The term *nacelle* is derived from the name for housing containing the engines of an aircraft. The rotor is attached to the nacelle, and mounted at the top of a tower. It contains rotor brakes, gearbox, generator and electrical switchgear and control. Brakes are used to stop the rotor when power generation is not desired. The gearbox steps up the shaft rpm to suit the generator. Protection and control functions are provided by switchgear and control block. The generated electrical power is conducted to ground terminals through a cable.

**Yaw-control Mechanism** The mechanism to adjust the nacelle around the vertical axis to keep it facing the wind is provided at the base of the nacelle.

**Tower** The tower supports the nacelle and rotor. For medium and large sized turbines, the tower is slightly taller than the rotor diameter. In case of a small-sized turbine, the tower is much larger than the rotor diameter as the air is erratic at lower heights. Both steel and concrete towers are being used. The construction can be either tubular or lattice type.

The tower vibrations and resulting fatigue cycles under wind speed fluctuations are avoided by careful design. This requires avoidance of all resonance frequencies of tower, the rotor and the nacelle from the wind-fluctuation frequencies.

### B. Types of Rotors

Depending on the number of blades, wind speed and nature of application, rotors have been developed in various types of shapes and sizes. These are shown in Fig. 7.15. The types of rotors shown in (a) to (e) are relatively high-speed ones, suitable for applications such as electrical power generation. Large HAWTs have been manufactured with two and three blades. A single blade rotor, with a balancing counterweight is economical, has simple controls but it is noisier and produces unbalanced forces. It is used for low-power applications. Those given in (f) and (g) are low-speed rotors and most suited for water-lifting applications, which require a high starting torque. They can capture power even from very slow winds.

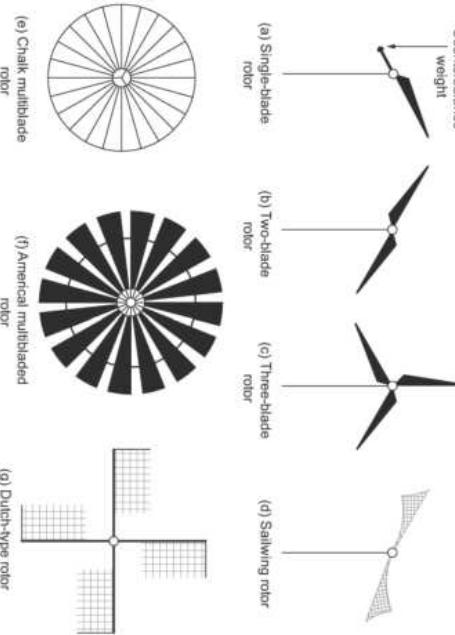


Fig. 7.15 Various types of rotors for HAWT

### C. Teetering of Rotor

As wind speed rises with height, the axial force on blade when it attains the upper position is significantly higher as compared to that when it is at a lower position. For one-and two-blade rotors, this causes cyclic (sinusoidal) load on a rigid hub leading to fatigue. This is greatly relieved by providing a teeter hinge (a pivot within the hub) that allows a see-saw motion to take place out of the plane of rotation (i.e., vertical plane). The rotor leans backwards to accommodate the extra force as shown in Fig. 7.16. This also reduces blade loads near the root by approximately 40%. The use of a third blade has approximately the same effect as a teeter hinge on the hub moments since the polar symmetry of the rotor averages out the applied sinusoidal loads. Therefore, teetering is not required when the number of blades is three or more.

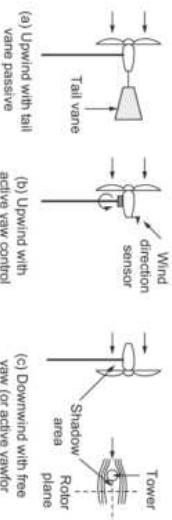
### D. Upwind and Downwind Machines

In an upwind machine, the rotor is located upwind (in front) of the tower whereas in a downwind machine, the rotor is located downwind of (behind) the tower as shown in Fig. 7.17. Both types have certain benefits. A downwind machine allows the use of a free yaw system (in low rating machines). It also allows the blades to deflect away from the tower when loaded. However, it suffers from **wind shadow** effects of the tower on the blades as they pass through the tower's wake, in a region of separated flow. For a high-solidity tower with limited rotor overhang, the wind speed might be effectively reduced to zero causing a severe impulsive load of periodic nature. This may be very dangerous as it may excite any natural mode of the systems if that lies near a rotor harmonics.

An upwind machine, on the other hand, produces higher power as it eliminates the tower shadow on the blades. This also results in lower noise, low blade fatigue and smoother power output.

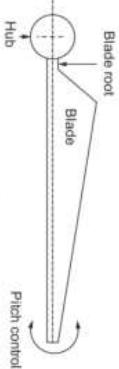
### E. Yaw-control System

Adjusting the nacelle about the vertical axis to bring the rotor facing the wind is known as *yaw control*. The yaw-control system continuously orients the rotor in the direction of wind. For localities with a prevailing wind in one direction only, the rotor can be in a fixed orientation. Such a machine is said to be *yaw fixed*. Most wind turbines however, are *yaw active*. In small wind turbines, a tail vane is used for passive yaw control. In large turbines however, an active yaw control with power steering and wind direction sensor is used to maintain the orientation.



**Fig. 7.17 Yaw control in upwind and downwind machines**

## F. Pitch Control System



**Fig. 7.18 Pitch control**

The pitch of a blade is controlled by rotating it from its root, where it is connected to the hub as shown in Fig. 7.18. The pitch control mechanism is provided through the hub using a hydraulic jack in the nacelle. The control system continuously adjusts the pitch to obtain optimal performance. In modern machines, pitch control is incorporated by controlling only the outer 20% length of the blade (i.e., tip), keeping the remaining part of the blade as fixed.

## 7.7.2 Vertical Axis Wind Turbine (VAWT)

VAWTs are in the development stage and many models are undergoing field trial. The main attractions of a VAWT are

- (i) it can accept wind from any direction, eliminating the need of yaw control,
- (ii) the gearbox, generator, etc., are located at the ground, thus eliminating the heavy nacelle at the top of the tower, thus simplifying the design and installation of the whole structure, including the tower,
- (iii) the inspection and maintenance also gets easier, and
- (iv) it also reduces the overall cost.

### A. Main Components

The constructional details of a vertical axis wind turbine (Darrieus-type rotor) are shown in Fig. 7.19. The details of the main components are as follows:

**Tower (or Rotor Shaft)** The tower is a hollow vertical rotor shaft, which rotates freely about the vertical axis between the top and bottom bearings. It is installed above a support structure. In the absence of any load at the top, a very strong tower is not required, which greatly simplifies its design. The upper part of the tower is supported by guy ropes. The height of the tower of a large turbine is around 100 m.

**Blades** It has two or three thin, curved blades shaped like an eggbeater in a profile, with blades curved in a form that minimizes the bending stress caused by centrifugal forces—the so called 'Troposkién' profile. The blades have an airfoil cross section with constant chord length. The pitch of the blades cannot be changed. The diameter of the rotor is slightly less than the tower height. The first large (3.8 MW), Darrieus type, Canadian machine has a rotor height as 9.4 m and the diameter as 65 m with a chord of 2.4 m.

**Support Structure** The support structure is provided at the ground to support the weight of the rotor. Gearbox, generator, brakes, electrical switchgear and controls are housed within this structure.

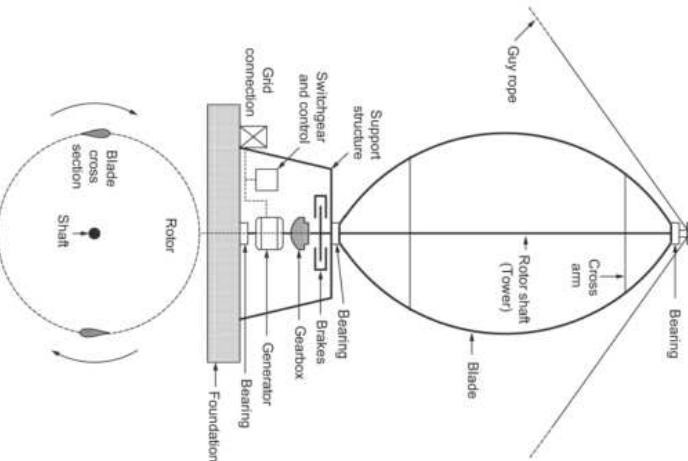


Fig. 7.19 Vertical axis wind (Darrieus) turbine



### B. Types of Rotors

Various types of rotors for VAWTs are shown in Fig. 7.20, the simplest being a three- or four-cup structure attached symmetrically to a vertical shaft. The drag force on the concave surface of the cup facing the wind is more than that on the convex surface. As a result, the structure starts rotating. Some lift force also helps rotation. However, it cannot carry a load and therefore cannot be used as power source. The main characteristic of this rotor is that its rotational frequency is linearly related to wind speed. Therefore, it is used as a transducer for measuring the wind speed and the apparatus is known as *cup anemometer*.

The Savonius or S-rotor consists of two half cylinders attached to a vertical axis and facing in opposite directions to form a two-bladed rotor. It has high starting torque, low speed and low efficiency. It can extract power even from very slow wind, making it working most of the time. These are used for low-power applications. A high starting torque particularly makes it suitable for pumping applications, using positive displacement pumps.

The Darrieus rotor is used for large-scale power generation. Its power coefficient is considerably better than that of an S-rotor. It runs at a large tip-speed ratio. The aerodynamic force on the blade reverses in every revolution, causing fatigue. This, along with centrifugal force, complicates the design of the blade. One of the drawbacks of this rotor is that it is usually not self-starting. Movement may be initiated by using electrical generator as motor. As the pitch of the blade cannot change, the rotor frequency and, thus, the output power cannot be controlled. Rotor frequency increases with wind speed and power output keeps on increasing till the blades stall. Hence, at high wind speed it becomes difficult to control the output. For better performance and safety of the blades, gearbox and generator, it is desirable to limit the output to a level much below its maximum possible value.

Musgrave suggested the use of an H-shaped rotor where blades with a fixed pitch are attached vertically to a horizontal cross arm. Power control is achieved by controlled folding of the blades. Inclining the blades to the vertical provides an effective means of altering the blades angle of attack and hence controlling the power output.

The Evans rotor, also known as gyromill, is an improvement over the H-shaped rotor. Here, the rotor geometry remains fixed (blades remain straight), but the blades are hinged on a vertical axis and the blade pitch is varied cyclically (as the blade rotates about the vertical axis) to regulate the power output. But the need to vary the pitch cyclically through every rotor revolution introduces considerable mechanical complexity. However, this enables it to self-start.

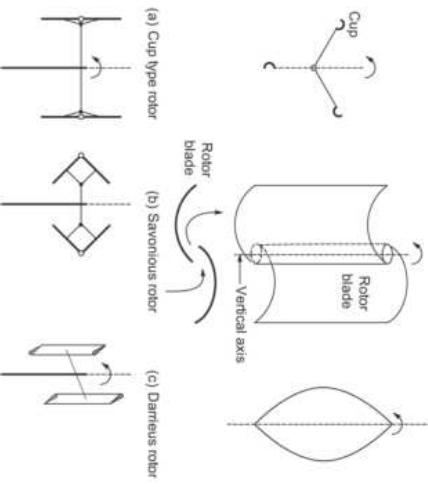


Fig. 7.20 Various types of rotors for VAWT

### 7.7.3 Lift-and Drag-Type Machines

Wind turbines make use of either lift force or drag force predominantly to cause motion and accordingly are known as lift or drag-type machines. In lift devices, the ratio of lift to drag forces may be as high as 30:1. For the drag design, the wind literally pushes the blades out of the way. Drag devices are less efficient and turn slower than wind. They produce high torque and thus are suitable for pumping applications. At high wind speeds, they spill wind instead of producing more energy. Thus, they do not benefit from high-energy density available in wind.

The lift-blade design employs the same principle that enables aeroplanes, kites and birds to fly. The blade is essentially an airfoil, or wing. When air flows past the blade, a wind speed and pressure differential is created between the upper and lower blade surfaces. The pressure at the lower surface is greater and thus acts to 'lift' the blade. When blades are attached to a central axis, like a wind turbine rotor, the lift is translated into rotational motion. Lift-powered wind turbines have much higher rotational speeds than drag types and, therefore are well suited for electricity generation. Lift devices are more efficient and turn faster than wind. They are able to benefit from high-power densities available in strong winds. The ratio of power extracted from wind by a lift device to that of a drag device is usually greater than 3:1 for the same swept area. Lift-type rotors often use tapered and/or twisted blades to reduce bending strains and improve the stalling performance. The types and characteristics of various types of rotors are given in Table 7.4.

**Table 7.4** Characteristics of various types of rotors

SN <sup>1</sup>	Rotor type	Tip speed ratio	RPM	Torque	Tip load
1.	Propeller (1-3 blades) (Lift)	6-20	High	Low	Electric power generation
2.	Sailwing (Lift)	4	Moderate	Moderate	Electric power generation or pump
3.	Chalk multiblade (Lift)	3-4	Moderate	Moderate	Electric power generation or pump
4.	American multiblade (Drag)	1	Low	High	Pump
5.	Dutch type (Drag)	2-3	Low	High	Pump
6.	Savonious (Drag)	1	Low	High	Pump
7.	Durrieus (Lift)	5-6	High	Low	Electric power generation
8.	Mosgrove and Egan (Lift)	3-4	Moderate	Moderate	Electric power generation or pump

#### 7.7.4 Effect of Solidity

High-solidity rotors use drag force and turn slower. The solidity of the Savonious rotor is unity, and that of the American multiblade rotor is typically 0.7. Low solidity rotors, on the other hand, use lift force. Lift devices usually have solidity in the range of 0.01 to 0.1. They have slender airfoil blades. When solidity is less than 0.1, the device will usually not start up without first being rotated to generate lift.

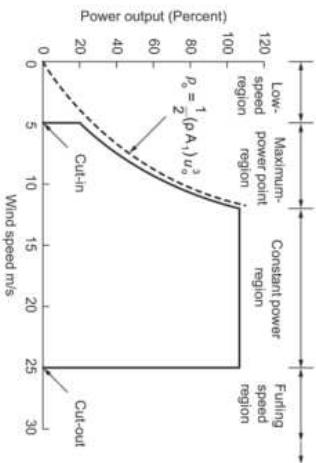
#### 7.7.5 Horizontal Axis Versus Vertical Axis Turbines

Most wind turbines used at present are of horizontal axis type. They have been well researched and have gone through extensive field trial. As a result, well-established technology is available for HAWTs. Some advantages of VAWT have recently generated considerable interest in this type of turbine. These are (i) it can accept wind from any direction without adjustment which avoids the cost and complexity of a yaw-orientation system, (ii) gearing and generators, etc., are located at ground level, which simplifies the design of tower, the installation and subsequent inspection and maintenance, and (iii) also they are less costly as compared to HAWTs.

The principal disadvantages of VAWTs are (i) many vertical-axis machines have suffered from fatigue arising from numerous natural resonances in the structure, (ii) rotational torque from the wind varies periodically within each cycle, and thus unwanted power periodicities appear at the output, (iii) it normally requires

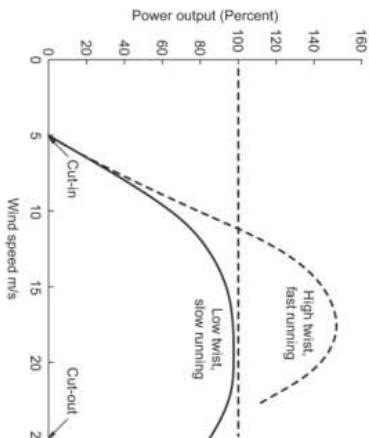
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designed as to crudely maintain the speed as constant. Such a machine is known as *stall regulated*. This is a simple system requiring only passive technique, as there are no moving blade surfaces or complicated hardware. However, power capture is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



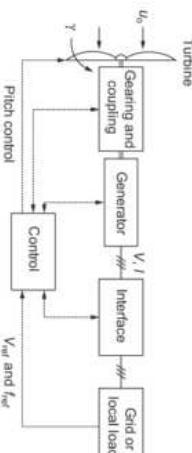
At still higher wind speeds, such as gusts, constant speed operation is maintained by employing additional means such as some kind of braking (e.g., eddy current braking).

#### (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.

### **WIND ENERGY CONVERSION SYSTEMS (WECS)**

**7.8** 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.



**(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.

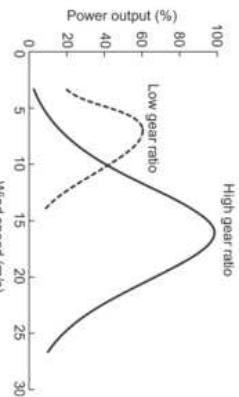


Fig. 7.24 Power output Vs wind speed for two fixed-speed drives

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.

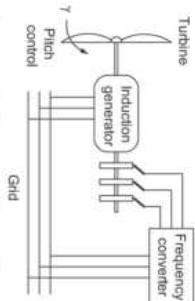
Apart from higher energy yield, use of power electronics offers remotely adjustable and controllable quality of power. This has two major benefits not

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 requirements is easy and change of speed setting is made without

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available in other systems: (i) opportunity for remote control which makes it attractive for offshore applications, (ii) and fine tuning for superior grid connection, to make it better suited for meeting the demand of weak grids.

Use of power electronics adds to the cost, electrical noise and losses of the system. However, the cost and benefit trade is generally positive for large machines.



**Fig. 7.25** Scherbius variable speed drive  
contacts at the slip rings lead to increased maintenance and the range of speed control is generally limited to 2:1.

### (c) **Scherbius Variable Speed Drive**

Scherbius drive makes use of wound rotor induction machine. The stator is connected to the grid and rotor is connected to variable frequency source via slip rings, as shown in Fig. 7.25. The speed is controlled by controlling the frequency of the external voltage injected into the rotor. It offers lower cost and eliminates the power quality disadvantages. However, sliding

contacts at the slip rings lead to increased maintenance and the range of speed control is generally limited to 2:1.

### (c) **Variable Speed Direct Drive**

In this scheme, the generator is directly coupled to the turbine shaft without gear and operates at turbine speed. Also, it does not make use of power electronics. The main benefits are: (i) the lower nacelle weight, (ii) reduced noise and vibration, (iii) lower power loss, and (iv) less frequent servicing requirement at the nacelle, which is particularly very attractive for offshore installations. For small-sized turbines, where the rotor speed is high, direct coupling to the generator is possible without much difficulty. Large rotors turn slowly and direct coupling requires large number of poles on electrical machines, which impose design limitations. To circumvent such limitations, the permanent-magnet synchronous machines with large number of poles are being considered. Another possible solution is the use of axial gap induction machines, where a large number of poles can be designed with less difficulty compared to conventional radial-gap induction machines. These systems are still under development stage and various alternatives are being tried.

## WIND-DIESEL HYBRID SYSTEM

**7.9** There are many remote and isolated areas in the world where utility power grid has no access due to techno-economic reasons. Power to such places is supplied by small locally installed diesel generator unit. In such places wind electricity may be very economical if favourable wind is available. Unfortunately, wind is a highly fluctuating power source and the raw output at the terminals of a wind turbine is incompatible with the demand of a normal domestic or commercial user. In such places isolated wind turbines can be installed in conjunction with diesel-generating units for backup. This hybrid system, popularly known as a

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.

*Methanogy*, 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

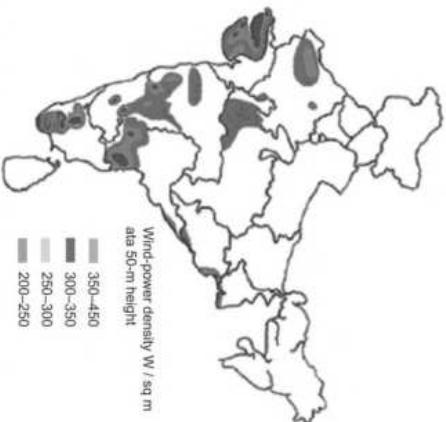
**(vii) Effects on Ecosystems** Large-scale use of wind generation can reduce wind speed and cause stress to an ecosystem. Lakes that are downhill from the wind turbines might become warmer because of reduced evaporation from their surface. Soil moisture might also increase. Nevertheless, these impacts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

### WIND-ENERGY PROGRAMME IN INDIA

**7.13** 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<sup>2</sup> (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 statewide 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, Karnataka, is given in Fig. 7.28.

**Table 7.5** Statewise wind power (Source: MNRES Annual Report, 2007–08)<sup>[54]</sup>

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 Joggimatti (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.



As many as 15 manufacturers are engaged in the production of wind turbine equipments. A large number of companies have tied up with foreign wind-turbine manufacturers for joint-Venture/licensed production of WECS in India. Wind turbines of unit size up to 750 kW are being manufactured in the country. Up to 250-kW capacities, on an average of up to 80% indigenization have been achieved. The current annual production capacity of domestic wind turbines is about 2000 MW. During 2007–08 (up to 31.12.2007), indigenously produced wind turbines valued at about US\$ 425 million have been exported to USA, Europe, Australia, Spain, Portugal and Brazil. This apart, wind turbine blades valued at US\$ 50 million have been exported to Germany, China and Spain.

Research and development activities are being undertaken through research institutions, national laboratories, universities and industry for the development of cost-effective technologies and systems to improve the quality of power generation from wind. R and D activities are coordinated through the Centre for Wind Energy Technology (C-WET).

### *Review Questions*

1. What range of wind speed is considered favourable for wind-power generation?
2. What factors led to accelerated development of wind power?
3. With the help of a diagram, indicate the circulation of global winds. What are the forces responsible for determining the speed and direction of global winds?
4. Explain the mechanism of production of local winds.
5. What are the factors responsible for distribution of wind energy on the surface of the earth?
6. What do you understand by gust?
7. What principles may be used for measurement of wind speed? What is the standard height for measurement of wind speed?
8. What are the advantages of presenting the wind data in the form of a wind rose?
9. With the help of a diagram, explain the nature of variation of wind speed with height from the ground. Explain the terms: wind shear, gradient height, free atmosphere, planetary boundary, surface layer and Ekman layer.
10. What are the most favourable sites for installing of wind turbines?
11. Explain the major applications of wind power.
12. With the help of a diagram, explain the terms: free and relative wind velocities, drag and lift forces, solidity, pitch angle and chord.
13. What do you understand by attached and separated flow? With the help of a diagram, show attached and stalled flow. What are the main features of stalled flow? How is the stalled performance improved?
14. Derive an expression for energy available in the wind.
15. Using Betz model of a wind turbine, derive the expression for power extracted from wind. What is the maximum theoretical power that can be extracted and under what condition?
16. Derive the expression for maximum axial thrust experienced by a wind turbine and also find the condition for such operation.
17. Explain the variation of power output of a wind turbine with tip speed of the rotor.

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18. Sketch the diagram of a HAWT and explain the functions of its main components.
19. Explain various designs of blades of HAWTs and their relative features.
20. What do you understand by teetering of rotor? In what cases is it required?
21. What do you understand by upwind and downwind machines, yaw active and yaw fixed machines?
22. Sketch the diagram of a VAWT and explain the functions of its main components.
23. Explain various designs of blades of VAWTs and their relative features.
24. What are the relative features of drag and lift-type machines?
25. What are the effects of solidity on the performance of a wind turbine?
26. Comment on the relative features of HAWT and VAWT.
27. With the help of a diagram, discuss the power versus wind-speed characteristics of a wind turbine.
28. Discuss the relative performances of a pitch-regulated and stall-regulated wind turbine.
29. With the help of block diagram, explain the functions of various blocks of a WECS.
30. Evaluate the suitability of various types of generators for wind-power generation.
31. Discuss various types of drive schemes used in wind turbines.
32. Explain the main features of wind-diesel hybrid generating systems. Also, point out various types of operational scheduling for diesel unit.
33. Comment on the environmental impacts of wind energy.

### Problems

1. The following data were recorded for a two-blade HAWT:  
Average free wind speed at a standard height of 10 m = 8 m/s  
 $\alpha = 0.13$   
Air density =  $1.226 \text{ kg/m}^3$   
Hub height from the ground = 80 m  
Rotor diameter = 60 m  
Downstream wind velocity is half that of upstream wind.  
Find  
 (i) power available in the wind  
 (ii) power extracted by the turbine  
 (iii) axial force on the turbine  
 (iv) axial force on the turbine  
 (a) when maximum power is extracted, and  
 (b) when no power is extracted and the blade stalls completely.
- (Ans. 1.995 MW, 1.1219 MW,  $1.429 \times 10^5 \text{ N}$ ,  $1.693 \times 10^5 \text{ N}$ , zero)
2. A HAWT has the following data:  
Speed of wind = 10 m/s at 1 atm and  $15^\circ\text{C}$   
Diameter of rotor = 120 m  
Speed of rotor = 40 rpm  
Calculate the maximum possible torque produced at the shaft.
- (Ans. 0.98 N)
3. A two-blade HAWT is installed at a location with free wind velocity of 20 m/s. The rotor diameter is 30 m. What rotational speed should be maintained to produce maximum output?
- (Ans. 80 rpm)

### Objective-type Questions

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1. The range of wind speed suitable for wind power generator is
  - (a) 0 to 5 m/s
  - (b) 5 to 25 m/s
  - (c) 25 m/s to 50 m/s
  - (d) 50 m/s to 75 m/s
2. Favourable winds for small-scale applications exists
  - (a) everywhere on the earth's surface
  - (b) on 75% of the earth's surface
  - (c) on 50% of the earth's surface
  - (d) on 25% of the earth's surface
3. Compared to conventional sources of power such as thermal plants, the cost of wind power is
  - (a) 100 times
  - (b) 10 times
  - (c) comparable
  - (d) 1/10 times
4. The energy payback period of wind generation is
  - (a) 1 year
  - (b) 2 years
  - (c) 3 years
  - (d) 4 years
5. There is little wind in the
  - (a) North pole region
  - (b) South pole region
  - (c) tropical region
  - (d)  $\pm 5^\circ$  around the equator
6. When solar radiation falls on the earth's surface, the temperature of
  - (a) land mass rises faster than water mass
  - (b) land mass rises slower than water mass
  - (c) land mass and water mass rises uniformly
  - (d) only land mass increases and water remains at fixed temperature
7. A wind turbine extracts maximum power from wind, when the downstream wind speed reduces to
  - (a) one-third that of upstream wind
  - (b) half that of upstream wind
  - (c) two-third that of upstream wind
  - (d) zero
8. Stalled flow occurs when the value of the incident angle is
  - (a) 0 degree
  - (b) 180 degrees
  - (c) in range from 0 to 16 degrees (approximately)
  - (d) beyond 16 degrees
9. If the speed of a wind stream remains unchanged while passing through the rotor,
  - (a) a large power will be generated
  - (b) zero power will be generated
  - (c) the flow is known as stalled flow
  - (d) the speed of the rotor will be very high
10. As per Betz criterion, the maximum energy extractable by an ideal wind turbine is
  - (a) 25% of that available in wind
  - (b) 39% of that available in wind
  - (c) 49% of that available in wind
  - (d) 59% of that available in wind
11. The maximum axial thrust occurs when interference factor  $\sigma$  is
  - (a) 0
  - (b) 0.33
  - (c) 0.5
  - (d) 1.0
12. A two-blade wind turbine produces maximum power when the tip-speed ratio is equal to
  - (a)  $\pi$
  - (b)  $2\pi$
  - (c)  $3\pi$
  - (d) 0.593
13. The wind turbine rotor having a low value of solidity
  - (a) runs slower
  - (b) runs faster
  - (c) produces high torque
  - (d) has low efficiency

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14. Stall regulation is used with turbines  
(a) having diameters less than 25 m  
(c) having rotors of large solidity
15. Grid-connected wind generators usually have maximum penetration of:  
(a) 10 to 20%      (b) 20 to 30%      (c) 30 to 40%      (d) 40 to 50%
16. As per the size of installed capacity of wind-power generation in the world, India ranks  
(a) first      (b) second      (c) third      (d) fourth
17. Potential sites for wind generation are those having average energy densities of  
(a) 25–50 W/m<sup>2</sup>      (b) 50–100 W/m<sup>2</sup>      (c) 100–200 W/m<sup>2</sup>      (d) 200 W/m<sup>2</sup> or more



# Biomass Energy

## *Introduction*

# 8

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 biofuels 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  $250 \times 10^9$  t/yr. The associated energy bound in photosynthesis is  $2 \times 10^{11}$  J/yr ( $0.7 \times 10^{11}$  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

- it is a renewable source,
- the energy storage is an in-built feature of it,
- it is an indigenous source requiring little or no foreign exchange,
- the forestry and agricultural industries that supply feed stocks also provide substantial economic development opportunities in rural areas,
- the pollutant emissions from combustion of biomass are usually lower than those from fossil fuels,
- commercial use of biomass may avoid or reduce the problems of waste disposal in other industries, particularly municipal solid waste in urban centres,
- 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,
- 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
- varying capacity can be installed; any capacity can be operated, even at lower loads, with no seasonality involved.

Its main disadvantages are:

- it is a dispersed and land-intensive source,
- it is often of low energy density,
- 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,
- capacity is determined by availability of biomass and not suitable for varying loads, and
- not feasible to set up at all locations.

## PHOTOSYNTHESIS PROCESS

**8.1**

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  $\text{CO}_2$  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.



The generalized symbol  $\text{C}_x (\text{H}_2\text{O})_y$  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

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



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  $\text{CO}_2$ ,  $\text{H}_2\text{O}$  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:



$\Delta Q$  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  $\Delta Q$  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  $\text{CO}_2$  by a plant leaf is function of many factors, especially temperature,  $\text{CO}_2$  concentration and the intensity and wavelength distribution of light. Solar radiation incident on a leaf is reflected, transmitted and absorbed.

Fig. 8.1 Photosynthesis and respiration processes in a plant

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.

### USABLE FORMS OF BIOMASS, THEIR COMPOSITION AND FUEL PROPERTIES

**8.2 Biomass** 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 (*dhulla*), 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'.



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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  $78^\circ C$  and energy density is  $26.9 \text{ MJ/kg}$ . 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 *lignin* (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, 0.5–0.7% with trace amounts of  $O_2$  and  $H_2S$ . Its energy density is about  $23 \text{ MJ/m}^3$ . 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<sub>2</sub>, 1% CH<sub>4</sub>, 11% CO<sub>2</sub> and the rest N<sub>2</sub>. It has a typical energy density of 4.8 MJ/m<sup>3</sup> (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.

### 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., *jyotiba* (a shrub, producing nuts) and *karanji* (a tree generally seen on roadsides in India, produces small seed(s) that take care of themselves, and (b) agricultural crops, e.g., *Jatropha curcas* (*Karunjal*) 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

## Biomass Energy

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*, *caster oil*, *soybean*, *groundnut* and *sunseed*. 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*, *kefir, 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.

## BIOMASS CONVERSION TECHNOLOGIES

### 8.4

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*.



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Fuel oils can be extracted from plant products by expelling them. Also, light hydrocarbons may be obtained from certain plants in the same way as production of rubber.

**(i) Pelletization** Pelletization is a process in which waste wood is pulverized, dried and forced under pressure through an extrusion device. The extracted mass is in the form of pellets (rod; 5 to 10 mm dia and 12 mm long), facilitating its use in steam power plants and gasification system. Pelletization reduces the moisture to about 7 to 10 per cent and increases the heat value of the biomass.

**(ii) Briquetting** Biomass briquettes are made from woody matter (e.g., agricultural waste and saw dust), are a replacement for fossil fuels such as oil or coal and can be used to heat boilers in manufacturing plants. Burning a wood briquette is far more efficient than burning firewood. The moisture content of a briquette can be as low as 4%, whereas for green firewood, it may be as high as 65%.

Briquetting is brought about by compression and squeezing out moisture and breaking down the elasticity of the wood and bark. If elasticity is not sufficiently removed, the compressed wood will regain its pre-compression volume. Densification is carried out by compression under a die at high temperature and pressure. It is a process similar to forming a wood pellet but on a larger scale. There are no binders involved in this process. The natural lignin in the wood binds the particles of wood together to form a solid piece.

Sawdust briquettes have developed over time with two distinct types: those with holes through the centre, and those which are solid. A solid briquette is manufactured using a piston press which simply sandwiches layers of sawdust together, and ones which have a hole are produced using a screw press. The hole is simply a by-product of the screw thread passing through the centre. The screw-press briquettes are more homogeneous, have better crushing strength and better storage properties with extraordinary combustion properties due to large surface area per unit weight.

**(iii) Expelling Agro Products** Concentrated vegetable oils may be obtained from certain agro products and may be used as fuel in diesel engines. However, difficulties arise with direct use of plant oil due to high viscosity and combustion deposits. Therefore, these oils are upgraded by a chemical method known as *trans-esterification* to overcome these difficulties. Categories of certain materials with examples are as follows:

- Seeds Sunflower, rapeseed, soya beans
- Nut Oil palm, coconut copra, jojoba nuts
- Fruits Olive
- Leaves Eucalyptus



**(iv) Fuel Extraction** Occasionally, milky latex is obtained from freshly cut plants. The material is called *exudates* and is obtained by cutting (tapping) the stems or trunks of living plants (a technique similar to that used in rubber production). Some plants are not amenable to tapping and in such cases, the whole plant (usually a shrub) is crushed to obtain the product. For example, the *Euphorbia lathyris* plant is crushed to extract hydrocarbons of less molecular weight than rubber, which may be used as a petroleum substitute.

#### 8.4.2 Incineration

Incineration means direct combustion of biomass for immediate useful heat. The heat and/or steam produced are either used to generate electricity or provide the heat for industrial process, space heating, cooking or district heating.

Furnaces and boilers have been developed for large-scale burning of various types of biomass such as wood, waste wood, black liquid from pulp industry, food industry waste, and MSW. The moisture content in the biomass and wide range of composition tends to decrease the efficiency of conversion. However, the economic advantage of cogeneration makes it attractive for adoption.

#### 8.4.3 Thermochemical

The basic thermochemical process to convert biomass into a more valuable and/or convenient product is known as *pyrolysis*. Biomass is heated either in absence of oxygen or by partial combustion of some of the biomass in restricted air or oxygen supply. Pyrolysis can process all forms of organic materials including rubber and plastics, which cannot be handled by other methods. The products are three types of fuels—usually, a gas mixture ( $H_2$ ,  $CO$ ,  $CO_2$ ,  $CH_4$  and  $N_2$ ), an oil-like liquid (a water-soluble phase including acetic acid, acetone, methanol and a non-aqueous phase including oil and tar) and a nearly pure carbon char. The distribution of these products depends upon the type of feedstock, the temperature and pressure during the process and its duration and the heating rate.

High temperature pyrolysis (~1000°C) maximizes the gaseous product. The process is known as *gasification*. Low temperature pyrolysis (up to 600 °C) maximizes the char output. The process has been used for centuries for production of charcoal. The process is known as *carbonization*. A liquid product is obtained through catalytic *liquefaction* process. Liquefaction is a relatively low temperature (250–450°C), high-pressure (270 atm) thermochemical conversion of wet biomass, usually with high hydrogen partial pressure and also a catalyst to enhance the rate of reaction and/or to improve the selectivity of the process.

#### 8.4.4 Biochemical

The process makes use of metabolic action of microbial organisms on biomass to produce liquid and gaseous fuel. Two major biochemical processes are explained below:

**(a) Ethanol Fermentation** Alcoholic fermentation is the decomposition in the absence of air of simple hexose sugars (sugars containing six carbon atoms per molecule, i.e.,  $C_6H_{12}O_6$ ) in aqueous solution by the action of an enzyme (a natural catalyst) present in yeast, in acidic conditions ( $p^H$  value of 4 to 5). Thus,



The products are ethanol and carbon dioxide.

**(b) Anaerobic Fermentation (Anaerobic Digestion)** This process converts decaying wet biomass and animal wastes into biogas through the decomposition process by the action of anaerobic bacteria (bacteria that live and grow in absence of oxygen). Carbon present in biomass may be ultimately divided between fully oxidized  $CO_2$  and fully reduced  $CH_4$ . Thus,



The biomass material in the form of water slurry is digested by the bacteria anaerobically for several days in an airtight container. The reactions are slightly exothermic and a small amount of heat (equivalent to 1.5 MJ per kg dry digestible material) is also generated that helps in maintaining a favourable temperature. The process may be expedited at somewhat higher temperature. The most useful biomass materials appear to be animal manure, algae, kelp, hyacinth, plant residues and other organic waste materials with high moisture content. The energy available from various biomass resources is listed in Table 8.1.

**Table 8.1** Energy available from various biomass resources

SN	Biomass source	Biofuel produced	Conversion technology	Available energy (MJ/kg)
1.	Wood chips, saw mill dust, forest residues	(Direct heat)	Incineration	16-20
2.	Wood chips, saw mill dust, forest residues	Gas Oil Char	Pyrolysis	40 (Nitrogen removed) 40 20
3.	Grain crops	Straw	Incineration	14-16
4.	Sugar-cane residue	Bagasse	Incineration	5-8 (fresh cane)
5.	Urban refuse	(Direct heat)	Incineration	5-16 (dry input)
6.	Sugar-cane juice	Ethanol	Fermentation	3-6 (fresh cane)
7.	Animal waste	Biogas	Anaerobic digestion	4-8 (dry input)
8.	Municipal sewage	Biogas	Anaerobic digestion	2-4 (dry input)



## 8.5

### URBAN WASTE TO ENERGY CONVERSION

#### 8.5.1 MSW Incineration Plant

Municipal solid waste is the solid waste generated by households, commercial and institutional operations and some industries. Disposal of MSW is a major problem in big cities where large quantities of waste is to be disposed of far away from the city centres. The emerging solution is to use this waste biomass as an energy resource in a waste-to-energy conversion plant near the city centre. The energy thus generated is used within the city itself and only a relatively small residue of used biomass (ash, etc.) is disposed away in landfills. Through incineration or gasification, electrical energy may be generated along with thermal energy for process heat. Alternatively, anaerobic digestion may be used to produce methane.

The composition of urban waste depends on the style and standard of living of the people. A general national profile of waste in USA is given in Table 8.2. The energy content of domestic refuse differs significantly from area to area. Generally, it lies in the range 4.2 to 14 MJ/kg.

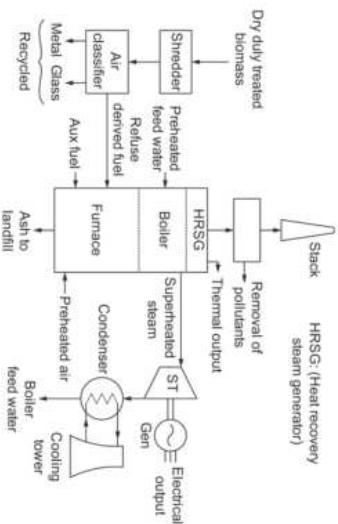
**Table 8.2** General composition of urban waste in USA

SN	Waste material	Percentage
1.	Paper and paper board	39.2
2.	Food and yard waste	21
3.	Glass	6.2
4.	Metals	7.6
5.	Plastics, rubber	9.1
6.	Wood	7.1
7.	Others (including hazardous wastes e.g. chemicals, lead, insecticides, house hold cleaning chemicals etc.)	9.8

A block diagram of MSW-to-energy incineration plant showing the sequence of various steps is shown in Fig. 8.3. The dry biomass is shredded to pieces of about 2.5 cm diameter. An air stream segregates the refuse-derived fuel (RDF), which is lighter than heavier metal and glass pieces. These are reclaimed and recycled. About 30% of the US waste stream is recycled. The RDF thus obtained is burnt in a furnace at about 1000°C to produce steam in the boiler. Combustion process may be assisted by a required amount of auxiliary fuel when RDF does not burn properly by itself. The superheated steam obtained from boiler is used in a steam turbine coupled with an alternator to produce electrical output in the same way as in a conventional thermal plant. The flue gases are discharged to the atmosphere through a stack after removal of pollutants such as particulate matter,  $\text{SO}_x$  and  $\text{NO}_x$ . A heat-recovery steam generator extracts maximum possible heat

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from flue gases to form thermal output. The ash is removed and disposed of to landfills.



**Fig. 8.3** MSW to energy incineration plant

Strong concerns exist about the pollutants emitted during combustion. Because of various materials contained in the waste stream, pollutants in the flue gases include derivatives of sulphur, chlorine, fluorine, nitrogen, chlorinated hydrocarbons and heavy metals. One particular important group of pollutants, polychlorinated dibenz-p dioxins (PCDD) and the dibenzofurans (PCDF) are possibly among the most acutely carcinogenic compounds known so far. It has been proven to cause cancer in animals and is linked with a variety of other health problems, including genetic defects. PCDD/PCDF are formed either in the combustion chamber or after combustion when the gases cool in the exhaust stack. Disagreement continues over establishing safe levels of dioxins emission from any incinerator. It has been discovered at various levels at every incinerator tested so far. The residual ash, which has high metal concentration, is also of concern. The ash is usually disposed of in landfills; the leachate (garbage juice; liquid that results when water percolates through the landfill) must be well contained to prevent groundwater contamination. The typical metal concentrations found in fly ash and bottom ash of an incinerator are listed in Table 8.3.

**Table 8.3** Typical metal concentrations in fly ash and bottom ash of an incinerator

SN	Elements	Fly ash (mg/kg or ppm)	Bottom ash (mg/kg or ppm)
1.	Calcium	54,500	50,500
2.	Cadmium	470	100
3.	Lead	3200	900
4.	Aluminum	70,000	33,000
5.	Iron	17,000	132,000



Financially, many incineration plants are breaking even with the income from the sale of process steam and electricity and tipping at the facility on each truck.

### 8.5.2 Sewage to Energy Conversion

Sewage produced by human settlements also has some energy potential as indicated in Table 8.1. It can also be anaerobically digested (after some processing) to produce methane in the same way as with animal manure. The gas produced can be used to heat the digester and/or to generate electricity for street lighting.

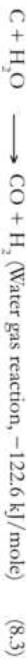
## 8.6

The word *gasification* (or thermal gasification) implies converting solid fuel into a gaseous fuel by thermochemical method without leaving any solid carbonaceous residue. Gasification is an established technology, the first commercial application of which dates back to 1830. During World War II, biomass gasification systems appeared all over the world to power vehicles to keep the basic transport systems running. Gasifier is the equipment that converts biomass into producer gas. The most common raw materials used are wood chips and other wastes from wood industry, coconut shells and straw. Biomass that has high ash content such as rice husk can also be handled with some difficulty.

Gasification involves partial combustion (oxidation in restricted quantity of air / oxidant) and reduction operations of biomass. In a typical combustion process, generally the oxygen is surplus, while in a gasification process, the fuel is surplus. The combustion products, mainly carbon dioxide, water vapour, nitrogen, carbon monoxide and hydrogen pass through the glowing layer of charcoal for the reduction process to occur. During this stage, both carbon dioxide and water vapour, oxidize the char to form CO, H<sub>2</sub> and CH<sub>4</sub>. The following are the typical reactions, which occur during gasification:



The moisture available in the biomass is converted to steam and generally no extra moisture is required. Thus the product of combustion of pyrolysis gases results in CO<sub>2</sub> and H<sub>2</sub>O (steam), which further react with char:



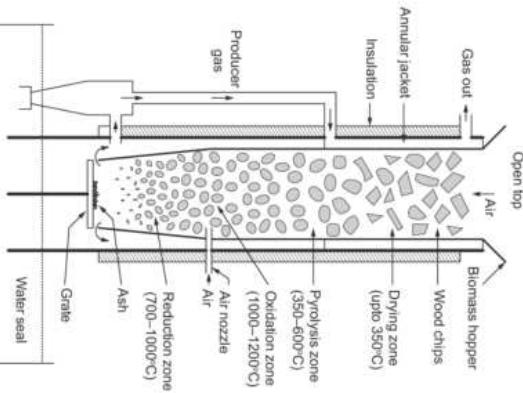
The composition of the gas produced depends on the degree of equilibrium attained among various reactions.

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Gasifiers are broadly classified into (i) fixed-bed gasifier and (ii) fluidized-bed gasifier. The fixed-bed gasifiers are further classified as (a) downdraft, (b) updraft, and (c) cross-draft types, depending upon the direction of air flow.

### 8.6.1 Downdraft Type

The downdraft type is best suited for a variety of biomass. Its design forces the raw products to pass through a high-temperature zone so that most of the unburnt pyrolysis products (especially tars) can be cracked into gaseous hydrocarbons, thus producing a relatively clean gas. A recently developed open-top downdraft-type gasifier is shown in Fig. 8.4.



**Fig. 8.4** Downdraft biomass gasification plant

across the bed. Combining the open top with the air nozzle towards the bottom of the reactor helps in stabilizing the combustion zone by consuming the uncovered char left and also by preventing the movement of the flame front to the top. As a consequence, the high-temperature zone spreads above the air nozzle by radiation and conduction, added by air flow from the top. The tar thus is eliminated in the best possible way by creating a high-temperature oxidizing atmosphere in the reactor itself. The gas produced is withdrawn from an exit at the bottom and reintroduced in the annular jacket for heat recovery. The hot gas which enters the annular jacket around 500°C, transfers some heat to the wood

In steady-state operation, heat from the combustion zone, near the air nozzle is transferred upwards by radiation, conduction and convection causing wood chips to pyrolyse and lose 70–80% of their weight. These pyrolysed gases

burn with air to form CO, CO<sub>2</sub>, H<sub>2</sub> and H<sub>2</sub>O, thereby raising the temperature to 1000–1200°C. The product gases from the combustion zone further undergo reduction reaction with char to generate combustible products like CO, H<sub>2</sub> and CH<sub>4</sub>.

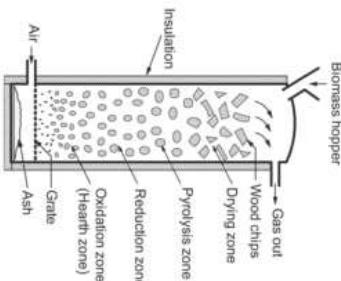
Generally about 40–70% air is drawn through the open top depending on the pressure drop conditions due to the size of wood chips and gas-flow rate. This flow of air opposite to the flame front helps in maintaining homogeneous air/gas flow



chips inside, improving the thermal efficiency of the system in addition to drying the wood in this zone. The inner wall temperature reaches more than  $350^{\circ}\text{C}$ , after a few hours of operation. This aspect enables the use of wood chips with moisture content as high as 25%. The regenerative heating due to the transfer of heat from hot gas to the biomass moving downwards also increases its residence time in the high-temperature zone. This leads to better tar cracking.

The raw producer gas thus obtained can be used as such for thermal applications. However, for use in IC engines, further processing is required. Admission of hot gas into an engine results in loss of power and hence the gas has to be cooled. Raw gas contains varying amounts of dust (ash and char) particles, moisture and tar. Dust and tar are detrimental to the life of an engine. Hence, the gas has to be cooled and cleaned before admitting to the engine. The upper limit of allowable tar is about  $50 \text{ mg/m}^3$  and that for particulate (size less than  $10 \mu\text{m}$ ) content is about  $50 \text{ mg/m}^3$ . The gas may be cooled to the ambient temperature by direct injection of cooling water from a spray tower. A sand-bed filter may be deployed to remove the particulate collected by the cooling water. Periodic washing of this sand bed is adequate to keep the operation smooth. For filtering of the gas, a sand-bed filter with specific particle size distribution is used. The filter is divided into coarse (sand particle size 0.5 to 2 mm) and fine sections (particle size 0.2 to 0.6 mm). The size of the filter area is so chosen that the gas velocities through the filter bed do not exceed  $0.1 \text{ m/s}$ . This low velocity coupled with a tortuous path causes the removal of a large part of the dust from the gas. Some part of the tar also gets deposited in the filter circuit, particularly when the moisture carried over from the cooler causes slight wetting of the sand bed.

### 8.6.2 Updraft Type



**Fig. 8.5** Updraft biomass gasification plant.

The updraft-type gasifier (also called counterflow gasifier) is the simplest as well as the first type of gasifier developed. This type of gasifier is easy to build and operate. The air enters below the combustion zone and the gas is drawn off at the top. The updraft gasifier achieves highest efficiency as the hot gas passes through the fuel bed and leaves the gasifier at a low temperature. The gas produced has practically no ash but contains tar and water vapour because of passing of gas through unburnt fuel. Hence, the updraft gasifiers are suitable for tar-free feed stock (fuels like charcoal) They are most unsuitable for high volatile fuels. The zones of various reactions are shown in Fig. 8.5.



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### 8.6.3 Crossdraft Type

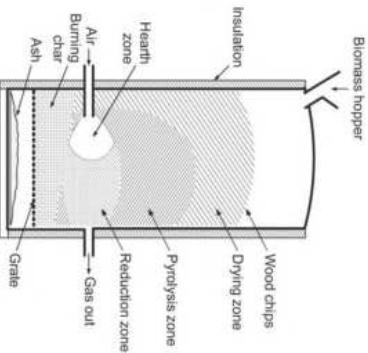


Fig. 8.6 Crossdraft biomass gasification plant

A crossdraft-type gasifier is shown in Fig. 8.6. Air enters the gasifier through a water-cooled nozzle mounted on one side of the firebox. It operates at a very high temperature and confines its combustion and reduction zone near the air nozzle. Because of short path length for gasification reactions, this type of gas producer responds most rapidly for change in gas production. The high exit temperature of the gas and low  $\text{CO}_2$  reduction results in poor quality of gas and low efficiency. Therefore, this type of gasifier is not in common use.

### 8.6.4 Fluidized-Bed Type

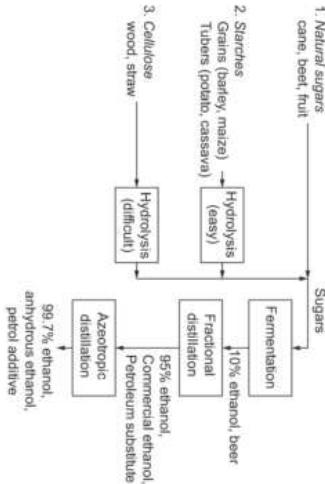
A fluidized-bed gasifier takes the advantage of excellent mixing characteristics and high reaction rates of gas-solid mixture. A simple fluidized bed gasifier is a chamber with a bed of inert particles such as sand or limestone supported by a distributor plate as shown in Fig. 8.7. Pressurized air is passed through a distributor plate. The velocity of the air is progressively increased till the upward drag of air on bed particles supports the entire weight of the bed. The bed is then said to be incipiently fluidized, and it exhibits fluidlike properties above this velocity, called the *minimum fluidization velocity*. This moving mass of solid is called a *fluidized bed*. The turbulence of the bed increases with velocity above the minimum fluidization velocity.

The fluidized bed is initially heated externally close to the operating temperature. The bed material, usually sand, absorbs and stores the heat while the turbulence and mixing of the bed keeps the temperature very uniform throughout the bed. When biomass fuel is introduced into the fluidized bed, the high heat and mass-transfer characteristics permits the rapid energy conversion at a particularly isothermal condition. The high surface area available in fluidized bed and constantly moving mass results in good conversion efficiency and lower operating temperature compared to fixed beds. The fluidized-bed design produces a gas with low tar content but high value of particulate. The high exit temperature complicates efficient energy recovery.

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get 99.7% pure ethanol. This is known as absolute or anhydrous ethanol. This anhydrous ethanol is used for blending with gasoline. This second distillation process is energy intensive process and accounts for about 40–60% of the total plant energy requirements. Various steps involved in the production of ethanol from the three types of biomass resources are shown in Fig. 8.8.

The ethanol fermentation process produces considerable quantities of carbon dioxide, which can be easily recovered, compressed and used as an additive in the beverage and food industries. It can also be made into dry ice and used for refrigeration process.



**Fig. 8.8** Ethanol production from various types of biomass

The fermentation yeast and other insoluble components of raw fermented products are rejected from the still as stillage (slops and vinasse). When starch is used as a feedstock, it has a high protein content, and can be used as livestock feed after evaporation and drying. The stillage from sugar fermentation is of low value and a major waste problem.

**Use of Ethanol as Fuel** Hydrous ethanol (95% by volume) or commercial ethanol is used as fuel in specially designed IC engines with 25% mileage penalty compared to conventional vehicles. Up to a 22% blend of anhydrous ethanol (99.7%, by volume) with petrol requiring no engine modification and incurring no mileage penalty is being used by a large number of automobiles in the world. The blended petrol is known as gasohol (in USA), proalcol (in Brazil) and carburol (in France). Note that water does not mix with petrol. In conventional vehicles, it is often present as sludge in a petrol storage tank without causing any difficulty. However, it cannot be tolerated in a gasohol storage tank. Therefore, anhydrous ethanol is required for the purpose of blending of petrol. The ethanol additive has antiknock properties and is preferred to the more commonly used tetraethyl lead, which produces serious air pollution. The excellent combustion properties of ethanol enables an engine to produce up to 20% more power as compared to that with petrol.

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## BIOGAS PRODUCTION FROM WASTE BIOMASS

**8.9** Biomass, if left to decompose in open air, is acted upon by aerobic bacteria (bacteria that require oxygen for their survival and growth) to produce mainly  $\text{CO}_2$  and  $\text{NH}_3$ . Thus, the total carbon component completely gets oxidized to produce  $\text{CO}_2$  and no fuel is produced. Some part of nitrogen is also lost in the form of ammonia.

Biogas is produced from wet biomass with about 90–95% water content by the action of anaerobic bacteria. Part of the carbon is oxidized and another part reduced to produce  $\text{CO}_2$  and  $\text{CH}_4$ . These bacteria live and grow without oxygen. They derive the needed oxygen by decomposing biomass. The process is favoured by wet, warm and dark conditions. The airtight equipment used for conversion is known as a *biogas plant* or *digester*, which is constructed and controlled to favour methane production. The conversion process is known as *anaerobic fermentation* (or biodegradation). Nutrients such as soluble nitrogen compounds remain available in solution and provide excellent fertilizer and humus. The energy available from the combustion of biogas is 60–90% of the input dry matter heat of combustion. Thus, the energy-conversion efficiency of the process is 60–90%.

The biochemical processes proceed in three stages, as shown in Fig. 8.9.

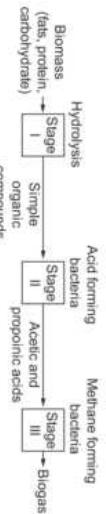


Fig. 8.9 Various stages of anaerobic digestion process

**(i) Stage I** First of all, the original organic matter containing complex compounds, e.g., carbohydrates, protein and fats is broken down through the influence of water (known as *hydrolysis*) to simple water-soluble compounds. The polymers (large molecules) are reduced to monomers (basic molecules).

The process takes about a day at 25°C in an active digester.

**(ii) Stage II** The micro-organisms of anaerobic and facultative (that can live and grow with or without oxygen) groups, together known as *acid formers*, produce mainly acetic and propionic acids. This stage also takes about one day at 25°C. Much of  $\text{CO}_2$  is released in this stage.

**(iii) Stage III** Anaerobic bacteria, also known as methane formers slowly digest the products available from the second stage to produce methane, carbon dioxide, a small amount of hydrogen and a trace amount of other gases. The process takes about two weeks time to complete at 25°C. This third stage, i.e., methane-formation stage is carried out strictly by the action of anaerobic bacteria.

The theoretical methane and carbon dioxide composition in the biogas produced from the above three main organic materials are given in Table 8.5.

**Table 8.5** Biogas production and its composition from three main organic matters

SN	Substance	Biogas produced in liter/ kg of dry substance	Methane content (%)	Carbon dioxide content (%)
1.	Fat	1200	67	33
2.	Protein	700	70	30
3.	Carbohydrate	800	50	50

### 8.9.1 Fuel Properties of Biogas

*Energy density*

- (i) with 40% CO<sub>2</sub> : 22.35 to 24.22 MJ/m<sup>3</sup>
- (ii) without CO<sub>2</sub> : 33.53 to 35.39 MJ/m<sup>3</sup>

*Octane rating*

- (i) with 40% CO<sub>2</sub> : 110
- (ii) without CO<sub>2</sub> : 130

*Ignition temperature*

: 650 °C

*Air-to-methane ratio (by volume)*

: 10 to 1

*for complete combustion*

*Explosive limits to air (by volume)*

: 5 to 10

### 8.9.2 Utilization of Biogas in IC Engines

As methane is the major constituent of biogas, it can be used in all natural-gas-fuelled IC engines. However, raw biogas contains corrosive constituents that can significantly shorten the useful life of the engine. This is particularly true when the engine is operated intermittently. During shutdown, the last few strokes of the engine piston intake unburned biogas. The various acidic components (for example, hydrogen sulphide) present corrode the surfaces of the cylinder walls, the piston rings, valve seats and spark plug. These acids leak by the corroded rings into the oil sump where they are pumped throughout the engine. The contaminated oil is particularly corrosive for copper and lead alloy components. As this corrosive process progresses, the engine becomes more difficult to start until it eventually fails completely.

Thus, the gas quality demands for IC engines are strict so the raw biogas from a digester or a landfill has to be upgraded. A gas-scrubbing system will probably need to be installed, to remove hydrogen sulfide from the biogas.

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value of 6.5 to 7.5 is maintained, as methane-forming bacteria are very sensitive to acidity. Too much and sudden deviation from this value is likely to cause imbalance in bacteria population affecting the production of gas.

**(v) Feeding Rate** If the digester is fed with too much raw material at a time, acids will accumulate and the digestion process may stop. Also, a faster feeding rate will not help increase the gas production. At higher feeding rate, the retention period will be less and undigested slurry may come out. Therefore, a uniform feeding rate should be maintained. For example, for desired retention period of 50 days, an amount equal to 1/50 of the volume of the digester should be fed daily.

**(vi) Carbon to Nitrogen (C:N) Ratio and Other Nutrients in Biomass** A digester is a culture of bacteria feeding upon organic wastes. For optimal growth and activity of bacteria, it is essential that required nutrients are available in correct chemical form and concentration. Carbon (in carbohydrate) and nitrogen (in proteins, nitrates, etc.) are the main nutrients for anaerobic bacteria. While carbon supplies energy, nitrogen is needed for building up cell structure (i.e. growth). The fact that anaerobic bacteria use carbon 25 to 30 times faster than nitrogen, necessitates the optimum C:N ratio as 30 : 1 for maximum microbiological activity. Deviation from this ratio slows down the digestion process. Various organic wastes used for biogas production markedly differ in their C:N ratio as shown in Table 8.6. A small amount of phosphorus (2% of dry input, by weight) is also required for proper microbiological activity. Proper balance of nutrients is maintained by supplementing the required amount of selected raw materials to make up the deficiency of a particular nutrient, e.g., night soil for phosphorus and chopped leguminous plants (plants producing seeds in a pod) for nitrogen.

**Table 8.6 C/N ratio of various input biomass materials of Biogas plant**

SN	Raw material	C/N ratio	SN	Raw material	C/N ratio
1.	Cow dung	25	11.	Wheat straw	150
2.	Poultry droppings	5.2	12.	Corn stalks	60
3.	Night soil	8.0	13.	Raw sawdust	511
4.	Farmyard manure	14	14.	Sea weeds	19
5.	Human urine	0.8	15.	Raw domestic garbage	25
6.	Sugar cane tops	500	16.	Bread	20
7.	Grass clippings/hay	19	17.	Potato tops	25
8.	Ripe leaves	203	18.	Kitchen veg. scraps	16
9.	Cut straw	48	19.	Rags	12
10.	Flax waste	58	20.	Household dirt	41

**(vii) Seeding of Biomass with Bacteria** To start and accelerate the fermentation process, a small amount of digested slurry, containing methane-forming bacteria is added to the freshly charged plant. This is known as *seeding*.

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**Table 8.8 Maximum allowable concentrations of toxic materials**

SN	Toxic material	Allowable concentration (mg/liter)	SN	Toxic material	Allowable concentration (mg/liter)
1.	Copper	100	7.	Magnesium	1,500
2.	Chromium	200	8.	Ammonia	3,000
3.	Nickel	200(500)	9.	Sulphate	5,000
4.	Sodium	5,500	10.	Sodium chloride	40,000
5.	Potassium	4,500	11.	Cyanide	Below 2.5
6.	Calcium	4,500	12.	Detergent compd.	40 ppm

Most of the organic matters containing proteins, fats and carbohydrates (except mineral oils and lignin) can be microbiologically transformed into biogas. These are (a) animal-waste based resources, such as animal and human excreta, slaughter house waste, etc., (b) land-based resources such as crop wastes, byproducts of agro-based industries, urban solid wastes, and (c) water-based resources such as algae, sea weed, water hyacinth, etc. The availability and gas yield from some of these resources is given in Table 8.9.

**Table 8.9 Raw material availability and gas yield**

SN	Raw material	Production rate (mt/year/kg of dry matter)	Gas yield (m <sup>3</sup> /year/kg of dry matter)
1.	Cow dung	10-15 kg/day/head	0.34
2.	Poultry manure	0.06 kg/day/head	0.46-0.56
3.	Sheep manure	0.75 kg/day/head	0.37-0.61
4.	Night soil	0.75 kg/day/head	0.38
5.	Rice husk	1-1.3 tons/ha/year	5.67
6.	Algae	40 tons/ha/year	0.32
7.	Water hyacinth	60 tons/ha/year	0.42

**Some Facts about Biogas Plants** Only 70% of the cow dung produced can be collected, as 30% is lost in fields during grazing. Solid-matter content in cow dung is about 18%. Biogas required for cooking is about 0.227 m<sup>3</sup>/person/day. Gas required for lighting a 100 CP (candle power) mantle lamp is 0.126 m<sup>3</sup>/hour. A biogas plant producing 2 m<sup>3</sup> gas/day could replace a fuel equivalent of 26 kg of LPG (nearly two standard cylinders) per month. The density of slurry is about 1090 kg/m<sup>3</sup>.

The required gas-holder capacity is an important planning parameter. If the gas holder is insufficient, part of the gas produced will be lost and the remaining

volume of the gas will not be enough at the time of demand. If the gas holder is much too large, the construction cost will be unnecessarily high. The gas holder must therefore be made large enough to accept the entire volume of the gas consumed at a time. It must also be able to accept all the gas produced between consumption times. It must be able to compensate for daily fluctuations in the gas production. These fluctuation range from 7.5–12.5%.

### Example

**8.1** Calculate the volume of a cow-dung-based biogas plant required for cooking needs of a family of five adults and lighting needs with two 100-W lamps for three hours daily. Also, calculate the required number of cows to feed the plant. Assume standard values of data where required.

#### Solution

Gas required for cooking for the family =  $5 \times 0.227 = 1.135 \text{ m}^3/\text{day}$

Gas required for lighting =  $0.126 \times 2 \times 3 = 0.756 \text{ m}^3/\text{day}$

Total daily gas requirement of the family =  $2.891 \text{ m}^3$

Let  $n$  be the number of cows.

Cow dung produced =  $10 n \text{ kg/day}$

Collectable cow dung (70%) =  $7 n \text{ kg/day}$

Weight of dry solid mass (18%) in cow dung =  $0.18 \times 7 n \text{ kg/day}$

Gas production per day =  $0.34 \times 0.18 \times 7 n \text{ m}^3/\text{day}$

Therefore,

$$0.34 \times 0.18 \times 7 n = 1.891$$

$$n = 4.41 \approx 5$$

Thus, five cows are required to feed the plant.

Daily feeding of cow dung =  $7 \times 5 = 35 \text{ kg}$

This will be mixed with equal quantity of water to make the slurry.

Thus, daily feed of slurry =  $70 \text{ kg} = 70/1090 = 0.0642 \text{ m}^3$   
(slurry density =  $1090 \text{ kg/m}^3$ )

For a 50-day retention time, volume of slurry in the digester  
=  $50 \times 0.0642 = 3.21 \text{ m}^3$

As about 90% volume is occupied by the slurry, the required volume of the digester =  $3.21/0.9 = 3.56 \text{ m}^3$

**Example**

A school in a remote place has the following energy requirements.

- 8.2**
- Ten lamps each of 100 CP that operate for 4 hours daily
  - Six computers, each of 250 W, that operate for 6 hours daily by a dual fuel-engine driven generator,
  - 2 hp water pump driven by dual fuel engine for two hours daily.

Calculate the size of the biogas plant, and the number of cows required to feed the plant. Assume standard values of data where required.

**Solution**

Gas required for lighting =  $10 \times 0.227 \times 4 = 9.08 \text{ m}^3/\text{day}$

Electrical energy required by ten computers =  $10 \times 250 \times 6 \times 60 \times 60 = 54 \text{ MJ}$

Assuming the conversion efficiency of generator to be 80% and the thermal efficiency of the engine to be 25%, the thermal input to the engine to generate 54 MJ electrical energy =  $54/(0.25 \times 0.80) = 270 \text{ MJ}$

Mechanical energy required for water pumping =  $2 \times 746 \times 2 \times 60 \times 60 = 10.74 \text{ MJ}$

Assuming the thermal efficiency of engine to be 25%, the required thermal input =  $42.96 \text{ MJ}$

Total thermal input required by the engine =  $312.96 \text{ MJ}$

Assuming the heating value of biogas to be 23 MJ/m<sup>3</sup>, the required volume of biogas for the engine =  $312.96/23 = 13.61 \text{ m}^3/\text{day}$

Therefore, total daily requirement of biogas =  $9.08 + 13.61 = 22.69 \text{ m}^3$

Let the cows required to feed the plant =  $n$

Collectable cow dung per day =  $7n \text{ kg/day}$

Weight of solid mass (18%) in the cow dung =  $7n \times 0.18 = 1.26n \text{ kg/day}$

Assuming gas yield of 0.34 m<sup>3</sup>/kg of dry mass, the gas produced per day =  $1.26n \times 0.34 = 0.4284 \times n \text{ m}^3/\text{day}$

Therefore,  $0.4284 \times n = 22.69$

$$n = 53$$

Thus, 53 cows are required to feed the plant.

Daily feeding of cow dung into the plant =  $7 \times 53 = 371 \text{ kg}$

This will be mixed with equal quantity of water to make the slurry. Thus the daily slurry produced =  $371 + 371 = 742 \text{ kg}$ . Assuming slurry density to be  $1090 \text{ kg/m}^3$ , the volume of slurry added per day =  $742/1090 = 0.6807 \text{ m}^3$

For a 50-day retention time, the total volume of the slurry in the digester =  $50 \times 0.6807 = 34.035 \text{ m}^3$

As only 90% of the digester volume is occupied by the slurry, the net volume of the digester =  $34.035/0.9 = 37.82 \text{ m}^3$

### Example

#### 8.3

A plant produces 1200 litres of biogas daily. Calculate the size of the gas holder and the gas-holder capacity for a biogas plant that feeds a constant load during the following periods daily. (Assume uniform consumption of gas.)

- From 0600 to 0800 hours (2 hours)
- From 1200 to 1400 hours (2 hours)
- From 1900 to 2100 hours (2 hours)

### Solution

Gas is produced uniformly for 24 hours, gas-production rate =  $1200/24 = 50 \text{ l/h}$

Gas is consumed uniformly in 6 hours, gas-consumption rate =  $1200/6 = 200 \text{ l/h}$

Gas-holder size required to supply gas for 2 hours during which the production is also continuing  $V_g(1) = (200-50) \times 2 = 300 \text{ l}$

The largest period of gas accumulation without its consumption is from 21:00 to 06:00 hours (9 hours), hence the necessary gas-holder size  $V_g(2) = 50 \times 9 = 450 \text{ l}$

$V_g(2)$  is the maximum relevant gas-holder size required.

With a safety margin of 25%, the required gas-holder size =  $1.25 \times 450 = 562.5 \text{ l}$

The gas-holder size required =  $562.5/1200 = 0.468 = 46.8\%$

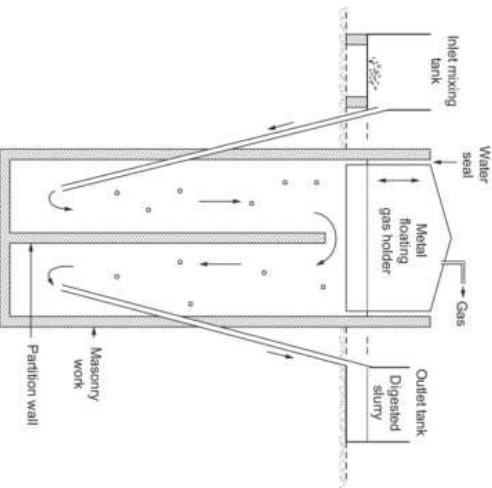
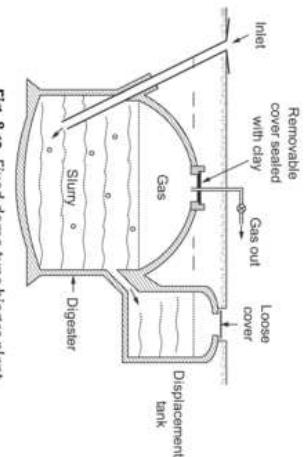


Fig. 8.12 Floating-drum-type biogas plant

### 8.9.8 Fixed-Dome (Constant Volume)-Type Biogas Plants

These plants are more economical as only masonry work is required. Gas pressure in the dome varies depending on the production/consumption rate. By construction, a dome structure is very strong for outside pressures but a weak one for inner pressures. As gas pressure is exerted from inside out, the dome structure may fail if proper care is not taken in its construction. Therefore, skilled masonry workmanship is required for construction of dome. Also, in case of any leakages/cracks, the plant may fail. A typical family-size Chinese model is shown in Fig. 8.13. Many variations of this basic design are developed to reduce the cost, making use of different materials to suit local conditions.

The slurry enters from an inlet and the digested slurry is collected in a displacement tank. Stirring is required if the raw material is crop residue. There is no bifurcation in the digester chamber and, therefore, the gas production is somewhat less as compared to a floating-point design. The gas produced is stored in the dome and displaces the liquids in inlet and outlet, often leading to gas pressures as high as 100 cm of water. The gas occupies about 10% of the volume of the digester. As the complete plant is constructed underground, the temperature tends to remain constant and is often considerably higher than the ambient temperature in winter.



**Fig. 8.13** Fixed-dome-type biogas plant

Many variations of the above two basic models are developed, keeping in view the portability, ease of installation and maintenance, local availability of material and cost. Some of them are plastic-bag reactor, prefabricated steel/bamboo/plastic reactors (both are portable models) and horizontal-type reactors.

### 8.9.9 Comparison of Floating-Drum and Fixed-Dome-Type Plants

The relative merits and demerits of the two basic designs of biogas plants are summarized in Table 8.10.

**Table 8.10** Relative merits and demerits of floating drum and fixed dome biogas plants

SN	Feature	Floating drum	Fixed dome
1.	Cost	More (due to steel drum)	Less
2.	Corrosion	Yes (likely in steel drum)	No
3.	Maintenance	More <ul style="list-style-type: none"> <li>drum requires painting, once or twice a year</li> <li>flexible gas pipe requires replacement</li> </ul>	Less <ul style="list-style-type: none"> <li>no steel part is used</li> <li>gas pipe is a fixed GI pipe</li> </ul>
4.	Thermal insulation	Bad (heat loss due to steel drum)	Good (temperature will be constant due to complete underground construction)
5.	Scum troubles	Less likely (as solids are constantly submerged)	More likely
6.	Gas production per unit volume of digester	High (due to bifurcation, both acid and methane formers find better environment for growth)	Low
7.	Scum braking	By rotation of drum (no stirrer required)	External stirrer is required



**Fig. 8.19** Biomethanisation of slaughterhouse waste at Al-Kabeer, Medak, AP

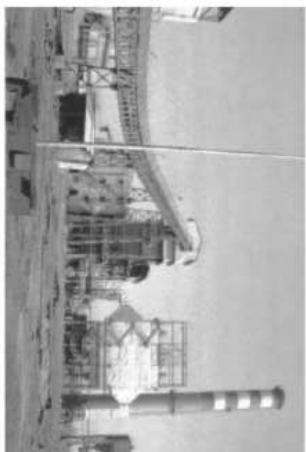
**Source:** MNES Annual Report



**Fig. 8.20** A 40-MW bagasse-based cogeneration power plant in Tamil Nadu

**Source:** MNES Annual Report

India is a predominantly agricultural country. The potential in agro-residues and plantations is estimated as 16,881 MW, out of which 605.80 MW has been realized. The bagasse-based cogeneration has an estimated potential of 5000 MW, out of which 710.83 MW has been realized so far. A total of 95 MW power is being generated from non-bagasse-based plants. Figures 8.20 and 8.21 show photographs of two such plants.



**Fig. 8.21** A 6-MW grid-connected biomass (rice husk) plant at Chhattisgarh

**Source:** MNES Annual Report

India has also launched blended petrol since 2003. The country currently imports about 70% of its crude requirements, worth about Rs 78,000 crore per annum. Blending of ethanol will result in considerable savings in precious foreign exchange. Moreover, the continuous requirement of ethanol will help sustain the demand for ethanol leading to higher sugar-cane cultivation and increased income to sugar-cane growing farmers.

*Jatropha Curcas* plantation has been taken up in a big way in different parts of the country. Its plantation has been carried out along the railway line between Delhi and Mumbai. Diesel locomotives are running with 15–20% blending of bio-diesel in the mineral diesel.

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**Fig. 8.22** A 500 kW biomass based gasifier plant at Chhotomollakhall Island in Sunderbans, West Bengal

**Source:** MNES Annual Report

Rural people depend mostly upon biomass fuels, such as firewood, animal waste and crop residues for meeting cooking and heating energy requirements. These fuels are burnt in an inefficient manner in traditional *chulhas*, causing not only economic loss to the nation but also posing serious health problems to people due to the smoke. Not only is the present level of consumption of firewood considered unsustainable, but the burning of animal waste and agricultural residues deprives our soils of much needed organic matter, adversely affecting soil health and agricultural productivity. Technologies have been developed indigenously to produce more efficient and clean fuel from biomass. Through thermal gasification, wood and crop residue is converted to producer gas, which can be burnt more efficiently. A total of 86.53 MW biogasifiers have been installed so far in the country. Fig. 8.22 shows a view of a 500-kW gasifier plant.

Cattle dung and other organic wastes can be used through a biogas plant to obtain both fuel as well as fertilizer. Out of a target of 120 lakh biogas plants, 39.40 lakh family-size cow dung/agro waste and 3,902 community/institutional, night-soil based plants have so far been installed in the country. A view of a floating-drum-type biogas plant is shown in Fig. 8.23. A fixed-dome-type plant under construction is shown in Fig. 8.24.



**Fig. 8.23** A Floating drum type (KVIC model) biogas plant

**Source:** MNES Annual Report



**Fig. 8.24** A fixed dome plant, under construction

**Source:** MNES Annual Report

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### Review Questions

1. What is the origin of biomass energy? What is its global potential? What is the average efficiency of photosynthetic conversion of solar energy into biomass?
2. What are the main advantages and disadvantages of biomass energy?
3. Explain the process of photosynthesis. How much energy is stored through this process? In what range of frequency spectrum is solar light photosynthesis most marked?
4. What is the approximate efficiency of fuel wood when used for cooking by conventional methods?
5. What is the heating value of charcoal? How much is the carbon content in it and what are its specific applications?
6. Explain the desirable features of bio-ethanol that makes it suitable as automobile fuel. What grade of bio-ethanol is required for blending with petrol and why?
7. What are the main advantages in the use of biogas? What are its main constituents and heating value? In which countries are these plants most popular?
8. Explain the process of gasification of solid bio-fuels. What is the general composition of the gas produced and what is its heating value? What are its main applications?
9. What do you understand by energy farming?
10. What are the different biomass energy resources and what is the energy yield from each of them?
11. With the help of a block diagram, explain the working of an MSW incineration plant. What is the general approximate composition of MSW and what is its heating value? What are the problems in its development?
12. With the help of a neat diagram explain the working of a gasifier using wood-chip biomass. What further processing is required to use the gas produced in a diesel engine?
13. Explain the process of commercial production of ethanol from biomass.
14. Explain the process of production of biogas from biomass. What are the main advantages of anaerobic digestion of biomass?
15. What are the factors affecting the performance of a biogas digester?
16. What raw materials can be used for production of biogas? What is the biogas yield of cow dung? How much LPG can a biogas plant with gas production of  $2\text{ m}^3/\text{day}$  replace in a month?
17. Compare the relative performances of a floating drum and fixed-dome type biogas plants.
18. Explain the details of a landfill reactor. What is the optimal moisture content in the MSW and what is the percentage (dry basis) of biodegradable part in the MSW? What is the gas-production rate in a landfill?
19. Explain the different types of bio-fuels.
20. What is the present status of development of biomass energy resources in India?

### Problems

1. Find the size of a cow-dung based biogas plant required for a house having the following requirements:
  - Cooking for two adults and two children
  - Lighting for three hours daily, using three gas mantle lamps, each of 100 CP power

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Also, calculate the number of cows required to feed the plant. Assume standard values of data where required.

(Note: two children may be considered as equivalent to one adult for cooking energy purpose.)

2. A community biogas plant is used for the following needs of a village having 100 adults and 50 children.

- Cooking needs of the people of the village
- Two lamps of 100 CP per family used for 1 hour in the evening
- A biogas operated 3-hp engine used for three hours per day to pump drinking water.

Calculate the size of the digester and the number of cows required to feed the plant.

Assume standard values of data where required.

(Ans. 71.1 m<sup>3</sup>, 100)

3. The consumption pattern of the biogas in a biogas plant is given below:

20 l/h from 08:00 to 12:00 hours  
40 l/h from 13:00 to 16:00 hours  
10 l/h from 20:00 to 24:00 hours

Determine the size of the gas holder and the required gas-holder capacity.

(Ans. 112.5 litres, 46.9%)

4. Calculate the volume of a fixed-dome type biogas digester for the output of four cows. Also, calculate the thermal power available from biogas. Use the following data:

Retention time = 30 days

Dry matter produced = 2 kg/day/cow

Biogas yield = 0.24 m<sup>3</sup>/kg of dry matter

Percentage of dry matter in cow dung = 18%

Density of slurry = 1090 kg/m<sup>3</sup>

Burner efficiency = 60%

Heating value of biogas = 22 MJ/m<sup>3</sup>

(Ans. 2.85 m<sup>3</sup>, 306.6 W.)

### 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/m<sup>3</sup>
  - (b) 14–18 MJ/m<sup>3</sup>
  - (c) 24–28 MJ/m<sup>3</sup>
  - (d) 34–38 MJ/m<sup>3</sup>
4. Fluidized bed gasifier produces
  - (a) low tar and high particulate
  - (b) high tar and low particulate
  - (c) gas at low conversion efficiency
  - (d) low exit temperature



## Non-conventional Energy Resources

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 first increases and then decreases  
(b) the gas production 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



# Geothermal Energy

## Introduction

**9** 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  $2.11 \times 10^{21}$  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 31,50,000 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 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 and direct thermal use installed capacity is 29,668 MW. 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, 99% 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  $2\text{ g kg}^{-1}$ ) 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  $\sim 30$  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  $\sim 30$  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<sub>e</sub> plant might serve an urban area of about  $20\text{ km} \times 20\text{ km}$ . 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 ( $> 90^\circ\text{C}$ ), 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.


**Geothermal Energy**

**Table 9.1** Geothermal energy: electricity generation and direct use at end of 2005 [3]

Country	Electricity generation Installed capacity (MW <sub>e</sub> )	Direct use installed capacity (MW <sub>e</sub> )
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.)



Non-conventional Energy Resources

Country	<i>Electricity generation Installed capacity (MW<sub>e</sub>)</i>	<i>Direct use Installed capacity (MW<sub>d</sub>)</i>
Italy	810	682
Lithuania		41
Netherlands		254
Norway		600
Poland		102
Portugal	18	31
Romania		194
Russian Federation	79	308
Serbia		89
Slovakia		188
Slovenia		50
Spain		22
Sweden		3,840
Switzerland		582
Ukraine		11
United Kingdom		10
Iran		30
Israel		82
Jordan		153
Australia		110
New Zealand	434	350
Total World	9,031	29,668

Note: Countries having a total installed capacity (electric + thermal) of less than 10 MW are not included in this table

## 9.2 ORIGIN AND DISTRIBUTION OF GEOTHERMAL ENERGY

Geothermal energy is the heat that originates from the *core* of the earth, where temperatures are about 4000°C. The heat occurs from a combination of two sources: (i) the original heat produced from the formation of the earth by gravitational collapse, and (ii) the heat produced by the radioactive decay of various isotopes. As the thermal conductivity of rocks is very low, it is taking many billions of years for the earth to cool. The average geothermal heat dissipation from the land and ocean surface is about 0.06 W/m<sup>2</sup>, which is negligible as compared to power dissipation due to other sources, e.g., solar energy ( $\sim 1 \text{ kW/m}^2$ ). The core is surrounded by a region, known as *mantle*, which consists of a semi-fluid material called the *magma*. The mantle is finally covered by the outermost layer known as *crust*, which has an average thickness of about 30 km. The temperature at the base of crust increases with depth at a rate of 30°C/km. The temperature at the base of crust

is about  $1000^{\circ}\text{C}$  and then increases slowly into the core of the earth. A section through the earth is shown in Figure 9.1.

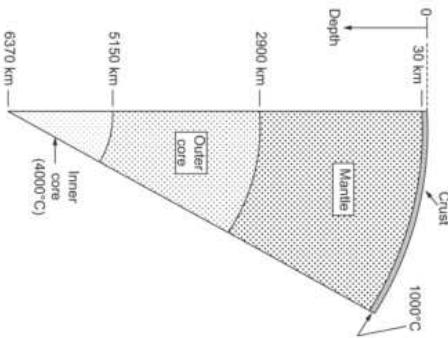


Fig. 9.1 Cross section of the earth

Though the general distribution of layers is as shown in Fig. 9.1, at certain locations, anomalies exists in the composition and structure of these layers. There are regions in which the hot molten rock (magma) of the mantle has pushed up through faults and cracks towards the surface. In an active volcano, the magma actually reaches the surface, but more often 'hot spots' occur at moderate depths (within 2 to 3 km), where the heat of the magma is conducted upward through an overlying rock layer. In fact, the zone of likely geothermal sites corresponds roughly to the regions of seismic and volcanic activities shown encircled in Fig. 9.2. High-enthalpy geothermal fields occur within well-defined belts of geologic activity.

The earth's crust consists of tectonic or crustal plates (six major plates and a number of smaller ones) as shown in Fig. 9.2. The geothermal belts are associated with the junctions of major tectonic plates, and are located mainly in the regions of recent volcanic activity or where a thinning of earth's crust has taken place. These plates are in a state of constant relative motion (several centimetres per year). Where they collide or grind, there are very strong forces that can cause earthquakes. It is near the junction of these plates that heat travels most rapidly from the interior via subsurface magma to surface volcanoes. Geothermal energy potential of these regions is great; owing to increased temperature gradients of about  $100^{\circ}\text{C}/\text{km}$ . Moderate increase in temperature gradient to about  $50^{\circ}\text{C}/\text{km}$  occur in localized regions away from plate boundaries, owing to anomalies in crust composition and structure.

Most of the world's geothermal sites today are located near the edges of the Pacific plate, the so-called 'ring of fire'. This belt rings the entire Pacific Ocean, including New Zealand, Indonesia, Japan, Philippines, Kamchatka, Western North America, Central America, Peru, Chile, Ecuador, and Argentina. An extension also penetrates across Asia into the Mediterranean area. Hot crustal material also occurs at mid-ocean ridges (e.g., Iceland and the Azores) and interior continental rifts (e.g., the east African rift, Kenya, and Ethiopia). Low-enthalpy



resources are more abundant and more widely distributed. They are located in many deep sedimentary basins of the world, e.g., certain areas of central and southern Europe, Western Siberia, Western Canada, Gulf Coast of United States as well as the fringe of high-enthalpy resources.

As mentioned above, at certain places the tectonic activity or the anomalies in the crust composition allow hot or molten rock to approach the earth's surface, creating pockets of higher temperature resources at accessible depths. The extraction and practical utilization of this heat requires technology, which depends on the nature of the resource.



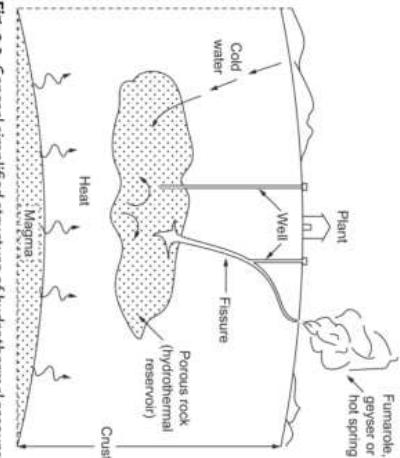
**Fig. 9.2** Region of seismic and volcanic activities (encircled) and tectonic plate boundaries

### TYPES OF GEOTHERMAL RESOURCES

There are four types of geothermal resources: (i) hydrothermal, (ii) geopressured, (iii) hot dry rock (HDR), and (iv) magma. At present, the technology for economic recovery of energy is available for hydrothermal resources only. Thus, this is the only commercially used resource at present. Other resources are going through a development phase and have not become commercial so far.

#### 9.3.1 Hydrothermal Resources

Hydrothermal resources occur when underground water has access to high temperature porous rocks, capped by a layer of solid impervious rock. Thus, water is trapped in the underground reservoir (aquifers) and is heated by surrounding rocks. Heat is supplied by magma by upward conduction through solid rocks below the reservoir. Thus, it forms a giant underground boiler. Under high pressure, the temperature can reach as high as 350°C. The hot water often escapes through fissures in the rock, thus forming hot springs or *geysers*. Sometimes steam escapes through cracks in the surface. These are called *fumaroles*. In order to utilize the hydrothermal energy, wells are drilled either to intercept a fissure or, more commonly, into the hydrothermal reservoir as shown in Fig. 9.3.



**Fig. 9.3** General simplified structure of hydrothermal resource

The hydrothermal resources are located at shallow to moderate depths (from approximately 100 m to 4,500 m). Temperatures for hydrothermal reserves used for electricity generation range from 90°C to 350°C but roughly two-thirds are estimated to be in the moderate temperature range (150°C to 200°C).

For practical purposes, hydrothermal resources are further subdivided into (i) vapour dominated (dry steam fields), (ii) liquid-dominated (wet steam fields), and (iii) hot-water resources. Vapour-dominated fields deliver steam with little or no water and liquid-dominated fields produce a mixture of steam and hot water or hot water only. The system to utilize the energy depends on the type of resource.

#### (i) Vapour-Dominated (Dry Steam) System

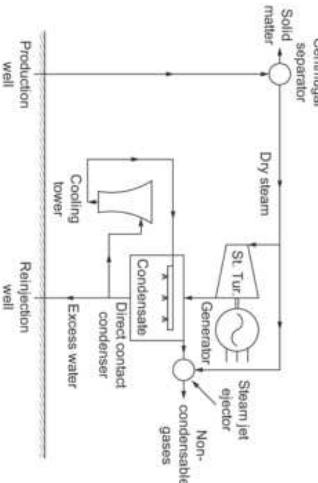
Dry steam fields occur when the pressure is not much above the atmospheric pressure and the temperature is high. Water boils underground and generates steam at temperatures of about 165°C, and a pressure of about 7 atm. The most important known dry steam fields are (a) The Geysers region in California, which may be the largest, (b) the Larderello and some smaller areas in Italy; and (c) a small field (or fields) at Matsukawa, Japan. The dry steam field at Larderello is especially ideal because its wells produce virtually pure steam with no water.

As shown in Fig. 9.4, steam is extracted from the well, cleaned in a centrifugal separator to remove solid matter and then piped directly to a turbine. The exhaust steam of the turbine is condensed in a direct contact condenser, in which the steam is condensed by direct contact with cooling water. The resulting warm water is circulated and cooled in a cooling tower and returned to the condenser. The condensation of steam continuously increases the volume of cooling water. Excess water is reinjected at some distance deep into the ground for disposal. The non-condensable gases are removed from the condenser by steam jet ejection.

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The major differences compared to conventional thermal (steam) plants are as follows:

- The temperature and pressure in such plants are much less (about 165°C and about 7 atm) compared to that in conventional thermal plants (where these are about 540°C and about 160 atm). As a result, the efficiency of this plant is much less; about 15%, compared to 35–40% in case of conventional thermal plants.
- In conventional thermal plants, a surface-cooling condenser is used as the condensed steam is to be used as boiler feed water and therefore condensate and cooling water are not allowed to mix. Whereas, in hydrothermal systems, steam is continuously supplied by the resource, which allows more simple and efficient direct-contact condensing.
- Hydrothermal systems produce their own cooling water, whereas in conventional thermal plants, make-up cooling water is required from an external source.
- In case of conventional thermal plants, the steam is not mixed with non-condensable gases, which are to be removed from the condenser.



**Fig. 9.4 Dry-steam hydrothermal system**

**(ii) Liquid-Dominated (Wet Steam) System** Steam plants offer the most cost-effective technology when the resource temperature is above about 175°C. Therefore, liquid-dominated or wet steam fields are further subdivided into (a) high temperature (above 175°C) fields, where steam plants can be used, and (b) low temperature (below 175°C) fields where other technologies are used.

**(a) Liquid Dominated—High-Temperature System** In a high-temperature, liquid-dominated reservoir, the water temperature is above 175°C. However it is under high pressure and remains in liquid state. The most developed such system is found at the Wairakei fields in New Zealand, where the reservoir temperature and pressures are 230°C and 40 atm respectively, and depths are 600 m to

1400 m. When water is brought to the surface and pressure is reduced, rapid boiling occurs and it 'flashes' into steam and hot water. The steam is separated and used to generate electrical power in the usual manner. The remaining highly saline hot water (known as brine) can be used for direct heat and then reinjected into the ground. In dual-flash systems, the steam is flashed a second time from the remaining hot fluid of the first stage, separated and fed into the dual inlet turbine or into two separate turbines. The efficiency of such a plant is around 8%. The single-and dual-flashed systems are shown in Fig. 9.5. These types of plants are being used at Salton Sea in California, Dixie Valley in Nevada and other places in USA. Such systems are also being implemented in Philippines and Mexico.

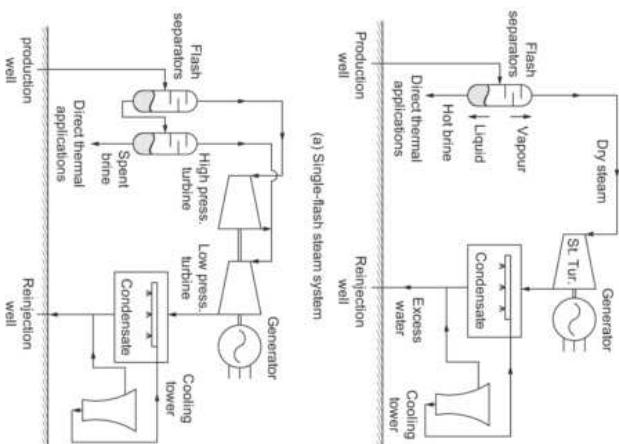


Fig. 9.5 Wet steam—high temperature hydrothermal system

(b) **Liquid Dominated—Low-Temperature System** These resources are available at moderate temperature ranges of 90°C–175°C. This temperature is not enough for efficient flash steam production. A binary-fluid system is employed, where the heat of geothermal fluid is used to vaporize a volatile organic fluid, such as isobutene ( $\text{BP} = 10^\circ\text{C}$ ), under pressure in a primary heat exchanger,

where the time constant  $\tau$  is given by

$$\tau = \frac{\{P_p \rho_w c_w + (1 - P_p) \rho_w c_w\} w}{(Q / A) \rho_w c_w} \quad (9.21)$$

The solution of the differential Eq. 9.20 may be written as

$$E = E_0 e^{-t/\tau} \quad (9.22)$$

The useful heat (energy) content of the hot aquifer at temperature  $T$

$$E = C_s T = C_s \theta_w e^{-t/\tau} \quad (9.23)$$

and the rate of decrease of thermal energy content:

$$\left| \frac{dE}{dt} \right| = \frac{E_w}{\tau} e^{-t/\tau} \quad (9.24)$$



**Fig. 9.9** Profile of hot aquifer system for calculating the heat content

### Example

A hot dry rock (HDR) resource has a geothermal temperature gradient at  $39^\circ\text{K km}^{-1}$ . The minimum useful temperature is  $120\text{ K}$  above the surface temperature  $T_w$ . Water at a flow rate of  $0.5\text{ m}^3 \text{ s}^{-1} \text{ km}^{-1}$  is used for heat extraction. The specific heat capacity for water may be assumed as  $1000\text{ kg m}^{-3}$  and  $4200\text{ J kg}^{-1}\text{ K}^{-1}$  respectively. Calculate:

- the heat content per square kilometre of HDR to a depth of  $10\text{ km}$ , assuming  $P = 2700\text{ kg m}^{-2}$  and  $c = 820\text{ J kg}^{-1}\text{ K}^{-1}$ .
- useful average temperature, initially and after 25 years
- useful average temperature, initially and after 25 years

**Solution(i)** From Eq. (9.3)

$$T_z = T_w + G b_z$$

$$T_z = T_w + 39 \times 10 = T_w + 390$$

**Example****9.2**

A 0.6-km thick hot aquifer is located at a depth of 2.5 km and has a porosity of 5%. The density of the under sediments is  $3000 \text{ kg m}^{-3}$  and its specific heat is  $750 \text{ J kg}^{-1} \text{ K}^{-1}$ . The temperature gradient in the overlying material is  $35^\circ \text{C km}^{-1}$ . Assuming the density and specific heat of water as  $1000 \text{ kg m}^{-3}$  and  $4200 \text{ J kg}^{-1} \text{ K}^{-1}$  respectively, find the:

- heat content per square kilometre above  $45^\circ \text{C}$  and the initial temperature of the aquifer, if the average surface temperature is  $12^\circ \text{C}$
- time constant for useful heat generation with pumped water extraction at a rate of  $0.75 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ .
- thermal power extractable per square kilometre initially and after 25 years

**Solution**

Given:  $w = 0.6 \text{ km}$ ,  $h_2 = 2.5 \text{ km}$ ,  $\rho = 0.05$ ,  $\rho_r = 3000 \text{ kg m}^{-3}$ ,  $c_r = 750 \text{ J kg}^{-1} \text{ K}^{-1}$ ,  $\rho_w = 1000 \text{ kg m}^{-3}$ ,  $c_w = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$ ,

$$G = 35^\circ \text{C km}^{-1}, T_i = 45^\circ \text{C}, T_o = 12^\circ \text{C}, Q = 0.75 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$$

(i) From Eq. (9.15), initial temperature of the aquifer,

$$T_i = T_o + G \cdot h_2$$

$$T_i = 12 + 35 \times 2.5 = 99.5^\circ \text{C}$$

$$0_o = T_i - T_i = 95 - 45 = 50^\circ \text{C}$$

From Eq. (9.19), Energy (heat) content per sq. km

$$E_o/A = \{p \rho_r c_r + (1-p) \rho_i c_i\} w \theta_o$$

$$\begin{aligned} E_o/A &= \{0.05 \times 1000 \text{ kg m}^{-3} \times 4200 \text{ J kg}^{-1} \text{ K}^{-1} + 0.95 \times 3000 \text{ kg m}^{-3} \\ &\quad \times 750 \text{ J kg}^{-1} \text{ K}^{-1}\} \times 0.6 \text{ km} \times 50 \text{ K} \\ &= 7.042 \times 10^{16} \text{ J km}^{-2} \end{aligned}$$

(ii) From Eq. (9.21), time constant,

$$\tau = \frac{\{p \rho_r c_r + (1-p) \rho_i c_i\} w}{Q / A \rho_r c_r}$$

$$\tau = \frac{\{0.05 \times 1000 \text{ kg m}^{-3} \times 4200 \text{ J kg}^{-1} \text{ K}^{-1} + (0.95 \times 3000 \text{ kg m}^{-3} \times 750 \text{ J kg}^{-1} \text{ K}^{-1}\} \times 0.6 \text{ km}}{0.75 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2} \times (1000 \text{ kg m}^{-3} \times 4200 \text{ J kg}^{-1} \text{ K}^{-1})}$$

$$\tau = 12.9 \text{ years}$$

(iii) From Eq. (9.24), initial extractable thermal power per square kilometre,

$$\left| \frac{d(E/A)}{dt} \right|_{t=0} = \frac{(E_o/A)}{\tau} e^{-t/\tau} = \frac{(E_o/A)}{\tau} = 173.1 \text{ MW km}^{-2}$$

Extractable thermal power per square kilometer after 20 years,

$$\left| \frac{d(E/A)}{dt} \right|_{t=20} = \frac{(E_o/A)}{\tau} e^{-t/\tau} = \frac{(E_o/A)}{\tau} e^{-25/12.9} = 24.925 \text{ MW km}^{-2}$$



## EXPLORATION AND DEVELOPMENT OF GEOTHERMAL RESOURCES

### 9.5

The development of a hydrothermal resource begins with exploration, to locate and confirm the existence of a reservoir with economically exploitable temperature, volume and accessibility. Most known reservoirs were discovered from surface manifestations such as hot springs. However, in some geothermal fields, the surface indications provide meagre (or misleading) information as to reservoir capacity. Because of the high cost of drilling, something needs to be known about energy potential of the reservoir before drilling is undertaken. Efforts are on to develop procedures for forecasting geothermal reservoir performance. The procedures under study include (i) rate of upward heat flow in the ground, (ii) chemical composition of surface and ground water, (iii) electrical resistivity of the ground at varying depths, and (iv) seismic measurements.

Exploratory drilling and production testing is then used to establish reservoir properties. If a suitable reservoir is confirmed, field development follows. Deep drilled survey wells commonly reach depths of 6 km, and the technology is available to drill to 15 km. Drilling technology used for geothermal development is historically derived from the petroleum industry. Geothermal drilling is, however, more difficult and expensive. Temperatures of up to 350°C encountered in geothermal drilling, are higher than those in oil (or gas) well drilling, and usually hard volcanic rock needs to be penetrated. This causes excessive wear of drill bit. The drilling mud used to lubricate and cool the drill bit deteriorates rapidly at temperatures above about 175°C.

Geothermal fields generally lend themselves to staged development. To begin with, a modestly sized plant can be installed at an early stage of field assessment based on the available information. The operation of this plant would provide more information about the reservoir, which can lead to the installation of future stages.

Geothermal energy is not as renewable as solar or wind energy. Like the energy of the sun, energy within earth is immense and has a lifetime measured in billions of years. However, unlike the use of sunlight, tapping into the local sources of the earth's heat can result in temporary decrease in the total amount of the heat available. Though reinjecting the used geothermal fluid can preserve the fluid volume of the reservoir, still the heat content of the reservoir gradually declines. Resources tapped for electricity generation could provide energy for about 50 years or more, if properly managed. Continuous long-term use of geothermal energy would require the periodic construction of new plants at new sites, while previously used reservoirs recover. The recovery period of the geothermal resource depends on how it is used. Recent survey indicates a recovery period of 100-200 years for district heating and several hundred years for electricity generation.

Other types of geothermal resources have special requirements in the exploration phase. Drilling technology requirements and cost increases as the geothermal environment becomes hotter, deeper and more abrasive to drill. Recovery of geopressured energy requires high-pressure technology and the use of heavy drilling mud. Hot dry rock requires drilling of deep wells in very hard rocks and creation of small artificial reservoirs. Successful magma drilling technology has not been established yet.

## 9.6

**ENVIRONMENTAL CONSIDERATION**

Hydrothermal (dry steam) resources contain some non-condensable gases, mainly  $\text{CO}_2$  and small amounts of  $\text{H}_2\text{S}$ , ammonia, methane, etc., which appear in turbine exhaust. The emission of  $\text{CO}_2$  is significantly less than from any fossil-fuel plant with the same output.  $\text{H}_2\text{S}$  is a noxious gas and has the smell of rotten eggs. In the past, non-condensable gases have been released to the atmosphere where hydrogen sulphide is gradually destroyed by oxidation. However, the products are oxides of sulphur which can themselves be harmful, if they accumulate at appreciable concentration. Plans are therefore underway to remove most of the hydrogen sulphide from the gases before they are discharged. Suitable means for mitigation of most of these releases can be adopted. In fact, Lake County dry steam plant (one of "The Geysers" plants, California) is reported to be in compliance with all of California's air quality regulations. Thus, geothermal energy tends to be quite clean.

Geothermal steam may also contain boron, arsenic, mercury and other potentially poisonous elements, which are found in condensate. This can contaminate the ground water and poison fish and other aquatic life, if not disposed of safely. The reinjection of excess condensate deep into the ground solves the problem of its safe disposal.

In wet steam fields, the mineral and salt content of the hot water (brine) can be as high as 20–30% dissolved solids. This poses liquid waste disposal problems. Also, withdrawal of large amounts of steam (or water) from hydrothermal resources may result in surface subsidence. These problems can also be dealt with by reinjection of used water deep into the ground. This also increases the useful life of the reservoir. A binary power plant, where geothermal fluid flows through a closed loop and the whole quantity is reinjected into the ground is most benign with almost zero pollutants.

Steam-electric plants of any type discharge much of the heat present in the turbine exhaust to the atmosphere. Because of the low thermal efficiency in case of hydrothermal plants, a much larger proportion of heat supplied is discharged to the atmosphere as compared to fossil fuels or nuclear plants. Vaporisation of water in the cooling tower also results in increased amount of moisture in the atmosphere.



## GEO THERMAL ENERGY IN INDIA

**9.7** A systematic collaborative, research, development and demonstration programme has been undertaken with different organisations, viz; IIT Delhi; National Aeronautic Limited, Bangalore; Geological Survey of India; National Geophysical Research Institute (NGRI), Hyderabad; Oil and Natural Gas Corporation, etc. As a result of various resource assessment studies/ surveys, nearly 350 potential hot springs, distributed in seven geothermal provinces, have been identified throughout the country. These springs are perennial and their surface temperatures range from 37 to 90°C with a cumulative surface discharge of over 1000 l/m. 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 potential for power generation at these sites has been estimated as about 10,000 MW. The use of geothermal energy has already been demonstrated in the country for small-scale power generation and thermal applications. Small direct heat pillow plants have been installed at Puga and Chumathang (in Ladakh, Jammu and Kashmir) and Mankaran (HP).

The seven geothermal provinces include:

*The Himalayas:* Sohna

*West coast:* Cambay

*Son-Narmada-Tapi (SONAT-A):* Godavari and Mahanadi

These provinces are associated with major rifts or subduction tectonics and have registered high heat flow and high geothermal gradient. The locations of geothermal fields in the country are shown in Fig. 9.10. The heat flow values and thermal gradients at these locations are listed in Table 9.2.

The geothermal reservoirs suitable for power generation have been located at Tatrapani (in Sarguja district), Chhattisgarh and Puga valley of Ladakh, and Jammu and Kashmir. The binary cycle system may be used for power generation from these medium enthalpy resources. A study by the National Geophysical Research Institute (NGRI), Hyderabad, has confirmed the presence of a 260°C hydrothermal reservoir at a depth of 3 km at Tatrapani. The Ministry of New and Renewable Energy Sources is planning to develop this field for power generation. The National Hydroelectric Power Corporation (NHPC) has been entrusted the job of installing a 300-kW demonstration electric power production plant at a cost of Rs 4.6 crore. In March 2008, the Puga valley in Ladakh has been selected for tapping the geothermal energy for power generation by the Union ministry of new and renewable energy. Exploratory study is underway by NGRI, Hyderabad, at Sutlej-Spitii, Beas and Parbati valley in Himachal Pradesh, Badrinath-Tapovan in Uttarakhand and Surajkund in Jharkhand to explore potential sites for power generation.

Since the majority of these resources are located in rural India, these springs can support small-scale industries in such areas.



# 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.

# 10

## TIDAL ENERGY

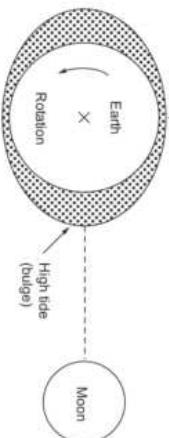
**10.1** Tidal energy exploits the natural rise and fall of coastal tidal waters caused principally by the interaction of the gravitational fields of the sun and the moon. The ocean level difference caused due to tides contains large amount of potential energy. The highest level of tidal water is known 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.

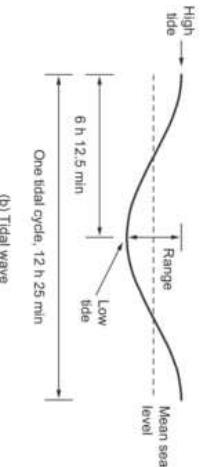
### 10.1.1 Origin and Nature of Tidal Energy

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.

Low tide



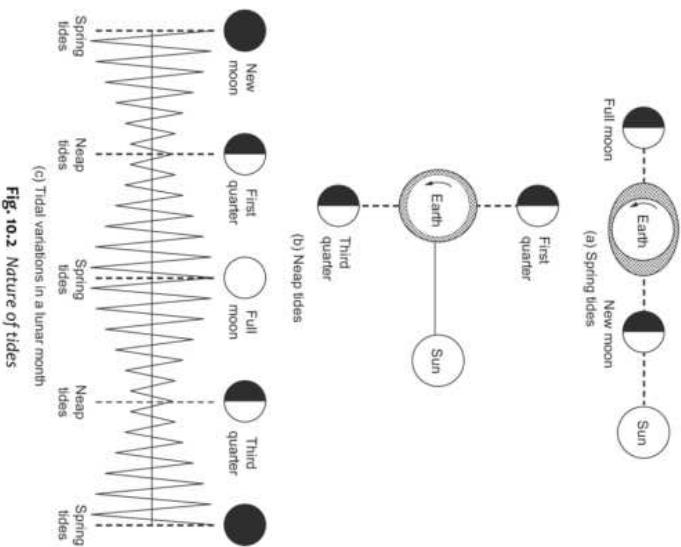
(a) Bulge on near and far sides of the earth



(b) Tidal wave

Fig. 10.1 Origin of tides

Ocean Energy 



**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  $2^\circ$  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  $3000 \times 10^3$  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 gates*: rapid controlled gates, used to fill a basin during high tides or emptying it during low tides, and
- (iii) *a spiral, 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:

$$dW' = dm \cdot g \cdot h$$

$$\text{but } dm = \rho \cdot A \cdot dh$$

Thus  $dW' = \rho \cdot A \cdot g \cdot h \cdot dh$

$$W' = \int_0^R \rho \cdot A \cdot g \cdot h \cdot dh$$

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

where  $\rho$  = 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  $1025 \text{ kg/m}^3$ , 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:

$$W' = P_t \cdot A \cdot g \cdot b \cdot dh \text{ joules}$$

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

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

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

### Ocean Tidal Energy Conversion Schemes

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

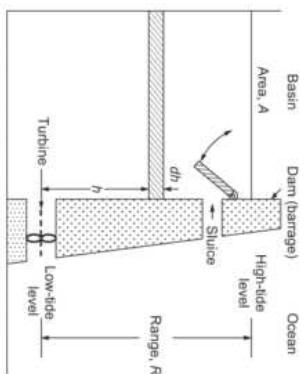
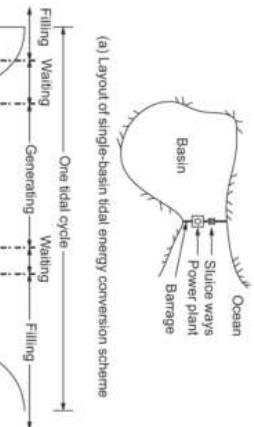


Fig. 10.3 Power generation from tides

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.



(a) Layout of single-basin 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:

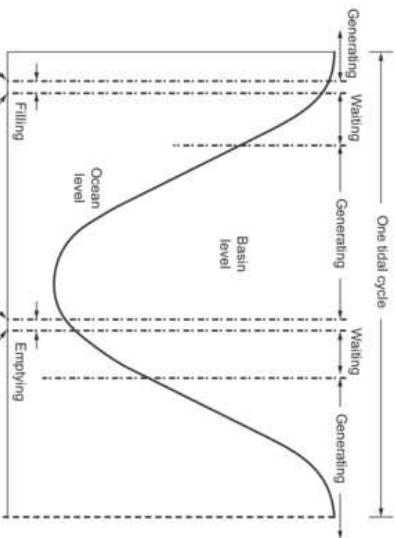
1. Inward sluicing to fill the basin
  2. Holding period
- (b) Sequence of operation steps

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

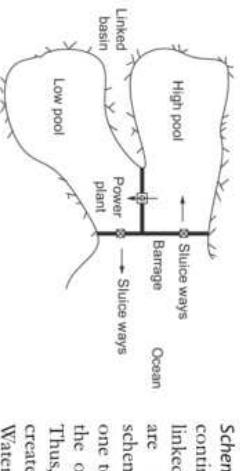


3. Ebb generation
4. Outward sluicing to empty the basin
5. Holding period
6. Flood generation

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.

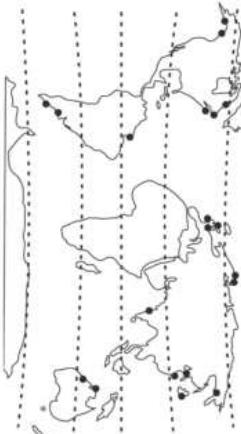
(iv) Two basin: **paired-basin scheme** A paired basin consists essentially of two single-basin schemes. One scheme generates on flood and the other on the ebb cycle.

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** Potential 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 ( $\text{km}^2$ )	Installed capacity (MW <sub>e</sub> )	Year of installation
1.	La Rance (France)	8	17	240	1966
2.	Kislaya Guba (near Murmansk, on Barnes 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 Durgadurani Creek in the Sundarbans 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 Grossaba 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 Durgadurani 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



## WAVE ENERGY

**10.2** 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 20,000,000 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:

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

where  $y$  = displacement above mean sea level, m

$a$  = amplitude, m

$\lambda$  = wavelength, m

$T$  = period, s

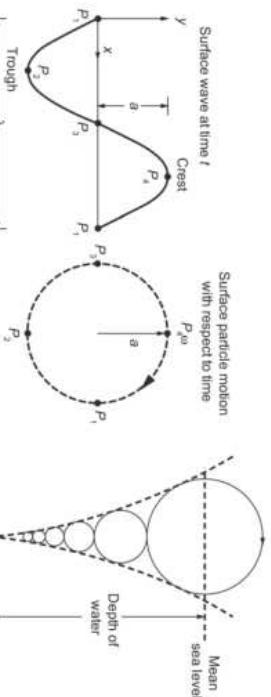
$t$  = time, s

Equation 10.1 can also be written as

$$y = a \sin(kx - \omega t) \quad (10.2)$$

where  $k = \frac{2\pi}{\lambda}$ , wave number, and  $\omega = \frac{2\pi}{T}$ , angular frequency, rad/s

As the wave moves in linear direction (along  $x$ -axis), every particle of water at the surface undergoes a circular motion of radius  $a$  (amplitude of the wave) and angular speed  $\omega$ . An object suspended in the water will exhibit this type of motion. Viewing the vertical cross section of the water column, the radius of circular motion of water particles continues to decrease with depth and becomes zero at the sea bed as shown in Fig. 10.9. Thus, while the wave propagates in the  $x$ -direction, there is no net flow of water.



**Fig. 10.8** Surface wave motion and surface particle motion

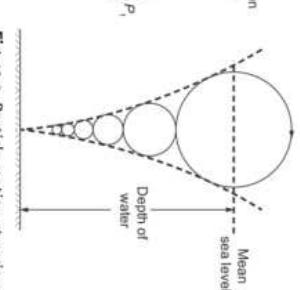
The wavelength of a travelling wave can be shown to be

$$\lambda = \frac{2\pi g}{\omega^2} \quad (10.3)$$

The period of motion is:

$$T = \frac{2\pi}{\omega} = \sqrt{\frac{2\pi g}{g}} \quad (10.3)$$

or  $\lambda = 1.5613 T^2$  (10.4)



**Fig. 10.9** Particle motion at various depths in water waves



## Ocean Energy



Linear velocity of the particle at the crest of the wave is  $a\omega$ . The wave velocity (also known as phase velocity) in the direction  $x$  is given by

$$v = \frac{\omega \lambda}{2\pi} = \frac{\lambda}{T} = \frac{\omega}{k} = \frac{g}{\omega} \quad (10.5)$$

From the above expression, it is clear that the wave velocity does not depend on amplitude of the wave.

Now, consider the unit width of wave front perpendicular to the direction of motion of wave as shown in Fig. 10.10. Vertical displacement of water particles at any instant (say  $t = 0$ ) is  $b = a \sin(kx)$ . Element of water mass  $(\rho dx dz)$  at distance  $x$  and height  $z$ , has moved from  $-z$  to  $+z$  and thus has potential energy of  $(\rho dx dz) g 2z$ . The total potential energy in one wavelength per unit width of wave front is

$$E_p = \int_{z=0}^{\text{wavelength}} \int_{x=0}^{a \sin b} (\rho dx dz) g 2z \quad (10.6)$$

$$\text{or } E_p = \rho g \int_{z=0}^{\text{wavelength}} b^2 dx$$

$$\text{or } E_p = \rho g a^2 \int_{z=0}^{\text{wavelength}} \frac{(1-\cos 2kx)}{2} dx$$

$$\text{or } E_p = \frac{1}{4} \rho g a^2 \lambda$$

Potential energy per unit length and per unit width of wave front (i.e., per unit surface area) is given by

$$E_p = \frac{1}{4} \rho g a^2 \quad (10.7)$$

In a harmonic motion, average kinetic and potential energy contributions are equal. Thus, kinetic energy per unit area is

$$E_K = \frac{1}{4} \rho g a^2$$

Total energy per unit surface area is

$$E = E_p + E_K$$

$$= \frac{1}{4} \rho g a^2 + \frac{1}{4} \rho g a^2$$

$$E = \frac{1}{2} \rho g a^2 \text{ J/m}^2 \text{ (or MJ/km}^3\text{)}$$

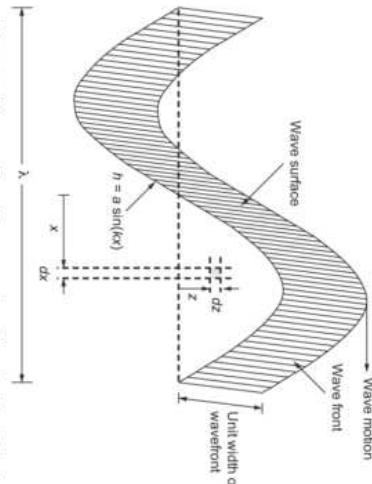
The power carried forward per unit width of wave front:

$$P = E_H = \frac{\rho g a^2}{2} v \text{ W/m}$$

where  $u = \frac{p}{2}$  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:

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

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

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 MJ/m<sup>2</sup>?

## 10.2

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

Period,  $T = 8$  s

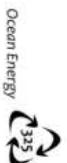
Density of sea water may be assumed as,  $\rho = 1025 \text{ kg/m}^3$

Angular frequency can be calculated as

$$\omega = 2\pi/T = 0.78539 \text{ rad/s}$$

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

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

Average annual wave energy at the site =  $31.399 \times 8.76 = 275 \text{ MWh/m}$

### 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 machine*. 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.

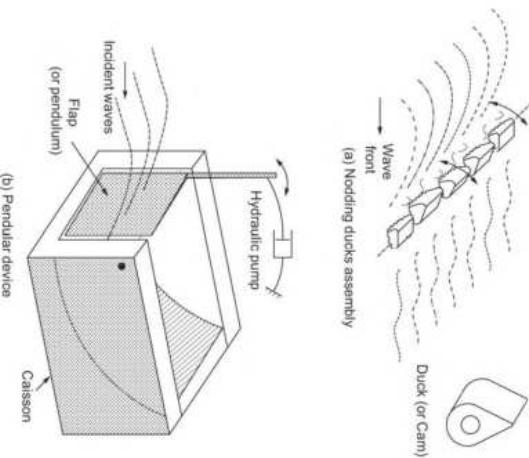
Depending on the actuating motion used in capturing the wave power, these devices are classified as (i) heaving float type, (ii) pitching type, (iii) heaving and pitching float type, (iv) oscillating water column type, and (v) surge devices. For each of these types several designs have been developed 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.

## Ocean Energy

motion is then used to power a hydraulic pump and generator. These designs are shown in Fig. 10.12.



**Fig. 10.12** Pitching-type devices

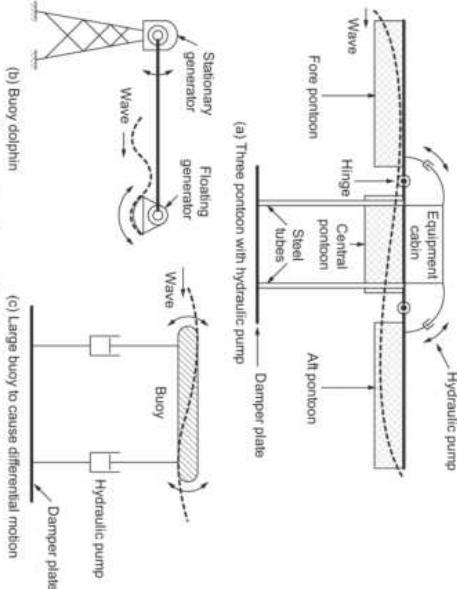
### (iii) Heaving and Pitching-float Type

Pitching and heaving motion of a float can also be used to extract wave energy. Several designs have been tried. A system consisting of three pontoons, which move relative to each other in the wave, is shown in Fig. 10.13(a). A damper plate is attached to a central pontoon, which ensures that it stays still as the fore and aft pontoon move relative to the central pontoon by pitching about the hinges. Energy is extracted by hydraulic pumps attached to hinges. Electricity can be generated via a hydraulic turbine and generator.

The idea of the three-pontoon system is further modified to form the 'Pelamis Wave Energy Converter'. In this design, a number of semi-submerged cylindrical sections (known as *Pelamis*) are joined with flexible linkages to follow the surface wave profile. The sections articulate with the movement of the waves, each resisting motion between it and the next section, creating pressurised oil to drive a hydraulic ram which drives a hydraulic motor. The machine is long and narrow (snake-like) and points into the waves; it attenuates the waves, gathering more energy than its narrow profile suggests. Its articulating sections drive internal hydraulic generators (through the use of pumps and accumulators).

3.8  
Non-conventional Energy Resources

A specially shaped float known as *Dolphin* rides the wave and rolls as well as heaves as the wave passes. The two motions are converted to unidirectional motion by a ratchet-wheel arrangement and used to operate floating and stationary generators respectively. In another very simple design, a large float is used to produce differential motion between two extreme sides of the float. The motion can be used to operate a hydraulic pump. These concepts are shown in Fig. 10.13.



**Fig. 10.13** Heaving and pitching float-type devices

**(iv) Oscillating Water-column Type** This device comprises a partly submerged concrete or steel structure, which has an opening to the sea below the water line, thereby enclosing a column of air above a column of water. The wave impinging on the device causes the water column to rise and fall, which alternately compresses or depressurises the air column. The air is allowed to flow through a turbine, which drives the generator. The specially developed axial flow Wells turbine, which operates with either directions of air flow, is used to extract energy as shown in Fig. 10.14. A conventional (unidirectional) air turbine with rectifying valves can also be used. Main advantages of oscillating water column device are the following:

- The air velocity can be increased by reducing the cross section area of the air channel. Thus the slow wave motion can be coupled to high-speed turbine motion.
- Generating equipments are kept away from immediate saline water environment.

(v) **Surge Devices** When a moving wave is constricted, a surge is produced raising its amplitude. Such a device is known as tapered channel device (TAPCHAN) and is shown in Fig. 10.15. The TAPCHAN comprises a gradually narrowing channel with wall heights typically 3 to 5 m above sea level. The waves enter from the wide end of the channel, and as they propagate towards narrower region, the wave heights get amplified until the crests spill over the walls to a reservoir, which provides a stable water supply to a low head turbine. The arrangement can be implemented successfully at low-tide sites only.

An offshore, floating wave power vessel having TAPCHAN plant on a steel platform is suggested to make the system insensitive to tidal range.

### 10.2.3 Present Status

Sea coasts with exposure to prevailing wind and long fetches are likely to have the greatest wave energy density. The United Kingdom, the west coast of United States and the south coast of New Zealand have good wave climate. Some of the important sites of the world along with wave energy potentials are indicated in Fig. 10.16.

Wave energy is passing through R and D phase and has not reached maturity from several points of view. Main countries involved in its development are Denmark, India, Ireland, Japan, Norway, Portugal, UK and USA. These efforts have largely been uncoordinated and so a wide variety of technologies have emerged. Some of them have been deployed in the sea as demonstration schemes.

Large-scale offshore devices are likely to remain uneconomical in the near future. The development of small-scale modular shoreline devices at shore-based sites seems to become more economical and competitive. Few small-scale devices are already operating satisfactorily.

Wave power projects are planned or committed in various regions, mainly as demonstration plants. Two 1 MWe TAPCHAN plants are under installation,

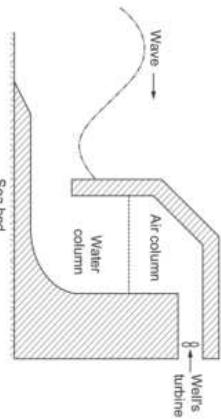


Fig. 10.14 Oscillating water column device

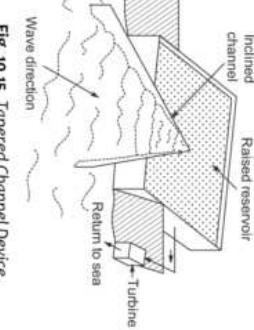
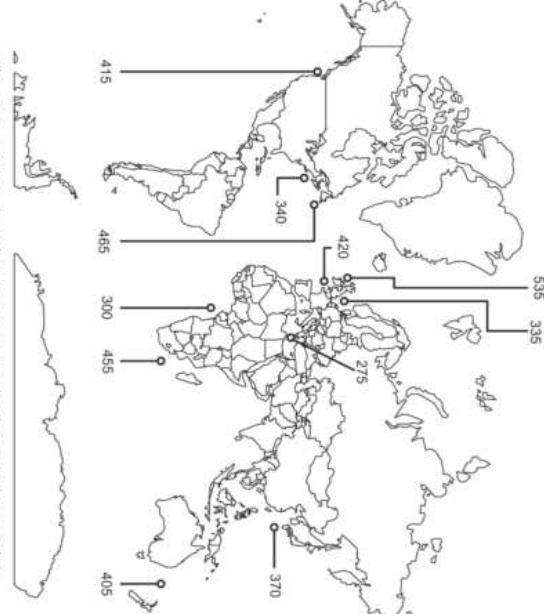


Fig. 10.15 Tapered Channel Device

one in Indonesia and the other on an island off the coast of Tasmania. Also, a 1 MWe multi-resonant oscillating water column unit is to be installed in Tonga. Oscillating water column plants of 75 and 50 kW have been built in UK and Japan respectively. The world's first commercial wave farm is recently (year 2008) commissioned in Portugal, at the Aguçadoura Wave Park, which consists of three 750 kilowatt Pelamis devices.

The wave energy programme was started in India in 1983 with preliminary studies at IIT Chennai. Initial research concluded that oscillating water column (OWC) was the most suitable for Indian conditions. A 150-kW pilot OWC plant was built onto the breakwater of the Vizhinjam Fisheries Harbour, near Trivandrum (Kerala) in 1991. The scheme operated successfully, producing data that were used for the design of a superior generator and turbine. This has led to the installation of improved power module in 1996. A plant of total capacity of 1.1 MWe comprised of 10 caissons is being developed at the same site.



**Fig. 10.16** Average annual wave energy at some locations in MWh/m

#### 10.2.4 Environmental Impacts

Wave power is essentially non-polluting. No appreciable environmental effects are foreseen from isolated floating wave power devices. However, onshore wave energy installations may change visual landscape and degrade scenic ocean front



views. It may also cause disturbance to marine life including changes in distribution and types of life near the shore, and possible threat to navigation from collision due to low-profile floating wave devices. It would usually be both possible and necessary to avoid hazards to or from marine traffic by judicious siting and by provision of navigation aids.

## 10.3

**OCEAN THERMAL ENERGY**

Ocean thermal energy exists in the form of temperature difference between the warm surface water and the colder deep water. A heat engine generates power utilizing a well-established thermodynamic principle, where heat flows from a high-temperature source to a low-temperature sink through an engine, converting a part of the heat into work. In the present case, the surface water works as a heat source and the deep water as a heat sink to convert part of the heat to mechanical energy and hence into electrical energy. The facility proposed to achieve this conversion is known as OTEC (ocean thermal energy conversion). A minimum temperature difference of  $20^{\circ}\text{C}$  is required for practical energy conversion. The resource potential is expected to be many terawatts. The main advantages of OTEC are: (i) the resource supplies steady power without fluctuations and independent of vagaries of weather, (ii) the availability hardly varies from season to season, (iii) at a suitable site the resource is essentially limited only by the size of the system, (iv) the required machinery requires only marginal improvements in well tried engineering devices, e.g., heat exchanger, turbine, etc. No dramatically new or physically impossible devices are required and (v) it also has the ability to create some useful by-products such as desalinated water and nutrients for mariculture. The major disadvantages are: (i) low efficiency, and (ii) high installation cost.

The possibility of using ocean water temperature difference to produce power was first conceived by a French physicist d'Arsonval in 1881 and verified by one of his students, Claude, on a test plant in Cuba in 1929. Subsequently, French scientists constructed two more OTEC plants, one on a ship stationed near Brazil and the other stationary plant off the West African coast. The process did not attract further attention until the 1970s, when the rising oil prices and perception of resource scarcity triggered serious development efforts. Since that time, some progress has been made in OTEC technology. Active developments are underway in France, USA and Japan.

### 10.3.1 Origin and Characteristics of Resource

The origin of OTEC may be traced to solar radiation on ocean surface. In fact the ocean is the world's largest solar collector. Therefore, the resource is a virtually inexhaustible source of energy. Absorption of solar energy in water takes place according to Lambert's law of absorption. This law states that each layer of equal thickness absorbs the same fraction of light that passes through it. Expressing mathematically,



$$-\frac{d}{dx} \frac{I(x)}{I_0} = k I(x) \quad (10.10)$$

or  $I(x) = I_0 e^{-kx}$

where  $I_0$  and  $I(x)$  are intensities of radiation at the surface (i.e.,  $x = 0$ ) and at depth  $x$  from the surface respectively. The factor  $k$  is known as extinction coefficient or absorption coefficient. The value of  $k$  for very salty sea water is  $0.5 \text{ m}^{-1}$  (for clear fresh water,  $k = 0.05 \text{ m}^{-1}$ ). At this rate, more than 95% absorption occurs within a depth of 6 m. Thus, almost all the absorption occurs very close to the surface raising its temperature, while the deep water at about 1000 m or so remains cool and unaffected by the solar radiation. There will be no thermal convection currents between the warmer, lighter water at the surface and cooler, heavier deep water. Also, heat transfer through thermal conduction across the large depth is too low. Thus mixing is retarded and so warmer water stays at the top providing a huge heat source while cold water stays at a depth providing a huge heat sink. Both reservoirs are maintained annually by solar radiation.

In most tropical and some subtropical areas, the surface temperature may reach  $27^\circ\text{C}$  while at 1 km depth water stays at about  $4^\circ\text{C}$ , providing a potential energy generation opportunity. Unlike tidal and wave energy, OTEC is a source of firm power. Such plants can operate indefinitely and are well suited to base load generation. The best sites are in the tropical belt between about  $20^\circ\text{N}$  and  $20^\circ\text{S}$  latitude. There are, however, several locations outside this area that might be suitable for OTEC plants. Some of these are in the Gulf Stream off the Florida coast, in the Gulf of Mexico and near the Hawaiian Islands.

Let us establish simplified mathematical expression for an ideal system to get an idea of the effect of temperature difference, flow rate, etc., on the output. The working fluid undergoes a temperature difference of  $\Delta T$ , between source temperature  $T_s$  and sink temperature  $T_h$ . Thus,  $\Delta T = T_h - T_s$ . The heat flow rate can be given as

$$P_r = \rho Q_s \Delta T$$

where  $\rho$  is density of sea water,  $s$  is the specific heat of water and  $Q$  is the working fluid flow rate. The mechanical power available from the heat engine,

$$P_e = \eta_{\text{carnot}} P_r$$

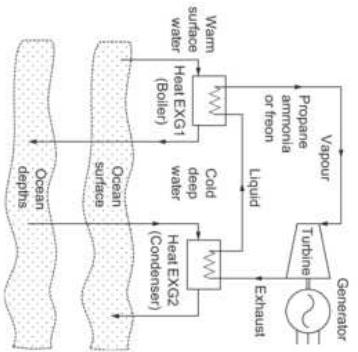
The efficiency of an ideal Carnot engine is given by  $\eta_{\text{carnot}} = \Delta T / T_h$

Thus, mechanical output power of an ideal Carnot engine is:

$$P_e = \frac{\rho s Q}{T_h} (\Delta T)^2 \quad (10.11)$$



by cold water pumped from the ocean depths. Because of the low quality of the heat, large surface areas of heat exchangers (evaporator and condenser) are required to transfer significant amount of heat and a large amount of water needs to be circulated. The schematic diagram of a closed-loop OTEC plant is shown in Fig. 10.18. The operating pressures of the working fluid at the boiler/evaporator and condenser are much higher and its specific volume is much lower as compared to that of water in an open-cycle system. Such pressures and specific volumes result in turbine that is much smaller in size and hence less costly as compared to that in an open cycle system. Although both systems are being explored, the closed-cycle system appears to be more promising in the near future.



**Fig. 10.18** Closed-cycle OTEC plant

where the sea bottom slopes sharply downwards. Their main advantage is the lower cost of installation, operation and maintenance.

In both open and closed cycle, cooling water taken from the sea depth is nutrient-rich and can be diverted to lagoon to develop mariculture after utilising its cooling effect.

### 10.3.3 Present Status

A 50-kWe floating closed-cycle test plant was installed off Hawaii in 1979. The Tokyo Electric Power Co. built and operated a 100-kWe shore-based closed-cycle plant in the Republic of Nauru. Encouraged by the performance of this plant, the company is now planning a 20-MWe plant on the same island of Nauru. The Japanese government is designing a 10-MWe floating plant and also considering a land-based plant. Several other countries are designing/proposing pilot OTEC

Both open and closed cycle plants can be mounted on a ship or built on shore. The ship option requires submarine power cable for power transport. However, if the plant is located far (more than about 50 km) from the shore, the transmission cost becomes prohibitive. Alternatively,

for a plant, which is hundreds of kilometres from the shore, it has been suggested that electricity be used on board to produce chemical storage of energy (e.g., H<sub>2</sub>). The hydrogen could be liquefied and transported by a tanker to the point of use. The shore option is feasible only at certain favourable locations,



### Review Questions

- What is the source of tidal energy? What is the minimum tidal range required for a practical tidal plant? How much is the potential in tides?
- What are the main hurdles in the development of tidal energy?
- Comment on the variation of tides with location.
- What do you understand by spring and neap tides? How are they caused?
- What is the effect of pumping on the output of the tidal plant?
- Where is the largest tidal plant located? Give its details.
- What are the potential sites for tidal energy in India?
- What is the present status of tidal current energy development?
- What are the main advantages and disadvantages of ocean wave energy?
- What types of sites are considered suitable for wave power development?
- Explain the operation of an oscillating water type of wave device.
- What are the main advantages and disadvantages of OTEC system?
- Explain the technologies available for OTEC.
- What are relative advantages and limitations of floating and shore-based OTEC plants?
- What are the environmental impacts of OTEC?
- What do you understand by biofouling? How is the problem handled?
- Draw a schematic layout of linked-basin tidal plant and explain its operation.
- Derive an expression for average annual wave energy at a particular site.
- Explain the present status of development of ocean energy resources.

### Problems

- A single-basin-type tidal power plant has a basin area of  $3 \text{ km}^2$ . The tide has an average range of  $10 \text{ m}$ . Power is generated during flood cycle only. The turbine stops operating when the head on it falls below  $3 \text{ m}$ . Calculate the average power generated by the plant in a single filling process of the basin if the turbine-generator efficiency is  $0.65$ . Estimate the average annual energy generation of the plant.

(Ans.  $39.93 \text{ MW}, 1.75 \times 10^6 \text{ kWh}$ )

- A deep ocean wave of  $2.5 \text{ m}$  peak to peak appears at a period of  $10 \text{ s}$ . Find the wavelength, phase velocity and power associated with the wave. At this power rate, what is the average annual wave energy in  $\text{MWh/m}$ ?

(Ans.  $156.14 \text{ m}, 15.61 \text{ m}, 61.3356 \text{ kW/m}, 537.2 \text{ MWh/m}$ )

### Objective-type Questions

- The tidal range
  - remains constant throughout the lunar month
  - is maximum in the middle of the lunar month and minimum by the end (also start) of the month
  - is minimum in the middle of the lunar month and maximum by the end (also start) of the month
  - is maximum in the middle and end (also start) of the lunar month and minimum in the first and third quarter of the lunar month



2. The turbine used in a tidal range plant is a
- Pelton turbine
  - Kaplan turbine with variable pitch blades
  - Kaplan turbine with fixed pitch blades
  - Francis turbine
3. Pumping of water from ocean to basin during high tide
- increases the net energy generation
  - decreases the net energy generation
  - helps in uniform power generation
  - decreases the net tidal range
4. The minimum tidal range required for power generation is about
- 1 m
  - 5 m
  - 10 m
  - 20 m
5. Two-basin tidal schemes
- are more economical than single-basin schemes
  - operate on ebb cycles in both basins
  - produce less uniform power
  - produce more uniform power
6. Power in waves is
- directly proportional to the square of its amplitude and to the period of motion
  - inversely proportional to the square of its amplitude and to the period of motion
  - directly proportional to the square of its amplitude and inversely proportional to the period of motion
  - inversely proportional to the square of its amplitude and directly proportional to the period of motion
7. The energy flux in waves is
- less than that in wind energy
  - more than that in wind energy
  - comparable to that in wind energy
  - more than that in wind energy but less than solar energy
8. Deep-water surface waves are those where the
- water depth is more than 1000 m
  - water depth is more than 100 m
  - water depth is more than the wavelength
  - water depth is more than about half the wavelength
9. Wave energy is basically harnessed in the form of
- thermal energy
  - chemical energy
  - mechanical energy
  - electrical energy
10. In pitching-type wave energy conversion machines
- the wave strikes horizontally
  - the wave strikes vertically
  - the wave moves the float up and down
  - none of the above
11. The minimum temperature difference between source and sink required by a practical heat engine is
- 540°C
  - 120°C
  - 10°C
  - 20°C

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## Non-conventional Energy Resources

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)  $80^{\circ}\text{C}$       (b)  $40^{\circ}\text{C}$       (c)  $17^{\circ}\text{C}$       (d)  $27^{\circ}\text{C}$
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



# Small Hydro Resources

## *§ 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 MW<sub>e</sub>) and small (1 MW<sub>e</sub>-25 MW<sub>e</sub>). 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/min/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

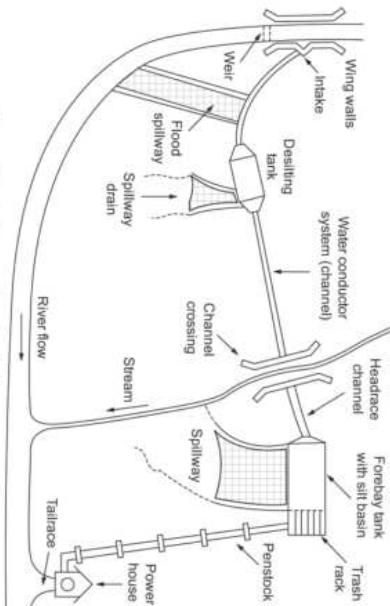
- (i) Hydro systems, unlike solar components for example, do require some maintenance.
- (ii) The quality of output of small power stations is not as good as that of bigger ones as these power plants are generally designed on the basis of short-term raw data. Thus, the ground conditions of operation 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

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.

## WATER TURBINES

Turbines convert energy available in the form of falling water into rotating shaft power. They operate on the principle of either 'impulse' (equal pressure on each side of the runner) or 'reaction' (pressure drops across the runner). A brief description of most common types of turbines is given here.

### 11.3.1 Impulse Turbines

In impulse turbines pressure energy is converted first in a nozzle into the kinetic energy of a high-speed jet of water, which is then converted to rotation in contact with the runner blades by deflection of water and change of momentum. The runner can operate in air and the water remains at atmospheric pressure before and after making contact with the runner blades. It needs casing only to control splashing and to protect against accidents. The three impulse turbines considered here are the (i) Pelton, (ii) Turgo, and (iii) crossflow (also known as Banki, Mitchell or Ossberger turbine).

#### (i) Pelton Turbine

The Pelton turbine consists of a wheel with a series of split buckets set around its rim as shown in Fig. 11.2. A high-velocity jet of water is directed tangentially at the wheel. The jet hits each bucket and is split in half, so that each half is turned and deflected back almost through  $180^\circ$ . Nearly all the energy of the water goes into propelling the bucket and the deflected water falls into a discharge channel below. Care must be taken to allow plenty of space on either side of a Pelton runner to allow deflected water to exit without splash interference. For optimum efficiency, the jet velocity needs to be about twice the speed of the bucket. The runner of such a turbine is large for the power produced. The use of two or more jets placed symmetrically around the rim will allow a smaller runner for a given flow of water and hence an increased rotational speed. The required power can still be attained.

The following options are available for control:

1. **Replacement of Nozzles** It is possible to divide the yearly flow variation in two, three or more parts and make a nozzle for each flow. The turbine operator can then remove one nozzle and replace it with the desired nozzle. This is a very low-cost method for controlling the flow.
2. **Spear Valves** The use of a needle valve or spear valve (as shown in Fig. 11.2), so called because a streamlined spearhead is arranged to move within the nozzle, allowing variation in effective orifice cross section area without introducing energy loss.

**3. Varying the Number of Jets** If a multi-jet turbine has shut-off valves fitted on each of its jets, it can be run at different flow rates by simply altering the number of jets playing on the runner.

**4. Deflector Plate** The water jet can be deflected away from the buckets of the runner if a jet deflector plate, (Fig. 11.2) is rotated into its path. This is very quick and does not require the shut-down of the flow in the penstock, with consequent pressure surge danger.

**5. Shut-off Valves** It is usual to place a valve, either a gate valve or a butterfly valve, in the turbine manifold. However, certain precautions are to be observed on its use. Pelton wheels are often driven by long penstocks in which surge pressure effects, due to valve closure, can be very dangerous and lead to damage caused by the bursting of the penstock. The valve must always be closed slowly, particularly during the last phase just before shut-off. Gate valves are sometimes used mistakenly to regulate flow, by partially closing them. This causes damage on the valve plate due to cavitation effects (explained in Section 11.4).

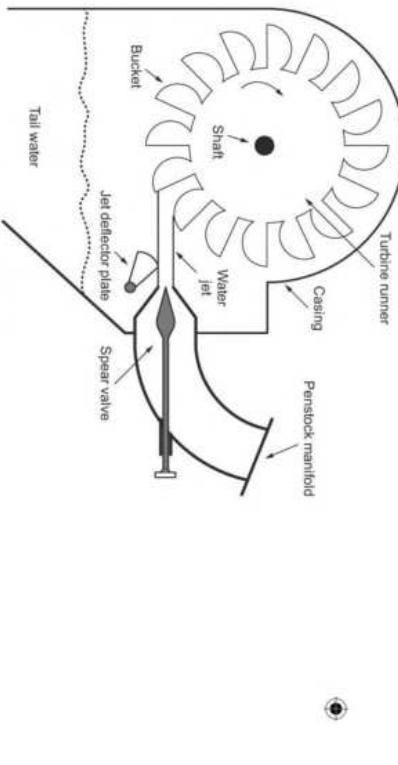


Fig. 11.2 Pelton turbine

Courtesy: [www.leonardo-energy.org](http://www.leonardo-energy.org) [46]

### (ii) Turgo Turbine

The Turgo turbine, shown in Fig. 11.3, is similar to the Pelton, but the jet is designed to strike the plane of the runner at an angle (typically  $20^\circ$ ) so that the water enters the runner on one side and exits on the other. Therefore, the flow rate is not limited by the spent fluid interfering with the incoming jet (as is the case with Pelton turbines). As a consequence, a Turgo turbine can have a smaller diameter for the runner than a Pelton for an equivalent power. It, therefore, runs at a higher speed. It shares the general characteristics of impulse turbines listed for Pelton turbines.

A Turgo turbine does have certain disadvantages also. Firstly, it is more difficult to fabricate as compared to a Pelton wheel, since the buckets (or vanes) are complex in shape, overlapping and more fragile than Pelton buckets. Secondly, the Turgo experiences a substantial axial load on its runner which must be met by providing a suitable bearing on the end of the shaft.

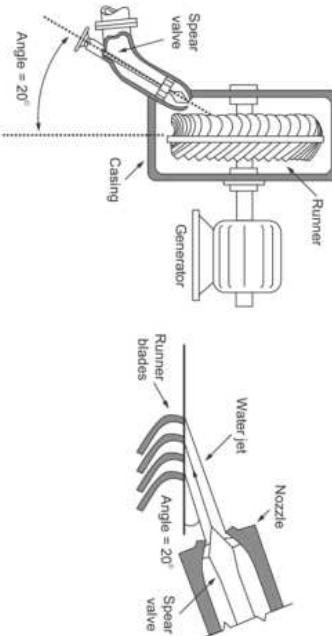


Fig. 11.3 Turgo turbine

### (iii) Crossflow Turbine

Crossflow turbines are also called Banki, Mitchell or Ossberger turbines. A crossflow turbine, shown in Fig. 11.4, has a drum-shaped runner consisting of two parallel discs connected together near their rims by a series of curved blades. The shaft of the runner is always kept horizontal in all cases (unlike Pelton and Turgo turbines which can have horizontal as well as vertical orientations). In operation, a rectangular nozzle directs the jet to the full length of the runner. The water enters the top of the runner through the curved blades imparting most of its kinetic energy. It then passes through the runner and strikes the blades again on exit, imparting a smaller amount of energy before falling away with little residual energy.

The effective head driving the crossflow runner can be increased by induction of a partial vacuum inside the casing. This is done by fitting a draught tube below the runner which remains full of tail water at all times. Careful design of valve and casing is necessary to avoid conditions where water might back up and submerge the runner.

Because of the symmetry of a crossflow turbine, the runner length can theoretically be increased to any value without changing the hydraulic characteristics of the turbine. Hence, doubling the runner length merely doubles the power output at the same speed. The lower the head, the longer the runner becomes and, conversely, on high heads the crossflow runner tends to be compact. There are, however, practical limits to length in both cases. If the blades are too long they will flex, leading quickly to fatigue failure at the junction of the blade and disc. In case of short runner operating on high head, efficiency losses at the edges become considerable.

Two major attractions in the crossflow have lead to a considerable interest in this turbine. Firstly, it is a design suitable for a wide range of heads and power ratings. Secondly, it lends itself easily to simple fabrication techniques, a feature which is of interest in developing countries. The runner blades, for instance, can be fabricated by cutting a pipe lengthwise in strips.

### 11.3.2 Reaction Turbines

Reaction turbines exploit the oncoming flow of water to generate hydrodynamic lift forces to propel the runner blades. They are distinguished from the impulse type by having a runner that always functions within a completely water-filled casing. All reaction turbines have a diffuser known as a 'draught tube' below the runner through which the water discharges. The draft tube slows the discharged water and reduces the static pressure below the runner and thereby increases the effective head. The two main types of reaction turbines are (a) Francis turbine, and (b) the propeller turbine (with Kaplan variant).

In general, reaction turbines will rotate faster than impulse types given the same head and flow conditions. The propeller type will rotate even faster than the Francis turbines. These high speeds have the very important implication that the reaction turbines can often be directly coupled to a generator without any speed-increasing drive system. Significant cost savings are made in eliminating the drive, and the maintenance of the hydro unit becomes very much simpler.

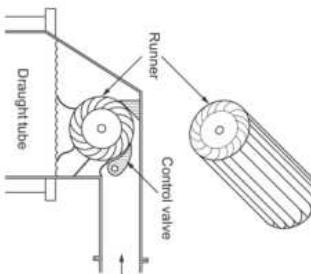


Fig. 11.4 Crossflow turbine

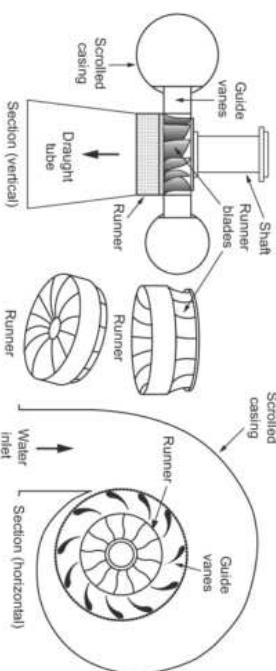


On the whole, reaction turbines need more sophisticated fabrication than impulse types, because they involve the use of large, more intricately profiled blades. The extra expense involved is offset by high efficiencies and the advantage of high running speeds at low heads from relatively compact machines. However, for use in micro hydro projects in developing countries, these turbines are less attractive due to fabrication constraints.

All reaction turbines are subject to the danger of cavitation (explained in Section 11.4), and tend to have poor part flow efficiency characteristics.

### (i) Francis Turbine

Figure 11.5 illustrates the construction of a Francis turbine. The inlet is spiral shaped. The casing is scrolled to distribute water around the entire perimeter of the runner. The guide vanes direct the water tangentially to the runner. The runner blades are profiled in a complex manner. In operation, water enters around the periphery of the runner through guide vanes, passes through the runner blades before exiting axially from the centre of the runner. This radial flow acts on the runner vanes (blades), causing the runner to spin. The guide vanes (or wicket gate) may be adjustable to allow efficient turbine operation for a range of water-flow conditions.



**Fig. 11.5** Francis turbine

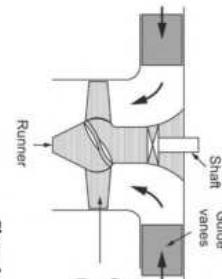
As the water moves through the runner, its spinning radius decreases, further acting on the runner. The water imparts most of its 'pressure' energy to the runner and leaves the turbine via a draught tube.

The guide vanes regulate the water flow as it enters the runner, and usually are linked to a governor system which matches the flow to turbine loading.

### (ii) The Propeller Turbine and Kaplan

Propeller-type turbines are similar in principle to the propeller of a ship, but operate in reversed mode. The typical construction is shown Fig. 11.6. It is often

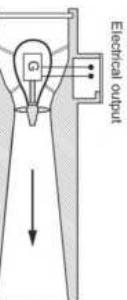
fitted inside a continuation of the penstock tube. Water flow is regulated by use of swiveling gates (wicket gates) just upstream of the runner (propeller). The part flow efficiency characteristic tends to be poor. This kind of propeller turbine is known as a 'fixed-blade axial-flow' turbine, since the geometry of the turbine does not change. Although traditionally, the propeller is profiled to optimise the effect of pressure lift force acting on it, designs have been produced with flat section blades which offer less efficiency but are more easily fabricated. This kind of design can be considered seriously for micro hydro applications where low cost and ease of fabrication are priorities. It is also possible to consider casting the propeller casing in concrete.



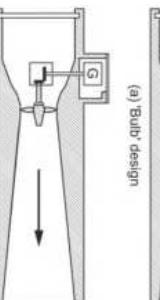
**Fig.11.6** Propeller turbine



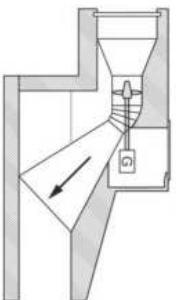
Courtesy: [www.leonardo-energy.org](http://www.leonardo-energy.org) [46]



(a) 'Bulb' design



(b) 'Cross' design



(c) 'S' design

A propeller (Kaplan) turbine can be installed in vertical, horizontal or inclined positions. A number of installation designs and arrangement of drives are possible. Figure 11.7 shows three typical designs for horizontal and inclined installations of the turbine. In the 'bulb type' design, the

Turbine runner	Head classification		
	High ( $> 50 \text{ m}$ )	Medium ( $10\text{--}50 \text{ m}$ )	Low ( $< 10 \text{ m}$ )
Reaction	Francis	Pump-as-turbine (PAT)	Propeller (axial flow)
Reaction			Kaplan (modified propeller)

Small turbines designed for micro hydro applications often will have no method of altering the flow rate of water. On larger machines, some method of altering the flow is normal. If flow control devices are fitted to the turbine, then the same head of water can be maintained above the turbine while the flow reduces. Different turbine types respond differently to changed flow at constant head. Therefore, an important aspect of their characteristics is their performance at part flow conditions. Typical efficiency characteristics are given in Fig. 11.9.

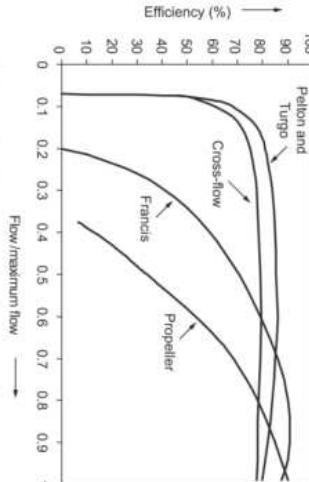


Fig. 11.9 Part flow efficiencies of various turbines

An important point to notice is that the Pelton and crossflow turbines retain high efficiency when running below design flow. In contrast, the Francis drops in efficiency, producing very poor power output if run at below half the normal flow. Fixed-pitch propeller turbines perform very poorly except at 80 to 100 per cent of full flow.

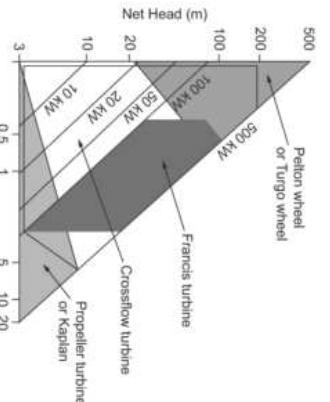
Francis is one of the few turbines which turns at a reasonable speed at certain power and head combination. An impulse turbine operated under these conditions of head and flow would be much larger, expensive, cumbersomely slow turning and would need a greater speed-increasing transmission.

In addition to giving high speed at low head-to-power ratios, reaction turbines are particularly suited to low-head applications for a second reason. Since power conversion is caused partly by pressure difference across the blades, the drop in head below the blades (known as 'suction head') is as effective in producing power as the head above the turbine. It is generally difficult or expensive to place micro hydro turbine lower than about 2 metres above the surface level of water

downstream of the turbine. On a low-head site of, say, 10 metres the suction head then represents 20 per cent of the power available at the site. This is likely to be very significant in terms of the overall economy of the scheme.

In contrast, impulse turbines do not usually make use of any suction head as their casing runs at atmospheric pressure. However, sophisticated cross flows on low heads often do use suction heads.

Having noted the advantage of using a suction head, it should also be observed that the magnitude of the usable suction is limited. This is because very low water pressures are induced on the blades of a reaction turbine running under high suction. These can be low enough to vapourise the water in pockets (or 'cavities') of vapour attached to the internal surfaces of the turbine. The cavities form and collapse at a very high rate which after a period of time can cause serious pitting and cracking of the blades. The phenomenon is known as 'cavitation'. In practical terms, great care must be taken to situate the runner at a position which prevents the possibility of cavitational damage.



**Fig. 11.10 Head-flow ranges of small hydro turbines [4]** The approximate ranges of head, flow and power applicable to the different turbine types are summarised in the chart of Fig. 11.10 (up to 500 kW power). These are approximate and dependent on the precise design of each manufacturer.

## GENERATORS

**11.5** Generation of electrical power is possible both by dc as well as ac generators. Dc generators above 2 kW are expensive and the brush gear requires appreciable maintenance. When the distribution network is small (less than 1000 m), and voltage transformation may not be necessary, dc generation may be considered favourably and have certain advantages:



- (i) The exact shaft speed is irrelevant so long as its automatic voltage regulator (AVR) maintains constant voltage. As a result no governor or load controller is required and there can be considerable saving in cost.
- (ii) Storage batteries may be charged during excess generation to provide for peak loads. Also, during shut down of the generator for maintenance, batteries may provide a standby supply.

In addition, low-power (12 V, 24 V at up to 2 kW) dc generators and associated low-voltage loads such as lights, radios, televisions, motors, fans, batteries, etc., are standard accessories for automobiles and are readily available in bulk at cheap rates. It is, therefore, sensible to consider the use of a low-voltage dc generation system for small schemes (less than 2 kW) and where all the loads are very close to the generator.

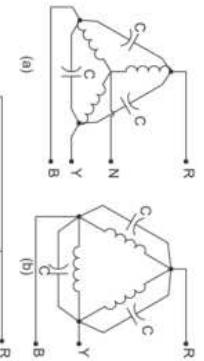
An ac system, in general, has many advantages and is an obvious choice except in small and very specialised cases. An ac supply system can be either single-phase or three-phase. A three-phase system is used universally in all conventional power systems. However, at low ratings, a single-phase system becomes more convenient as the complexity of a three-phase system is not justified at this level. As an approximate rule, therefore, systems up to 10 kW may be single-phase, while those above 5 kW may be three-phase.

Both synchronous and induction types of ac generators are suitable for micro-hydro power generation. Induction generators are less common but are increasingly being used in small schemes. The main advantages of induction generators are that they are easily and cheaply available (as motors), are rugged, reliable, require little maintenance and can withstand 100% over speed. Induction machines with a below 25 kW rating are less costly than synchronous machines.

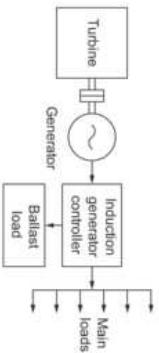
The voltage of a simple synchronous generator falls very rapidly with load. An AVR must therefore be provided to control the dc field current to stabilise the voltage. The frequency of a synchronous generator is directly related to shaft speed. A good governor is required for speed control in order to limit the frequency variations within acceptable limits. In a simple non-conventional approach as explained above, the flow at the turbine input is set to a constant value. An ELC senses the frequency variations and switches appropriate ballast load to keep these variations within limits. Thus, an ELC ensures constant speed and therefore, frequency by maintaining a constant total (resistive) load at the generator. It would appear that voltage will also remain constant and AVR may be avoided. However, if the power factor of the load changes, the output voltage would also change, requiring change of excitation to maintain the voltage.

Induction motors are simple, rugged, reliable, and plentiful. These are the most common type of electrical machines. Manufacturers generally do not make induction machines specified as generators. Therefore, an induction motor is

used as induction generator. For up to 25 kW rating an induction motor tends to cost less than a synchronous generator. A larger-size induction generator costs more than a synchronous generator of the same rating, but may still be selected in preference to the latter because of other advantages of induction machine. When an induction motor is used as a generator, the losses in the generator mode will be supplied from the mechanical input power, and the rated electrical power of the machine as generator will be significantly less than its rating as motor. A derating factor of 0.8 is normally used to accommodate this feature. Also, when an induction machine is driven as a generator it will produce a terminal voltage approximately 10% lower than the supply voltage for which it is designed as a motor.



**Fig. 11.11** Exciter capacitor connections for 3-phase self-excited Ind Gen



**Fig. 11.12** Induction generator controller scheme

then controls by diverting the required amount of power to a ballast load. This will also correct the frequency variation if the load is purely resistive. When the load is reactive, provided the load power factor is not less than 0.8, a limited frequency rise (10% maximum) is allowed and thus it effectively increases the leading VAR available from the generator excitation capacitors. The increased

induction generators can be easily used when connected to the existing grid. However, when used in stand-alone applications, such as a micro-hydro scheme, capacitors can be used across its terminals for excitation. Various configurations of a capacitor connection are shown in Fig. 11.11. Such self-excited induction generators are now increasingly being used in schemes of less than 50-kW size. The most important drawback of an induction generator is its poor voltage regulation. Even when driven at constant speed, its output voltage drops rapidly with load. On the other hand, even at constant load, its voltage changes rapidly with speed. A recently developed IGC (induction generator controller) combines the functions of both a load controller and an automatic voltage regulator. A scheme with IGC is shown in Fig. 11.12. Essentially, the IGC senses the generator output voltage, which it

## Small Hydro Resources

### **PRESENT STATUS**

**11.6** The present global installed capacity of hydropower plants is about 6,27,000 MW, which accounts for about 23% of the world's total installed electric power generation capacity and about 5% of the world's primary energy supply. A number of large and medium sized hydro schemes have been developed. Large hydro schemes are commonly associated with large reservoirs, which give rise to much environmental concern.

Small hydro plants generally do not displace large numbers of people as large projects sometimes do or cause other environment problems. There is a growing trend in developing small hydro plants with only a small upstream pondage. River courses suitable for accommodating hydro plants of up to 10 MW capacities are more common than larger ones, but the exploitable potential is limited for technical and economic reasons. The total installed capacity of small hydro plant is about 66,000 MW (year 2006).

Starting in 1958, China has continued a focused policy on small-scale hydropower development at the local level in parallel with the large-scale development planned and executed by the central government. By the end of 2004 in China, 43,809 SHP projects had been built with a total installed capacity of over 34,661 MW, accounting for 28.9% of the total exploitable potential. These installations produce annually a total of 97.8 billion kWh of electricity, and the above numbers are growing fast each year. This is by far the largest capacity installed in any country. Over 300 million people in China enjoy the benefits of electrification through SHP USA with an installed capacity of 3,000 MW stands second.

India's small hydroelectric capacity has been estimated as 15,000 MW, out of which 2,045 MW has been developed by December 31, 2007, from 611 projects. Many other schemes are at various levels of construction and planning.

### **REVIEW QUESTIONS**

1. What are the major advantages of mini/micro hydro resources?
2. With the help of a neat diagram explain the layout of a typical micro hydro plant.
3. Explain the various types of generating systems and generators considered for use in micro hydro resources.
4. Discuss various types of speed governors used in SHPs. Which type is justified in a micro hydro scheme?
5. Explain the various types of turbines considered for use in micro hydro resources.
6. Explain the various types of controls available in a Pelton turbine.
7. Compare the relative advantages and disadvantages of Pelton and Turgo turbines.
8. Compare the part-flow characteristics of various types of turbines.
9. What do you understand by 'cavitation'?
10. What are the present trends in micro hydropower development?



### Problems

1. Estimate the net power available from a proposed micro hydro scheme at a site having a small stream with a flow rate of 200 litres per second at a head of 35 m. Assume density of fresh water as  $995 \text{ kg/m}^3$  and overall efficiency of the whole system as 50%.

(Ans. 34.16 kW)

2. A micro hydro system is to be designed to supply a 1-phase, 220-V, 50-Hz electrical-distribution system having a predicted demand of 5.2 kW at 0.8 pf lagging. An ELC governor and AVR are used to regulate the output. Calculate the required VA rating of the generator. A water-cooled ballast comprising ordinary kettle elements each rated at 230 V, 1200 W is to be used. Calculate the number of kettle elements required in the ballast load and the available over ballasting. The temperatures of water entering and leaving the ballast tank are  $15^\circ\text{C}$  and  $45^\circ\text{C}$  respectively. Calculate the required flow of water in the ballast tank. Assume specific heat of water as  $4200 \text{ J/kg K}$ .

(Ans. 10.4 kVA, 5.558%, 0.0557 ltr/s)

### Objective-type Questions

- Which one of the following factors is not responsible for recent development of SHPs?
  - Advancements in the design of low-head turbines
  - Improvements in construction technology
  - Availability of better control techniques
  - Availability of small streams
- Small hydro plants (SHPs) have
 

(a) high head and small capacity	(b) low head and small capacity
(c) low head and large capacity	(d) large head and large capacity
- Which one of the following statement is not true for a micro hydro scheme?
  - It has a capacity less than 100 kW.
  - It is used where a grid does not exist.
  - Power is generated for local use only.
  - A complicated and sophisticated control scheme is used.
- In micro hydro projects the allowable voltage and frequency variations are
  - $\pm 7\%$  and  $\pm 5\%$  respectively
  - $\pm 7\%$  and  $+ 5\%$  respectively
  - $\pm 7\%$  and  $- 5\%$  respectively
  - $\pm 7\%$  and  $\pm 5\%$  respectively
- An electronic load controller
  - saves energy and stores it for later use
  - dissipates surplus energy in the ballast load
  - controls the flow of water into the turbine
  - controls the power generated by the generator
- In impulse turbines
  - water remains at atmospheric pressure before and after making contact with the runner blades



# 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.

## FUEL CELL

**12.1** 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,  $\text{NO}_x$  and  $\text{SO}_x$  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**

- Low temperature fuel cell (below 150°C)
- Medium temperature fuel cell (150°C–250°C)
- High temperature fuel cell (250°C–800°C)
- Very high temperature fuel cell (800°C–1100°C)

**(d) Based on Application**

- Fuel cell for space applications
- Fuel cell for vehicle propulsion
- Fuel cell for submarines
- Fuel cell for defense applications
- Fuel cell for commercial applications

**(e) Based on the Chemical Nature of Electrolyte**

- Acidic electrolyte type
- Alkaline electrolyte type
- Neutral electrolyte type

**12.13 Phosphoric Acid Fuel Cell (P AFC)**

P AFC 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 onto 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,



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

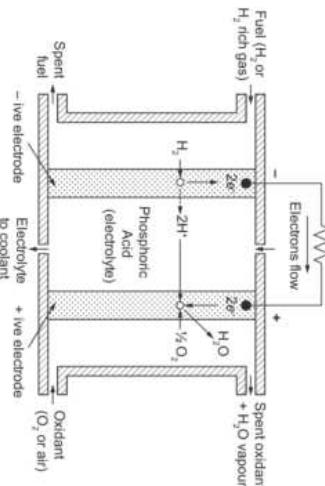
towards the positive electrode through the electrolyte. On reaching the positive electrode, they interact with  $O_2$  to produce water. Thus,



Combining the above equations indicates that a fuel cell combines  $H_2$  and  $O_2$  to produce water (plus electrical energy). The overall reaction is therefore,



This is true for any type of hydrogen–oxygen cell. The operating temperature of PAFC is  $150^\circ\text{C}$ – $200^\circ\text{C}$ . At atmospheric pressure it produces an ideal emf of  $1.23\text{ V}$  at  $25^\circ\text{C}$ , which reduces to  $1.15\text{ V}$  at  $200^\circ\text{C}$ . The actual value is always less than this and decreases with current. Normally, at rated values of current the voltage lies between  $0.7\text{ V}$  to  $0.8\text{ V}$ .



**Fig. 12.1** Phosphoric Acid Fuel Cell

#### 12.1.4 Alkaline Fuel Cell (AFC)

An alkaline fuel cell, the oldest of all fuel cells, uses 40% aqueous KOH as electrolyte. The operating temperature is about  $90^\circ\text{C}$ . The electrodes and other details are same as explained for PAFC. Like PAFC it also works with  $H_2$  and  $O_2$  active materials and the same level of emf is produced. The operation and movements of charge carriers is shown in Fig. 12.2. At the positive electrode, oxygen, water (from electrolyte) and returning electrons from the external load combine to produce  $OH^-$  ions:



These  $OH^-$  ions migrate from the positive to the negative electrode through the electrolyte. On reaching the positive electrode, these  $OH^-$  ions combine with

$H_2$  to produce water. An equivalent number of electrons are liberated that flow through the external load towards positive electrode. Thus,



The overall reaction is same as that with PAFC. That is,



The fuel used in AFC must be free from  $CO_2$  because this gas can combine with potassium hydroxide electrolyte to form potassium carbonate. This increases the electrical resistance of the cell, which in turn decreases the available output voltage of the cell. Similarly, if air is used instead of pure oxygen, the  $CO_2$  must first be removed from the air by scrubbing with lime.

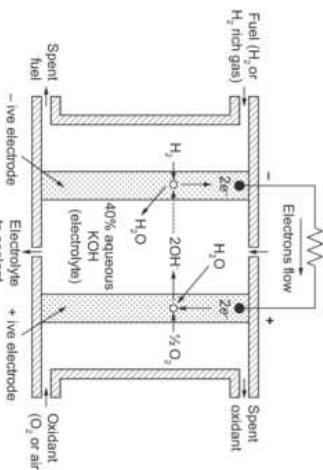


Fig. 12.2 Alkaline Fuel Cell

### 12.1.5 Polymer Electrolyte Membrane Fuel Cell (PEMFC) or Solid Polymer Fuel Cell (SPFC) or

A solid membrane of organic material (such as polystyrene sulphonic acid) that allows  $H^+$  ions to pass through it, is used as an electrolyte. The desired properties of the membrane are (i) high ionic conductivity, (ii) non-permeable (ideally) to reactant gases, i.e., hydrogen and oxygen, (iii) low degree of electro-osmosis, (iv) high resistance to dehydration, (v) high resistance to its oxidation or hydrolysis, and (vi) high mechanical stability.

The basic components of the cell are shown in Fig. 12.3. A thin layer (about 0.076 cm thickness) of the membrane is used to keep the internal resistance of the cell as low as possible. Finely divided platinum deposited on each surface of the membrane serves as the electrochemical catalyst and current collector. Hydrogen enters a closed compartment, interacts with negative electrode and gets

converted into  $\text{H}^+$  ions and equal number of electrons ( $e^-$ ):



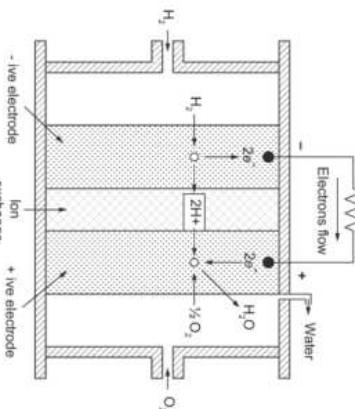
The  $\text{H}^+$  ions are transported to a positive electrode through the membrane and electrons return to a positive electrode through external resistance. At positive electrode, the ions, electrons and oxygen ( $\text{O}_2$ ) interact to produce water.



Thus the overall reaction is



On the positive electrode, the coolant tubes run through the ribs of current collectors. The current collectors also hold wicks, which absorb water, produced in electrochemical reaction and carry it over by capillary action. Water leaves the oxygen compartment through an exit. The advantageous feature of this membrane is that it retains only limited quantity of water and reflects excess water produced in the cell. The cell operates at  $40^\circ\text{C}$ – $60^\circ\text{C}$ . The ideal emf produced is 1.23 V at  $25^\circ\text{C}$ .



**Fig. 12.3 Polymer Electrolyte Membrane Fuel Cell**

In a modified version of this fuel cell, methanol is used directly without reforming, instead of pure hydrogen. This is known as **Direct Methanol Fuel Cell (DMFC)**. The complicated catalytic reforming process is not required. Storage of methanol is much easier than that of hydrogen because it does not need to be done at high pressures or low temperatures.

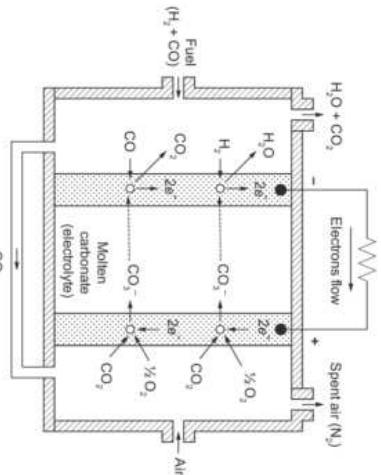


Fig. 12.4 Molten Oxide Acid Fuel Cell

### 12.1.7 Solid Oxide Fuel Cell (SOFC)

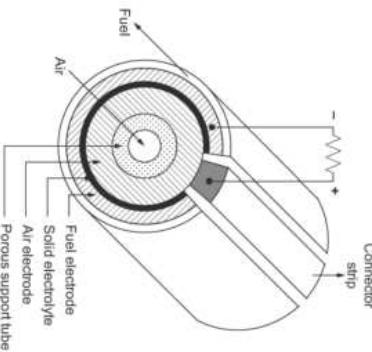


Fig. 12.5 Solid Oxide Fuel Cell

Certain solid oxides (ceramics) at high temperature can be used as electrolyte. For example, zirconium oxide containing a small amount of other oxide to stabilise the crystal structure has been used as an electrolyte. The material is able to conduct O<sup>2-</sup> ions at high temperature. The negative electrode is made of porous nickel and the positive electrode employs a metal oxide, e.g., indium oxide. The operating temperature is in the range of 600°C–1000°C. Due to high temperature operation, a catalyst is not required. These cells could utilise the same fuels as used in MCFC. At the fuel electrode H<sub>2</sub> and CO react with O<sup>2-</sup> ions present in the electrolyte to produce H<sub>2</sub>O and CO<sub>2</sub>. The two electrons released (per ion) flow through external path to constitute load current. Like MCFC, the heat of discharge can be utilised as process heat or for additional power generation using a steam plant. The output voltage at full load is about 0.63 V. A tubular construction of SOFC is shown in Fig. 12.5. The reactions at the electrodes are:

## (32) Non-conventional Energy Resources

decomposition. The product, i.e., mixture of H<sub>2</sub> and N<sub>2</sub> is introduced in a fuel cell (e.g., AFC). Nitrogen present in the mixture is discharged with exhaust.

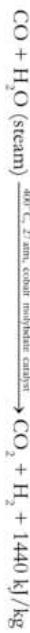
**(iv) Hydrocarbons (Gases)** Hydrocarbons such as methane, propane, etc., are first converted to a mixture of H<sub>2</sub> and CO by steam reforming.



The mixture is then used as such or after removal of CO by water-gas shift reaction, as required. Commercial fuels such as natural gas, LPG, biogas, coal gas, landfill gas and gasified coal can be used in this way for large-scale generation of power.

**(v) Hydrocarbons (Liquid)** Light hydrocarbons (naphtha) are first steam reformed to get H<sub>2</sub> and CO. The product gas mixture is then used as fuel as explained above.

**(vi) Synthesis Gas** Mixture of H<sub>2</sub> and CO in various proportions, along with other impurities (known as synthesis gas) can be produced economically from conventional or non-conventional sources. The (H<sub>2</sub> + CO) mixture can be used as fuel in MCFC and SOFC. For use in hydrogen fuel cells, CO is to be removed and hydrogen content is increased by a process known as water-gas shift reaction, as given below:



CO<sub>2</sub> present in the products is also removed if the mixture is to be used in AFC.

**(vii) Methanol** Methanol is used both as direct as well as indirect type fuel. It can be catalytically reformed with steam at about 200°C to yield a mixture of H<sub>2</sub> and CO. The mixture is then used as discussed above.

Methanol can also be used directly without reforming in direct methanol fuel cell, a modified version of proton membrane exchange fuel cell.

### 12.1.10 Efficiency of a Fuel Cell

In a fuel cell, electrochemical reactions take place whereby reactants are converted to products in a steady flow process. If the temperature and pressure of the flow stream from entrance to exit (during reaction) remain unchanged, from the first law of thermodynamics:

$$\Delta Q - \Delta W' = \Delta H + \Delta(\text{KE}) + \Delta(\text{PE}) \quad (12.1)$$

where  $\Delta Q$  = heat transferred to the steady flow stream from the surrounding

$\Delta W'$  = work done by the flow stream on the surrounding



$$E = \frac{-\Delta G}{nF} \quad (12.8)$$

where  $n$  no. of electrons transferred per molecule of the reactant

$F$  Faraday's constant (96500 coulombs per gram mole)

For  $\text{H}_2\text{-O}_2$  cell,  $n = 2$ . Also at  $25^\circ\text{C}$ , and at atmospheric pressure,  $\Delta G = -237191 \text{ kJ/kg mole}$  and  $\Delta H = -285838 \text{ kJ/kg mole}$ . Therefore, cell emf

$$E = \frac{-237191}{2 \times (96500)} = 1.23 \text{ V}$$

The value of  $E$  at  $200^\circ\text{C}$  is 1.15 V. The actual value of cell output voltage,  $V$  attained on load is less than  $E$ . The difference between actual and theoretical voltage is known as *polarisation*,  $V_p$ . The effect of polarisation is to reduce the voltage and thereby efficiency of the cell from its maximum value. All the losses in the fuel cell may be included under voltage efficiency, which may be expressed as

$$\eta = \frac{\text{on load voltage}}{\text{theoretical open circuit voltage (emf)}} = \frac{V}{E}$$

The VI characteristic of a fuel cell is shown in Fig. 12.6. Voltage regulation is poor for small and large values of output current. Therefore, in practice the operating point is fixed in the range  $BC$  of the characteristics where voltage regulation is best and the output voltage is roughly around 0.6–0.8 V.

At no load, the terminal voltage is equal to the theoretical open-circuit voltage. As the cell is loaded (current  $i$  is supplied to load), voltage and hence efficiency drops significantly. The departure of output voltage from ideal emf is mainly due to the following reasons.

(i) **Activation Polarisation (Chemical Polarisation)** This is related to activation energy barrier for the electron transfer process at the electrode. Certain minimum activation energy is required to be supplied so that sufficient number of electrons is emitted. At low current densities significant numbers of electrons are not emitted. This energy is supplied by the output of the cell, resulting in potential loss. It can be reduced by an effective electrochemical catalyst and also by increasing the operating temperature.

(ii) **Resistance Polarisation** At larger current, there is additional contribution from internal electrical resistance of the cell. The internal resistance is composed mainly of resistance of bulk electrolyte and interface contact resistance between electrode and electrolyte. The resistance polarisation can be reduced by (a) using more concentrated (i.e., high conductivity) electrolyte, (b) increasing the operating temperature, and (c) using proper shape and spacing of electrolyte to reduce the contact resistance.



$\Delta H_f^\circ = -56.83 \text{ kcal/mol}$ , which is equivalent to

$$\Delta H^\circ = -238.7 \text{ kJ/mol}$$

From Eq. 12.6, the electrical work output per mole of fuel (methanol) consumed:

$$\Delta W_{\text{max}} = -\Delta G = 166.3 \text{ kJ}$$

That means, 166.3 kJ electrical work is produced from 1 mole (i.e., 32 g) of methanol and  $\frac{3}{2}$  mole (i.e.,  $1.5 \times 32 \text{ g}$ ) of oxygen

In other words, 166.3 kW electrical power is produced from flow rate of 32 g/s of methanol and 48 g/s of oxygen.

Required flow rate of methanol for electrical output of

$$100 \text{ kW} = \frac{32 \times 100}{166.3} = 19.24 \text{ g/s}$$

$$= 23.09 \text{ kg/h}$$

Required flow rate of oxygen for electrical output of 100 kW

$$= \frac{48 \times 100}{166.3} = 28.86 \text{ g/s}$$

$$= 34.63 \text{ kg/h}$$

The heat transferred is given by Eq. 12.3

$$\Delta Q = T \Delta \Sigma$$

which from Eq. 12.7, may be written as

$$\Delta Q = \Delta H^\circ - \Delta G^\circ$$

$$= -56.83 + 39.59 = -17.24 \text{ kcal/mol}$$

The negative sign indicates that heat is removed from the cell and transferred to the surroundings.

Thus 1 mole (i.e., 32 g) of methanol produces 17.24 kcal of heat.

As calculated above, the fuel consumption rate for 100 kW electrical power generation is 19.24 g/s

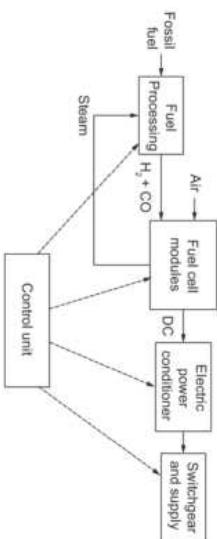
Consumption of fuel at the rate 19.24 g/s produces heat at the

$$\text{rate of } \frac{17.24 \times 19.24}{32} = 10.366 \text{ kcal/s}$$

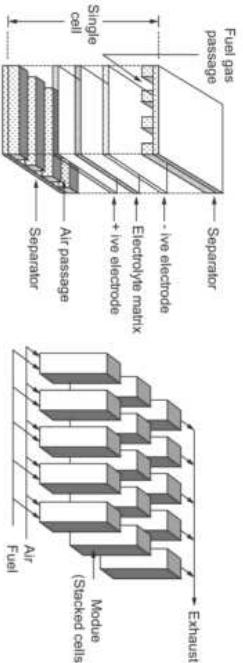
Thus, the required heat removal rate from the cell at electrical output of 100 kW is 10.366 kcal/s.

### 12.1.12 Fuel Cell Power Plant

The block diagram showing the main components of a fuel-cell power plant is given in Fig. 12.7. Electrical energy is generated from primary fossil fuels through a fuel cell. Fuel is managed and supplied by a fuel processing unit. In this unit, fuel is received, stored, reformed, purified and supplied to fuel-cell modules. Fuel-cell modules convert fuel energy electrochemically into dc power using ambient air as oxidant. Basic configurations of cell, module and plant are shown in Fig. 12.8. A number of cells are stacked to form a module. Several modules are interconnected to form a power-generating unit. Fuel gas and air are supplied to modules from common supply pipes. The exhaust is collected in a common pipe and discharged to the atmosphere either directly or after recovery of heat in a cogeneration unit. The power-generating unit generates electrical power as dc. Industrial/commercial loads are rated for standard ac supply such as 3 ph., 400 V, 50/60 Hz or 1 ph., 230/110 V, 50/60 Hz. The electrical power-conditioning unit, converts dc output of fuel cell to ac using inverter and also controls and regulates it.



**Fig. 12.7** Fuel-cell based electrical power-generation scheme



**Fig. 12.8** Power-generation unit



### 12.1.3 Present Status

Fuel-cell technology and its applications in various fields are at the development stage. Stackable modules of size 200–250 kW are available. Demonstration projects are being installed at different places.

A number of companies are engaged in manufacturing fuel cells. For example, 'UTC Fuel Cells' has delivered more than 250 fuel-cell power plants around the world that can run on waste methane such as landfill gas. 'Fuel Cell Energy' offers 1.5 MW and 3 MW sized plants for stationary applications utilising natural gas or waste methane gas as fuel.

Fuel cell units for homes and small commercial applications are in the initial stages of commercialisation. 'Avista Labs' is marketing fuel cells with capacities 100–5000 W to USA and European Union.

All major automakers are working on fuel cell and/or hydrogen vehicle programmes. A number of demonstration vehicles are being tested including cars, buses, trucks and locomotives, etc., in USA, Canada, Europe, Japan, China and Australia. Fuel cells are also powering boom lifts, fork lifts, golf carts and utility vehicles in USA and other developed countries. In USA, a 1-MW fuel cell plant is being developed to replace diesel locomotive engine.

The US army is very much interested in portable fuel cells to replace batteries for powering field equipments. Sony, Motorola, Panasonic, Casio and NEC are developing fuel cells for devices including cellular telephones and hand-held computers. The main hurdles in the popularity of fuel cells are lack of hydrogen infrastructure and limited lifespan of fuel cells. However, these issues are making progress.

### 12.1.4 Environmental Effects

With hydrogen as fuel, the exhaust of a fuel cell contains only water vapour, which is not a pollutant, apart from some amount of heat. If air is used as oxidant, spent air, which is mostly nitrogen, is also present in the exhaust. This is again not a pollutant. No cooling water is required as the generated heat can be easily utilised in a cogeneration unit or discharged easily to the atmosphere. The heat can also be utilized for fuel-reforming process. In case of hydrocarbon fuels, CO<sub>2</sub> is also produced. However, as the fuel is used more efficiently, the amount of CO<sub>2</sub> emission is less, compared to that when the same fuel is used in conventional thermal plants with the same output. Other pollutants are negligible compared to conventional thermal plants, as shown in Table 12.2.

Splitting of water is thus possible at the expense of renewable energy to produce the secondary fuel, H<sub>2</sub>. On use, H<sub>2</sub> and O<sub>2</sub> recombine to produce water again and energy is released. This route is therefore a clean and sustainable route of energy supply.

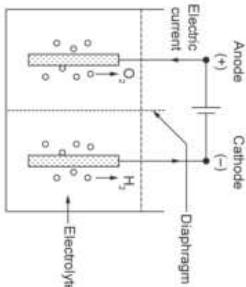
### (a) Thermo-chemical Methods

Steam reforming of methane is the most energy-efficient, commercialised technology currently available and most cost-effective when applied to large, constant loads. The method accounts for 95% of the hydrogen production in USA. The steam-reforming method has been described in the previous section on fuel cells. Partial oxidation method of biomass has been described in Chapter 8 on biomass.

### (b) Electrolysis of Water

Electrolysis is the simplest method of hydrogen production. Currently this method is not as efficient or cost-effective as thermo-chemical method using fossil fuels or biomass. But it would allow for more distributed hydrogen generation and open the possibilities for use of electricity generated from renewable and nuclear resources for hydrogen production.

An electrolysis cell essentially consists of two electrodes, commonly flat metal or carbon plates, immersed in an aqueous conducting solution called electrolyte, as shown in Fig. 12.10. A direct current decomposes water into H<sub>2</sub> and O<sub>2</sub>, which are released at the cathode (-ive electrode) and anode (+ive electrode) respectively. As water itself is a poor conductor of electricity, an electrolyte, commonly aqueous KOH, is used.



Ideally, a decomposition voltage of 1.23 V per cell should be sufficient at normal temperature and pressure; however, due to various reasons a voltage of about 2 V per cell is applied in practice. The energy required is 3.9–4.6 kWh per m<sup>3</sup> of hydrogen produced. About 60–70% of this energy is actually utilised in electrolysis. Therefore, the efficiency of electrolysis process is about 60–70%, which can be improved up to 80% by using a catalyst such as porous platinum or nickel. A diaphragm (usually woven asbestos) prevents electronic contact between the electrodes and passage of gas or gas bubbles. The electrolysis method is most suitable when primary energy is available as electrical energy, e.g., solar photovoltaic energy. It is also suitable where cheap electricity is available from other sources such as wind, geothermal, etc.

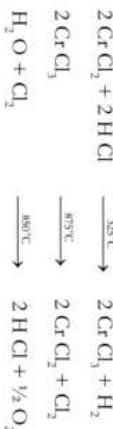
**Fig. 12.10** Electrolytic cell

woven asbestos) prevents electronic contact between the electrodes and passage of gas or gas bubbles. The electrolysis method is most suitable when primary energy is available as electrical energy, e.g., solar photovoltaic energy. It is also suitable where cheap electricity is available from other sources such as wind, geothermal, etc.

### (c) Thermolysis of Water

When primary energy is available in the form of heat (e.g., solar thermal), it is more logical to produce hydrogen by splitting water directly from heat energy using thermolysis. This would be more efficient than conversion of heat, first to electricity (using a heat engine-generator) and then producing hydrogen through electrolysis. The efficiency of a thermal plant is usually in the range of 32–38% and that of electrolysis is 80%. The overall efficiency through thermal-electrical-hydrogen route would thus be only 25–30%.

Direct thermal decomposition of water is possible but it requires a temperature of at least 2500°C. Because of temperature limitations of conversion process equipments, direct single-step water decomposition cannot be achieved. However, sequential chemical reactions at substantially lower temperature can be devised to split water into H<sub>2</sub> and O<sub>2</sub>. In the reaction series, water is taken up at one stage and H<sub>2</sub> and O<sub>2</sub> are produced in different stages. The energy is supplied as heat at one or more stages and partly released at some stage in the cycle. Apart from decomposition of water, all other materials are recovered when the cycle is completed. Therefore, the method is known as *thermo-chemical cycle*. The efficiency of conversion from heat energy to hydrogen is better than its conversion through electrolysis route only when the upper temperature of thermo-chemical cycle is above 700°C. For the upper temperature of 950°C, the efficiency of conversion is about 50%. This is a marked improvement over what is possible through the electrolysis route. Several thermo-chemical cycles have been proposed and are under investigation. One such cycle is given below:



At present, no commercial process for thermal splitting of water using thermo-chemical cycle is in operation.

### (d) Biophotolysis

In this method, the ability of the plants (especially algae) to split water during photosynthesis process is utilised. An artificial system is devised, which could produce hydrogen and oxygen from water in sunlight using isolated photosynthetic membrane and other catalysts. Since this process is essentially a decomposition of water using photons in the presence of biological catalysts, the reaction is called photolysis of water.

There are three distinct functional components coupled together in the system as shown in Fig. 12.11 (i) photosynthetic membrane, which absorbs light and splits water to generate oxygen, electrons and protons, (ii) an electron mediator,

which is reducible by photo-synthetically generated electrons, and (iii) a proton activator that will accept electrons from the reduced mediator and catalyze the reaction:  $2 \text{H}^+ + 2e^- \longrightarrow \text{H}_2$ .

A system with chloroplast (small bodies containing the chlorophyll in green plants) as a photosynthetic membrane to split hydrogen and oxygen, ferredoxin as  $e^-$  mediator and hydrogenase (an enzyme) or finely dispersed platinum as proton activator, has been successfully tested. The method is being extensively studied further.

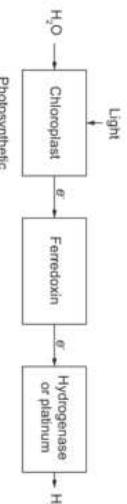


Fig. 12.11 Functional components of biophotolysis

### 12.2.3 Storage

Hydrogen can be stored as a discrete gas or liquid or in a chemical compound. For a given amount of energy, hydrogen weighs about one third of the fossil fuels, but it is bulkier. In liquid form it occupies 3.8 times the volume occupied by gasoline and in gaseous form it occupies 3.6 times the volume occupied by natural gas. However, in practice, the volume penalty is 20 to 50 per cent less, since hydrogen can be converted to other forms of energy at the user end more efficiently than fossil fuels.

Large amounts of hydrogen for subsequent distribution would probably be stored in the underground facilities similar to those used for natural gas, e.g., depleted oil and gas reserves and aquifers. On low or moderate scale, hydrogen is frequently stored in a strong steel tank or cylinder. The storage of compressed hydrogen gas in tanks is the most mature technology though the very density of hydrogen translates to inefficient use of space. The inefficiency can be mitigated with high compression such as 350–700 atm. However, further improvement in cost, weight and volume efficient storage is required in order to make it more acceptable by the end user.

Hydrogen can also be stored as compact storage in liquid form at low temperature. It takes up low storage volume but requires cryogenic containers, as the boiling point of hydrogen is 20° K. Furthermore, the liquefaction of hydrogen is an energy intensive process and results in large evaporative losses. About one third of the energy content of hydrogen is lost in the process.

Hydrogen can be stored at high densities in reversible metal hydrides. When required, it can be released by heating the hydride, and the original metal or alloy is

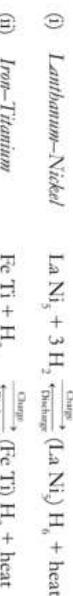
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recovered for further recycling. The pressure of gas released by heating depends mainly on temperature. At fixed temperature, the pressure remains essentially constant until the hydrogen content is almost exhausted. Metal hydrides offer the advantage of lower pressure storage, comfortable shape and reasonable volumetric store efficiency but have weight penalties and thermal management issues. It is also very safe. In case of accidental breakdown or storage, the gas remains in hydride and does not escape. To be suitable as a storage medium, a metal hydride should have following desirable properties:

- The metal (or alloy) should be inexpensive.
- The hydride should contain a large amount of hydrogen per unit volume and per unit mass.
- Formation of hydride from metal by reaction with hydrogen should be easy and the hydride should be stable at room temperature.
- The gas should be released from hydride at significant pressure and moderately high temperature (preferably below 100°C).

The reactions with three more promising hydrides of alloys are given below:



These hydrides contain somewhat more hydrogen than an equal volume. In theory  $(\text{La Ni}_3) \text{H}_6$  contains 1.35 per cent of hydrogen by weight,  $(\text{Fe Ti}) \text{H}_2$  contains 1.9 per cent and  $(\text{Mg}_2 \text{Ni}) \text{H}_4$  contains 3.6 per cent. Due to its heavy weight, hydride storage is not suitable for mobile storage such as vehicles. Some complex-based reversible hydrides such as aluminates have recently demonstrated improved weight performances over metal hydrides along with modest temperatures for hydrogen recovery.

Chemical hydrides are emerging as another alternative to direct hydrogen storage. The chemicals considered for store applications are a class of compounds that can be stored in solution as an alkaline liquid. Since the hydrogen is chemically bound in a compound and released by catalytic process, chemical hydrides present an inherent safer option than direct storage of volatile and flammable fuel. It is also volumetric efficient, however, cost and recycling issues are to be addressed.

Hydrogen can, in principle, be reversibly adsorbed on carbon structures (e.g., carbon nano-tubes). However, the design of a practical system requires a better understanding of the fundamental adsorption/desorption process and development of high-volume manufacturing process for the material.



### 12.2.4 Delivery

A key element in the overall hydrogen energy infrastructure is the delivery system that moves hydrogen from its point of production to an end-use device. Delivery system requirements vary with production method and end-use application. Hydrogen is a very efficient energy carrier. For distances greater than 300 km, it is cheaper to transmit energy as hydrogen than electricity via overhead transmission lines.

Hydrogen produced in centralised locations can be delivered: (i) via pipe line, or (ii) stored in tanks, cylinders, tubes, etc, that are loaded onto trucks and rail cars and transported to consumers. For high-demand areas, pipelines are the cheapest option. For low-demand areas, it is transported via road/rail. In the range of about 300 km, hydrogen is being transported via high-pressure cylinders. For very long distances in the range 1500 km, hydrogen is usually transported as liquid in super insulated, cryogenic tankers on road or rail. At present, the hydrogen delivery technologies cost more than the conventional fuel delivery. Improvements are needed in areas such as fueling components (like compressors, seals, valves, hose pipes and hydrogen detectors), material selection for pipelines and transportation containers for hydrogen.

### 12.2.5 Conversion

Hydrogen can be converted into useful forms of energy in several ways. Some of the hydrogen conversion technologies are unique to hydrogen, but all of them are efficient and less polluting than conventional fuels.

Once produced and delivered to consumer centre, hydrogen is used (i) to fuel internal combustion engines in the same manner as gasoline or natural gas to produce mechanical and electrical energy; (ii) for electrochemical conversion in fuel cells that generate electrical and thermal energy; (iii) for hydrogen/oxygen combustion for steam generation, (iv) for catalytic combustion, and (v) in metal hydride technologies.

Hydrogen and electricity are often considered as complementary energy carriers for the future. Hydrogen has some unique properties, which in conjunction with electricity makes it an ideal energy carrier for the future.

The specially designed/modified IC engine with hydrogen as fuel operates at high efficiency and produces no pollutants (except  $\text{NO}_x$  which is typically one order of magnitude smaller than emission from a comparable gasoline engine). Small amounts of unburned hydrocarbons, CO and  $\text{CO}_2$  have also been detected in hydrogen engines due to lubricating oil. A hydrogen engine is able to run even on lean mixtures of fuel, though with lower output. Due to lower energy content in a stoichiometric mixture in the engine's cylinder, the use of hydrogen in IC


  
Non-conventional Energy Resources

engines leads to some loss of power. The same engine running on hydrogen will have about 15% less power output as compared to its operation with gasoline.

In turbines and jet engines hydrogen can be used similar to conventional jet fuels. Use of hydrogen avoids the problem of sediments and corrosion of turbine blades. This prolongs the life and reduces maintenance. The inlet gas temperature can be increased beyond a normal gas turbine temperature of 800°C. Thus overall efficiency can be increased. However, the exhaust contains NO<sub>x</sub> which is a pollutant.

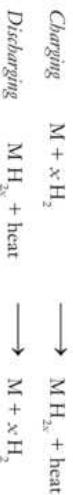
Hydrogen has traditionally been used in space programmes as fuel for rocket engines. The space programmes are currently the biggest consumers of liquid hydrogen. In fact, tremendous experience in hydrogen technology, including production, handling, liquefaction, storage, transportation, operational use and safety procedures has been gained as a result of space programmes. This experience may serve as the basis for further development and diversification of hydrogen energy technologies.

Combustion of hydrogen in oxygen results in pure steam with a flame zone temperature above 3000°C. Additional water has to be added to adjust the steam temperature to the desired level. Such a steam generator is close to 100% efficient, since there are no emissions and little or no losses. The hydrogen steam generator can be used to generate steam for spinning reserve in power plants, for peak-load power generation, for industrial use and as a micro-steam generator in medical and biotechnology.

It is also possible to burn hydrogen in oxygen in the presence of a suitable catalyst at temperatures significantly lower than flame combustion (i.e., from ambient to 500°C). This principle can be used to design catalytic burner and heaters. These burners can be used in household applications such as cooking ranges and space heaters.

Direct generation of electricity from hydrogen is possible through a fuel cell. Fuel-cell technologies have already been covered in detail in the previous section. These are more efficient than conversion through thermal link.

The property of hydrogen to form reversible metal hydrides may be used not only for its storage but also for various thermal energy conversion processes. Heat is generated while charging, i.e., chemical combination of hydrogen with metal (and alloy). Conversely, heat is absorbed while discharging, release of hydrogen from metal hydride.





Using this principle, any heat, such as waste heat, solar heat, geothermal heat, etc., can be stored, which can be released later for use. By increasing the pressure of hydrogen supplied, the temperature of heat released can be increased. Thus by regulating the pressure at the time of release of heat, the temperature can be increased or decreased.

The above-mentioned principle of controlling the temperature by regulating the pressure, can be used for space heating/ cooling/ refrigeration, operated by a heat energy source such as solar thermal energy.

In many applications, such as hydrogenation of vegetable oils, high purity hydrogen is needed. A hydriding substance absorbs only hydrogen but not other elements, which may be present as impurities. Using this property of hydrides, it is possible to purify hydrogen, in an inexpensive way.

The hydrogen purification technique may also be applied for separation of deuterium. Using a titanium–nickel alloy as the hydriding substance, it is possible to obtain 85% pure deuterium after only two steps. With three or four steps, it is possible to obtain 99.9% and 99.999% pure deuterium respectively.

### 12.2.6 Applications

Hydrogen can be used in combustion-based power generation, such as gas turbine using hydrogen alone or mixed with natural gas. Such applications are proposed for stationary power generation including backup power units, stand-alone power plants, distributed generation for buildings and cogeneration. Alternatively, hydrogen may be obtained from steam reforming of natural gas and then used in fuel cell to generate electricity.

Portable applications for fuel-cell based generation include consumer electronics, business machinery and recreational devices. These portable power applications range from 25 W for portable electronics to 10 kW system for critical commercial and medical functions and on-site power generation for individual homes and office buildings.

Hydrogen is also being proposed for commercial vehicles (bus, trucks, cars, trains etc.). Technologies are being developed to use hydrogen both in fuel cells and IC engines including methanol system.

### 12.2.7 Safety Issues

Like any other fuel or energy carrier, hydrogen poses risks if not properly handled or controlled. Some properties of hydrogen make it potentially less hazardous while other characteristics could make it more dangerous in certain situations.

Since hydrogen has the smallest molecule it has a greater tendency to escape through small openings than other liquid or gaseous fuels. As natural gas has over

three times the energy density per unit volume, the natural gas leak would result in more energy release than a hydrogen leak.

In case of a leak, hydrogen will disperse much faster than any other fuel, thus reducing the hazard level. The key parameter that determines if a leak would ignite is the lower flammability limit and hydrogen's lower flammability limit (which is 4% by volume) is four times higher than that of gasoline and slightly lower than that of natural gas.

Hydrogen has very low ignition energy (0.02 mJ) about one order of magnitude lower than other fuels. Consequently, a very weak spark can ignite it.

Because of its low density, hydrogen disperses more readily in an open (or ventilated) space, and it would therefore take much longer for the flammability limit to be reached.

Hydrogen flame is nearly invisible, which may be dangerous, because people in the vicinity of the flame may not even know there is fire. This may be remedied by adding some chemicals that will provide the necessary luminosity.

The emissions from hydrogen flame make it less likely to ignite or hurt nearby people or material by radiant heat transfer.

Liquid hydrogen presents another set of safety issues, such as risk of cold burns and the increased duration of leaked cryogenic fuel. The low temperature of the liquid may cause air to liquefy around control valves and pipes if they are not properly insulated. Since oxygen is more readily liquefied than air, oxygen-rich liquids may form around these points. This would greatly increase the flammability danger.

Liquid oxygen could also be formed from the air present in an empty tank or pipe when it is being filled with liquid hydrogen. The air must therefore be removed by purging with helium before filling with hydrogen.

Hydrogen onboard vehicles may pose a safety hazard. The hazards should be considered in different stages, i.e., when (i) the vehicle is inoperative, (ii) the vehicle is in normal operation, and (iii) in collision. The source of fire or explosion may arise from the fuel storage, from fuel supply line or from a fuel cell. The largest amount of hydrogen at any given time is present in the tank. Several tank failure modes may be considered both in normal operation and collision. Most of the failure modes may be either avoided or the occurrences and the consequences minimized by (i) leak prevention through proper system design and installing protection equipments, (ii) leak detection by adding an odorant to the hydrogen fuel, and (iii) ignition prevention by automatically disconnecting battery, thus eliminating the electrical spark, which are the cause of 85% fire after collision, in gasoline-powered vehicles.



### 12.2.8 Present Status

The United States currently produces about nine million tonnes of hydrogen per year. This hydrogen is used primarily in industrial processes including petroleum refining, petrochemical manufacturing, glass purification, and in fertilizers. It is also used in the semiconductor industry and for the hydrogenation of unsaturated fats in vegetable oil.

Only a small fraction of the hydrogen produced in the United States is used as an energy carrier, most notably by the National Aeronautics and Space Administration (NASA). Hydrogen is the optimum choice for fuel cells, which are extremely efficient energy-conversion devices that can be used for transportation and electricity generation.

Expanding the use of hydrogen as an energy carrier requires a fundamental change in the way we produce, deliver, store, and use energy. Putting it all together is the ultimate challenge. To achieve the goal of commercially-viable hydrogen and fuel-cell systems, research and development efforts are focused on the most promising technologies, and demonstrations are validating fully integrated systems operating in real-world conditions. While there are barriers to overcome, the benefits outweigh the costs.

In 2003, President George Bush proposed what is called the Hydrogen Fuel Initiative (HFI), which was later implemented by legislation through the 2005 Energy Policy Act and the 2006 Advanced Energy Initiative. These aim at further developing hydrogen fuel cells and its infrastructure technologies with the ultimate goal to produce fuel cell vehicles that are both practical and cost-effective by 2020. Thus far the United States has contributed 1 billion dollars to this project.

### Review Questions

1. What is a fuel cell and what are its main advantages?
2. What are potential applications of a fuel cell?
3. What are the main obstacles in the way of widespread use of fuel cells?
4. Describe the classification of fuel cells.
5. Comment on relative performances of various types of fuel cells.
6. Explain the principle of operation of an alkaline fuel cell.
7. Describe various fuels used in fuel cells along with chemical reaction involved.
8. Discuss the characteristics of a fuel cell and define various types of polarisations.
9. Draw a conceptual block diagram of a fuel-cell power plant and explain the details of each block.
10. What is the present state of development in fuel-cell technology?
11. Comment on environmental effects of fuel cell.
12. Comment on the possibilities of hydrogen as a potential energy carrier in future.
13. Explain various methods of production of hydrogen for use as energy carrier.
14. Describe various methods of storage of hydrogen.

10. 95% of the hydrogen production in USA is met  
(a) through electrolysis of water      (b) through thermolysis of water  
(c) through steam reforming of methane      (d) through biophotolysis
11. The simplest method of hydrogen production is  
(a) electrolysis of water      (b) thermolysis of water  
(c) steam reforming of methane      (d) biophotosynthesis
12. The most mature technology available for hydrogen storage is  
(a) liquid hydrogen storage at low temperature  
(b) metal hydride  
(c) carbon nano tubes  
(d) compressed hydrogen gas in steel tank or cylinder



# Miscellaneous Non-conventional Technologies

## *Introduction*

In this chapter, some technologies that convert thermal energy directly into electrical energy (without a mechanical link) are covered. The technologies considered are (i) MHD, (ii) thermoelectric, and (iii) thermionic power converters. These technologies are based on new concepts and at present are in initial stages of exploration. A feature common to all of them is that there are no moving parts. This feature is particularly of special interest to overcome motion related limitations/problems of conventional power conversion systems. While MHD is intended for large-scale central station power generation, the latter two are being developed for low power special purpose applications.

## **MAGNETO HYDRODYNAMIC (MHD) POWER CONVERSION**

A magneto-hydrodynamic (MHD) power generator is a device which converts the kinetic energy of the conducting (electrically) material, flowing in the presence of magnetic field directly into electrical energy. In a practical MHD generator, the energy of motion of the conducting fluid is derived from heat obtained by the burning of fossil fuel. Thus, heat is converted directly into electrical energy.

Faraday demonstrated the principle of MHD generation in 1836 by conducting an experiment on the Thames river. Because the water of the Thames is salty, it has a certain conductivity. The conducting fluid interacts with the earth's magnetic field to produce a small current through electrodes connected across the banks. Conventional electromagnetic power converters use the same principle. However, instead of using a solid metal, a conducting fluid is utilised in MHD generation.

MHD generators have not been employed for large-scale mass energy conversion because other techniques with comparable efficiency have a lower lifecycle investment cost. Advances in natural gas turbines achieved similar thermal efficiencies at lower costs, by having the turbine's exhaust drive a Rankine cycle steam plant. To get more electricity from coal, it is cheaper to simply add more low-temperature steam-generating capacity.

### 13.1.1 Basic Principle

Let a conducting gas, having a conductivity of  $\sigma \text{ mho/m}$ , moves at a speed  $u$  across the magnetic field  $B$ . The speed  $u$  and magnetic field  $B$  are held mutually perpendicular along the  $x$ -axis and  $y$ -axis respectively. The electrodes, having area  $A$ , are held at a distance,  $d$  along the  $z$ -axis, thus perpendicular to both  $u$  and  $B$ , as shown in Fig. 13.1. The magnitude of a force acting on a charged particle having charge  $q$  is given by  $q u B$ . This force, as per right-hand rule, will be acting in the upward direction (on a positively charged particle). The positively charged particles will be collected by the upper electrode and the negatively charged particles by the lower electrode, causing a potential difference  $V$  across them. The resulting electric field between the plates is given by:

$$E = -\frac{V}{d}$$

Due to this field, another force  $q E$  will be acting on the charged particle in the downward direction. The net force acting on the charged particle:

$$F_{\text{net}} = q E + q u B$$

$$\text{or } F_{\text{net}} = -q \frac{V}{d} + q u B$$

If no load is connected across the electrodes (i.e., open-circuit condition), no current will flow, and there will be no net movement of carriers between electrodes. Therefore, no net force will be acting on the charged particles. A voltage,  $V_o$  (open circuit voltage) appears across the electrodes. Thus,

$$F_{\text{net}} = -q \frac{V_o}{d} + q u B = 0$$

$$V_o = B u d \quad (13.1)$$

Now, if an external load  $R_L$  is connected across the terminals, current starts flowing through the load transferring power to the electrical load. As per maximum power transfer theorem, maximum output,  $P_{\text{max}}$  is obtained when the load resistance is equal to the internal resistance,  $R_i$  of the MHD generator.

$$P_{\text{max}} = V' I \quad (\text{for } R_L = R_i)$$

$$= (I R_i) I = I^2 R_i$$

$$\text{or } = \left( \frac{V_o}{R_L + R_i} \right)^2 R_i$$

$$P_{\text{max}} = \frac{V_o^2}{4 R_i} \quad (13.2)$$



From Eq. 13.1:

$$P_{\max} = \frac{B^2 \mu^2 d^2}{4 R_s} \quad (13.3)$$

Internal resistance of MHD generator is the resistance of the conducting fluid flowing between the electrodes. Thus,

$$R_s = \frac{1}{\sigma A} \frac{d}{A}$$

Therefore,

$$P_{\max} = \frac{1}{4} \sigma \mu^2 B^2 A d \quad (13.3)$$

The maximum power output per unit volume is given by

$$P_{\max}/A d = \frac{1}{4} \sigma \mu^2 B^2 \quad (13.4)$$

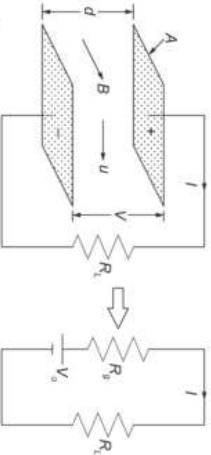


Fig. 13.1 Basic principle of MHD generation and equivalent circuit

### 13.1.2 MHD Generator

An MHD generator is a divergent channel or duct made of a heat-resistant alloy (e.g. inconel) as shown in Fig. 13.2. A magnetic field is applied at right angles to the channel length and electrodes are provided at right angles to both the magnetic field and flow of gas. A conducting fluid (ionized gas) is forced into the MHD channel at high speed and high temperature through a nozzle. It expands as it moves forward and leaves the duct at lower temperature and pressure. In this respect, an MHD converter system is a heat engine, which receives heat at high temperature, converts a part of it into useful work (electricity in this case) and rejects the remaining heat at a lower temperature. The efficiency of an MHD converter alone is about 20–25 %. In practice, however, an MHD converter is never made to operate alone. The exhaust of an MHD system is used to raise steam

for a conventional steam plant. Thus, by using MHD as a topping cycle for the conventional steam system, an overall efficiency of 50–60% should be possible.

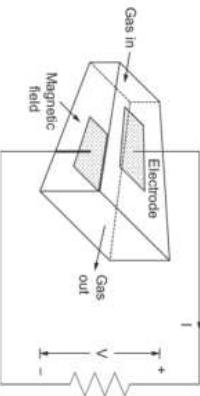
MHD generation looks more promising for direct thermal to electrical power conversion in large-scale central power stations. Several economical and physical factors have led to design outputs of the order of 1000 MW or so.

As seen in Eq. 13.4, the output power per unit volume of the duct is proportional to the conductivity of the working fluid. A practical MHD generator requires minimum conductivity of 10 mho/m. The working fluid, a gas, itself is a non-conductor at ordinary temperature. It is rendered conducting in two ways:

### (i) By Inducing Ionization in the Working Fluid

Ionization by thermal means alone would require a temperature of several tens of thousands of degrees Celsius. A more practical way is to inject a solid seed material up to about 1% of the total flow rate. The seed material contains an element, commonly potassium or cesium, which ionizes relatively easily when heated.

### (ii) By Incorporating a Liquid Metal into Flowing Carrier Gas



The power output of an MHD generator is also proportional to squares of magnetic flux density and gas speed. Due to limitations of enhancing conductivity beyond a certain limit, a strong magnetic field and high gas velocities are required for large outputs.

Conventional electromagnets are not practical in the range of required flux density of above 2 Tesla. Consequently, superconducting magnets are being proposed for such applications. The required gas velocities for large outputs are in the range of around 1000 m/s.

### 13.1.3 Advantages

The main advantages are the following:

- (i) Conversion efficiency of MHD–steam hybrid plant may be as high as around 50–60%. The fuel is better utilised.
- (ii) MHD generation uses no moving parts and therefore, all problems/



limitations associated with it are also absent.

- (iii) MHD unit is capable of rapid starting (reaching full power level soon after starting) and taking up peak loads in an interconnected system.
- (iv) Lower emission of pollutants due to better pollution control.
- (v) An MHD plant is compact and requires comparatively less space.

#### **13.1.4 Disadvantages/Limitations**

MHD generation has some serious limitations. The most important among them are:

- (i) Very high operating temperature restricts the choice of material for various equipments.
- (ii) Life of equipments is short due to high temperature stresses.
- (iii) The output power is available as dc. Inversion is required for integrating it into a grid.
- (iv) There are technical limitations on enhancing the fluid conductivity and the strength of magnetic field.

#### **13.1.5 MHD Systems**

There are two types of MHD generating systems: (i) open cycle, and (ii) closed cycle. In an open-cycle system, the working fluid is used on once-through basis, whereas in closed cycle system, the working fluid is continuously recirculated.

##### **(i) Open-cycle System**

The main features of an open-cycle system are shown in Fig. 13.3. Hot flue gases at about  $2300\text{--}2700^{\circ}\text{C}$ , obtained from burning of coal (or other fuel) in a combustor are used as working fluid, after mixing with seed material. Aqueous potassium carbonate is generally sprayed for the purpose of seeding. To attain such a high temperature, compressed air is preheated at least up to  $1100^{\circ}\text{C}$  before supplying to the combustor. The working fluid enters the MHD channel through a nozzle and produces dc output. An inverter is used to obtain  $50\text{ Hz}$  ac output for supply to consumers. The exhaust of an MHD channel is first used to preheat the air intake for combustor and then to raise the steam in a waste-heat steam generator. The steam so produced is used to generate additional power through a conventional turbine-generator system. The flue gases are released to the atmosphere through a chimney after seed recovery and removal of pollutants. The recovered seed material is recycled after mixing the additional quantity to make up for the loss of seed. Seed recovery is important for prevention of atmospheric pollution and for economic reasons.

seed material is then added to make up for the loss of seed through leakage. The seed, cesium metal, is more expensive than potassium but attains adequate conductivity at a relatively lower temperature of  $1900^{\circ}\text{C}$ . As little makeup seed is required due to closed-loop operation, an expensive but better seed material may be advisable. The lower temperature operation also permits wider choice of material for various equipments. However, operation at lower temperature also reduces the thermal efficiency of the cycle. The dc output available from the MHD generator is inverted to obtain grid quality ac.

The residual heat of a used organ is utilized to generate additional power through a waste heat boiler (secondary heat exchanger, HX2), turbine and generator. A part of the steam produced is also used to power the argon cycle compressor through a steam turbine.

**(b) Liquid Metal-Inert Gas Carrier System** In this system, instead of seeding a liquid metal (such as Na, K or Li) is incorporated in the inert carrier gas for conductivity requirement. These metals are excellent electrical conductors in the liquid state but their vapours are poor conductors. Therefore, these are used in the working fluid in the liquid state only.

A liquid sodium-based closed loop MHD generating system with coal as input energy is shown in Fig. 13.5. The carrier gas is pressurised and heated by a passage through primary heat exchanger within the combustor. The hot gas is then incorporated into the liquid metal (usually sodium) to form the working fluid. The working fluid thus consists of gas bubbles uniformly dispersed in an approximately equal volume of liquid sodium metal. After passing through the MHD duct, the liquid metal is separated from the carrier gas. The residual heat in the gas is utilized in the same way as explained above for the case of seeded inert gas carrier system.

The boiling point of sodium is below  $882.9^{\circ}\text{C}$  and therefore the working fluid temperature is usually kept around  $815^{\circ}\text{C}$ . A lower operating temperature offers the benefit of wider material choice but at the same time lowers the thermal efficiency. The operating temperature and hence the efficiency can be increased by replacing sodium by lithium that has a boiling point of  $1300^{\circ}\text{C}$ . However, lithium is much more expensive than sodium.

An MHD system can also be coupled to a fast breeder reactor. Liquid metals have both excellent electrical and thermal conduction properties. Therefore, a liquid metal is used as coolant in the reactor as well as a working fluid in the MHD duct. A layout diagram of liquid potassium fast breeder reactor fueled MHD system is shown in Fig. 13.6. After receiving heat from the reactor, the liquid potassium is passed through a nozzle to get high speed. The vapours formed due to nozzle action are separated, condensed and returned to the reactor. The

**Example****13.1**

Calculate the open-circuit voltage and maximum power output for an MHD generator having the following data:  
 Plate area =  $0.25 \text{ m}^2$   
 Distance between the electrodes =  $0.50 \text{ m}$   
 Flux density =  $1.8 \text{ WB/m}^2$   
 Average gas velocity =  $1200 \text{ m/s}$   
 Gaseous conductivity =  $10 \text{ mho/m}$

**Solution**

Given,

$$A = 0.25 \text{ m}^2, d = 0.5 \text{ m}, B = 1.8 \text{ WB/m}^2, \mu = 1200 \text{ m/s}, \sigma = 10 \text{ mho/m}$$

From Eq. 13.1, the open-circuit voltage of the generator:

$$\begin{aligned} V' &= B \mu d \\ &= 1.8 \times 1200 \times 0.5 \\ &= 1080 \text{ V} \end{aligned}$$

Maximum power output of the generator is given by Eq. 13.4:

$$\begin{aligned} P_{\max}/Ad &= \frac{1}{4} \sigma \mu^2 B^2 \\ P_{\max} &= \frac{1}{4} \sigma \mu^2 B^2 Ad \\ &= \frac{1}{4} \times 10 \times 1200^2 \times 1.8^2 = \times 0.25 \times 0.5 \\ &= 1.458 \text{ MW} \end{aligned}$$

**13.2 THERMOELECTRIC POWER CONVERSION**

Thermoelectric power converters, converts heat directly to electricity through thermoelectric effect. Its salient features compared to other methods are compactness, light weight, noiseless operation, no moving parts and high reliability. It has the lowest maintenance of any commercial power source and can also be operated by low-grade waste heat ( $< 200^\circ\text{C}$ ). It is ideally suited for remote and harsh environments. It is being intended for high-tech applications associated with aerospace, military, telecommunications and control of unmanned vehicles monitored from remote locations. It is designed for 20 years of service life.

The basic principle behind a thermoelectric power generator is the Seebeck effect, which was discovered in 1821 and is stated as "whenever there is a temperature difference between the two junctions in a loop, made up of two dissimilar conductors, a thermal electromotive force is produced in the loop". Such a loop is known as a thermocouple and is shown in Fig. 13.7. The effect is more

pronounced in thermocouples formed with *P*-type and *N*-type semiconductor materials. In *N*-type materials, the current flows in the direction of heat flow. The emf produced is proportional to the temperature gradient between the two junctions. The power produced, *P* is

$$P = Q_e - Q_i = I^2 R_{ij}, \text{ which is proportional to } \Delta T^{1.2} \quad (13.5)$$

where  $Q_e$  = heat flow rate into hot junction

$Q_i$  = dissipated heat flow rate from cold junction

$$\Delta T = T_h - T_c$$

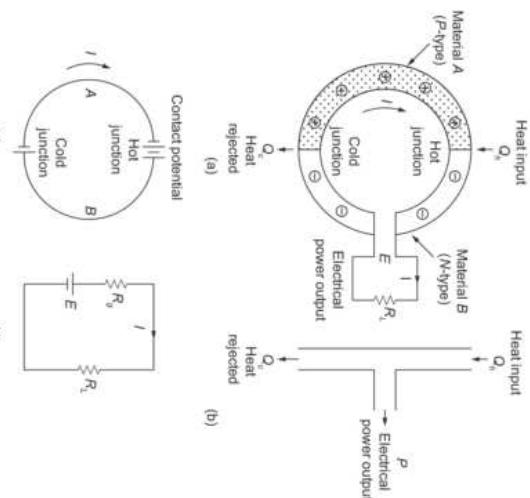


Fig. 13.7 Elementary thermocouple

Materials *A* and *B* have different carrier concentrations. When a junction is formed, a contact potential is produced due to transfer of carriers across the junction from the high-concentration to the low-concentration side. When both junctions are held at the same temperature, contact potentials are same and the net voltage in the loop is zero. In case of differential temperature, more carriers at the high-temperature junction will cross to other side of the junction as they acquire higher energy, thus increasing the contact potential at this junction. A net emf is thus produced in the loop.



The open circuit emf of the thermocouple is given by

$$E = \Delta\alpha \Delta T \quad (13.6)$$

where  $\Delta\alpha = \alpha_A - \alpha_B$ ; Seebeck coefficient for junction of materials A and B

$\alpha_A$  = Absolute Seebeck coefficient for the material A, V/K

$\alpha_B$  = Absolute Seebeck coefficient for the material B, V/K

A figure of merit Z for thermocouples is defined as

$$Z = \frac{(\alpha_A - \alpha_B)^2}{(\sqrt{\rho_A k_A} + \sqrt{\rho_B k_B})^2} \quad (13.7)$$

where  $\rho_A$  and  $\rho_B$  are resistivities of materials A and B respectively in  $\Omega \text{ m}$ , and  $k_A$  and  $k_B$  are the thermal conductivity in  $\text{W/m K}$ .

Seebeck effect can be +ive or -ive. A high magnitude of Z requires two materials with a wide difference of the absolute Seebeck coefficients (i.e., opposite polarity) and low resistivity as well as low thermal conductivity. For high efficiency,  $ZT$  should be as high as possible. The power output can also be given as:

$$P = \Delta\alpha \Delta T I - R_{\text{L}} I^2 = R_{\text{L}} I^2 \quad (13.8)$$

For maximum output power,  $R_{\text{L}} = R_{\text{g}}$

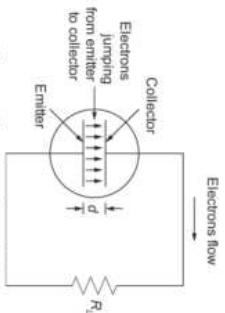
$$\text{Therefore, (using Eq 13.6), } I = \frac{E}{R_g + R_{\text{L}}} = \frac{\Delta\alpha \Delta T}{2R_g}$$

$$\text{Maximum output power, } P_{\text{max}} = I^2 R_g = \frac{E^2}{4R_g}$$

$$\text{or } P_{\text{max}} = \frac{\Delta\alpha^2 \Delta T^2}{4R_g} \quad (13.9)$$

### 13.2.1 Thermolectric Power Generator

An elementary thermoelectric generator consisting of one pair of thermocouples is shown in Fig. 13.8. The voltage and power output of one pair is very small. Several such units may be connected in series to get a workable voltage.



**Fig. 13.9 Elementary thermionic converter**

In principle, a thermionic converter consists of two metals (electrodes) with different work functions sealed into an evacuated vessel. The electrode with larger work function is maintained at higher temperature than one with a smaller work function. The hot electrode (emitter) emits electrons and acquires a +ive charge, whereas colder electrode (collector) collects electrons and becomes negatively charged.

A voltage is thus developed between the electrodes and a direct current will flow in an external circuit connecting them as shown in Fig. 13.9. The voltage, which may be around 1 V (or so), is determined primarily by the difference in work functions of the electrode materials. Current densities of few tens to few hundreds of amperes per square cm of emitter area are achieved above 1000°C. emitter temperature.

The output voltage is the Fermi potential difference between the emitter and the collector (assuming thermoelectric effect in the converter to be negligible). The output power depends on emitter temperature and work function magnitude difference between emitter and collector. Thermal efficiencies in range 5–25% have been achieved.

The emission of electrons from an emitter is inhibited by space charge (electron cloud) resulting from the accumulation of electrons in its vicinity. The electron cloud deters additional electrons from crossing the gap. This space charge can be greatly reduced (i) by decreasing the gap between the electrodes, and (ii) by introducing a small quantity of cesium to neutralise the space charge. Cesium has low ionization potential and thus can be ionized relatively easily through thermal means. At high temperature (above about 1000°C), cesium ionizes to produce + ions. By combining with electrons in the vicinity of the emitter, the +ive ions help to decrease the space charge.

In the ideal case, the space charge barrier and back emission current from the collector to the emitter are neglected. The ideal current density,  $J_o$ , would then be given by

$$J_o = \begin{cases} A_E T_E^2 \exp\left(-\frac{\Phi_E}{k T_E}\right), & V_o \leq V_c \\ A_E T_E^2 \exp\left(-\frac{\Phi_c}{k T_E}\right) \cdot \exp\left(-\frac{eV_o}{k T_E}\right), & V_o > V_c \end{cases} \quad (13.10)$$

where  $V_o$  : output voltage, V



$\phi_E - \phi_C$  : work functions of emitter and collector respectively, eV

$V'_C := (\phi_E - \phi_C)/e$ , contact potential between emitter and collector, V

$A_E$  : Richardson constant of emitter (ideal value =  $120\text{ A}/(\text{cm}^2 \cdot \text{K}^2)$ )

$T_E$  : temperature of emitter

From Eq. 13.10, it is clear that emitter work function and temperature are two critical parameters for large thermionic current. Low emitter work function is needed for high emission at low temperature. For significant emission, an emitter temperature of at least  $1000^\circ\text{C}$  is generally needed and still higher temperatures are better. Also, a large work function difference between emitter and collector is desirable for large output voltage. Although temperature has little effect on the generated voltage, the current (per unit emitter area) increases with temperature, resulting in the increase in the power output.

A common thermionic combination is a tungsten emitter and a cesium-coated copper, nickel or silver collector. Cesium is coated on a collector in such a way that final work function potential of the collector becomes that of cesium. Cesium has one of the lowest work functions of about  $1.75\text{ eV}$ . The magnitudes of work functions for some materials are given in Table 13.2.

**Table 13.2** The magnitude of work functions for some materials

SN	Material	Work function (eV)
1.	Pt (Platinum)	6.15
2.	Ni (Nickel)	5.0
3.	Ag (Silver)	4.65
4.	W (Tungsten)	4.5
5.	Cu (Copper)	4.3
6.	Mo (Molybdenum)	4.25
7.	Li (Lithium)	2.21
8.	Na (Sodium)	2.0
9.	K (Potassium)	1.9
10.	Cs (Cesium)	1.75

The biggest problem with thermoelectrics is that while heat pushes electrons in one direction, the material itself redistributes most of that heat through simple conduction. This means that most of the heat is not usefully harnessed, and instead flows through the system in all directions, drastically reducing efficiency. In addition, fabrication and operation of TEC's has been difficult and expensive.

Thermionic converters are special because the electrons move across a gap—and that gap, since it is not a solid, is an excellent insulator. The heat is trapped on one side; leaving the other side ready to accept a steady flow of excited electrons. This means the heat is utilised more efficiently.



Thermionic emission can be further enhanced by lowering the work function of the cathode by optimizing the 'Avio effect'. The method involves precise texturing of the cathode surface at the nanoscale level. This causes a marked reduction in the material's work function, allowing electrons to flow more freely into the vacuum. Power Chips plc (US OTC: PWCHF) is working on developing 'Power Chips<sup>TM</sup>', which are projected to be the most effective heat-energy converters. Power Chips will operate up to 70–80% of the maximum (Carnot) theoretical efficiency. This may be one of the first industrial applications of nanotechnology. 'Power Chips plc' also proposes to use this device in a hybrid electric car to harness additional power from the waste heat of the exhaust.

In the past, application of thermionic converters has been limited to space power systems, because of their high operating temperature and relatively low efficiency. Several recent advances in thermionic energy conversion technology have greatly improved the efficiency of these devices.

Potential areas of applications identified for thermionic converters are (i) centralised and distributed power generation, (ii) residential and commercial site applications, (iii) land, sea and air vehicles, (iv) aerospace and military systems, and (v) electronics and data communications.

Applications can be divided into two categories according to their heat source: (a) primary heat, the system is called topping cycle, or (b) waste heat, the system is called bottoming cycle. Bottoming cycle consumes no fuel, and hence they are some of the most cost-effective applications.

Concentrating solar power collectors currently harvesting thermal energy in residential and commercial venues could be retrofitted with a topping cycle based thermionic converter. Compared to a photovoltaic system, which produces only high-cost electricity, a thermionic-based system could convert one-fifth of the captured energy into electricity and the rest into thermal energy for water and/or space heating. Heating systems fired by gas, oil or other fuel could also be used to provide electrical supply through thermionic converter during power-grid outage periods.

High power-to-weight ratio, low noise and broad scalability, offers great potential in aerospace and military systems. Applications range from portable power generators for tactical systems, solar energy arrays to waste heat recovery from exhaust of a variety of land, sea and air-propulsion systems.

In fossil-fuel based conventional plants, a part of waste heat may be recovered as useful electricity using a thermionic converter in the bottoming cycle. It increases the overall generating efficiency by reducing fuel consumption. Also, it releases no additional chemical emissions into the atmosphere or water supplies.



### Review Questions

1. Describe the basic principle of operation of an MHD generator. Derive expressions for maximum power generation per unit volume of a generator.
2. What are the major advantages and limitations of an MHD generating system?
3. With the help of a schematic diagram, explain the operation of closed cycle MHD generating system.
4. Explain the heating and cooling applications of a thermoelectric system. Comment on the type of materials used for low and high-temperature applications.
5. Mention the merits of a thermionic converter. On what parameters do the output voltage and current depend?
6. Comment on the type of materials required in a thermionic converter.
7. What are the potential applications of thermionic converters?

### Problem

1. Calculate the open-circuit voltage and maximum power output for an MHD generator having following data:  
 Plate area =  $0.25 \text{ m}^2$   
 Distance between the electrodes =  $0.50 \text{ m}$   
 Flux density =  $2 \text{ Wb/m}^2$   
 Average gas velocity =  $1000 \text{ m/s}$   
 Gaseous conductivity =  $10 \text{ mho/m}$

(Ans. 1000 V, 1.25 MW)

### Objective-type Questions

1. In a practical MHD system, the exhaust of MHD generator is
  - used as hot air for combustion in a furnace
  - used as input to a gas turbine to generate additional power
  - used as input to a boiler to raise steam for steam turbine to generate additional power
  - let-off to atmosphere
2. Techno-economic factors make MHD generator feasible
  - only for large-scale central power stations
  - only for small-scale distributed power generation
  - at any situation irrespective of size
  - only to meet peak power demand
3. The working fluid used in an MHD system coupled to a fast breeder reactor is a
  - hot flue gas
  - seeded inert gas
  - liquid metal-inert gas mixture
  - liquid metal only
4. MHD generators have not become popular because
  - of difficulties in material selection
  - of difficulties to obtain strong magnetic field



# Financial and Economic Evaluation

## Introduction

For all projects aiming at the production/consumption of energy it is necessary to choose the most economic energy supply route for a given requirement. A large number of energy systems with unique peculiar features are available. The energy supply through a solar energy system for example, is diurnal and generally requires storage for its use, whereas wind energy is fluctuating and intermittent and generally requires a grid connection to maintain steady supply. To get a meaningful insight of these complex alternatives, a systematic evaluation of their financial and economic aspects is essential. Such studies also help to optimise the allocation of funds by concentrating on those applications which are financially/economically more rewarding besides being socially acceptable and environmentally sustainable. Many failures can be avoided by proper understanding of the financial and economic strengths/weaknesses of various available options.

This chapter explains to students how to conduct economic feasibility studies to help the management make sound investment decisions for capital projects in the private and public sectors with particular reference to renewable energy systems. Engineering economics seeks to provide the analytical framework for decision making from an economic point of view, and to advance the engineer's role in the decision process. The economic concepts and analytical methods required for the preparation of economic feasibility studies are briefly discussed in this chapter.

## 14.1

### BASIC TERMS AND DEFINITIONS

#### 14.1.1 Cash-flow Diagram

Any organisation usually has frequent receipts and disbursements taking place over a particular interval of time. These transactions can be shown on a cash-flow diagram. A cash-flow diagram is simply a graphical representation of cash flows drawn on a time scale, as shown in Fig. 14.1. The horizontal line represents the progression of time from left to right. The time scale is divided into equal intervals, known as interest periods. The numbers 1, 2, 3, ...,  $n$ , on the time scale represent the end of corresponding periods. Time '0' represents the starting date or present time. The vertical arrow pointing upwards indicates positive cash flow (cash receipt, income), and the arrow pointing downwards indicate negative cash flow (disbursement, cost). At any point in time, the net cash flow would be represented as:

Net cash flow = receipts – disbursements

Within one interest period cash flows may take place at any time. However, a simplifying assumption made is that all cash flows occur at the end of an interest period. This practice in engineering economics is known as **end of period convention**. Thus, for all receipts and disbursements occurring within a given interest period, the net cash flow is assumed to occur at the end of the interest period.

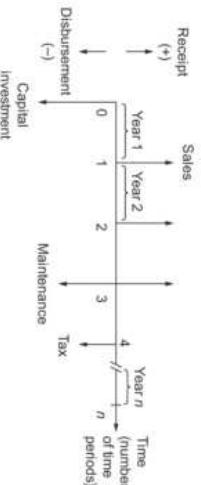


Fig. 14.1 Cash-flow diagram

### 14.1.2 Principal Amount, $P$

This is the amount of money that is considered initially. It might be an amount to be invested or loaned, or it may refer to the initial value or cost of a plant or machinery.

### 14.1.3 Interest

Interest is the payment (other than the sum borrowed) made for the money borrowed from a bank or financier. In other words, interest is the consideration which the moneylender receives for the use of the money lent. Alternatively, interest may be regarded as the return obtained by the productive investment of capital.

**Interest Rate,  $i$**  Interest rate is essentially a measure of the productivity of money as a resource. Alternatively, interest rate is a measure of the investor's preference for the time value of the money. Thus an interest rate of 10 per cent would mean that the investor regards a sum of money worth 10 per cent less next year than it is worth this year. Interest rates are also quoted for a period other than one year. However, unless otherwise stated, it is customarily understood to be specified on annual (per annum) basis.

**Cost of Capital** It is usually defined as the minimum rate of return that an investor (or company) expects to earn on his/her investment.



#### 14.1.4 Number of Time Periods, $n$

This is the number of time intervals over which the amount of money is being invested or borrowed. Although  $n$  is usually the number of years, it may represent other time periods such as the number of quarters or months.

#### 14.1.5 Kind of Interest

(a) **Simple Interest** Simple interest is directly proportional to the capital involved, the number of interest periods and the interest rate. The total interest  $I$  on the principal  $P$  for  $n$  number of interest periods at the interest rate  $i$  (expressed as fraction) is given by,

$$I = P n i$$

In general, simple interest is applied only for short-term periods like a duration of less than one year.

(b) **Compound Interest** When the simple interest is added to the principal amount so that the resulting amount becomes the principal amount for the next term (period), the interest so obtained is called compound interest. These days, a compound-interest approach is used more frequently than that of simple interest.

An amount  $P$  invested at an annual interest rate of  $i$  compounded annually, after  $n$  years becomes,

$$F = P (1 + i)^n \quad (14.1)$$

In the above equation,

$P$  is known as the present value of the investment,

$i$  is the annual interest rate,

$n$  is number of interest periods, and

$F$  is the future value of the investment.

When the period of interest is less than one year, compound interest rates may be quoted in two ways:

(i) **Nominal Interest Rate** Nominal interest rate is the annual interest rate obtained simply by converting the interest rate specified for one period (where the period is less than one year) to a year disregarding the effect of compounding after each period. For example, an interest rate of 2% compounded each month for a year is typically quoted as 24% ( $2 \times 12$ ) nominal interest rate or annual interest rate.



(ii) **Effective Interest Rate** It represents the actual or exact rate of interest upon the principal during a specified period. The effective interest rate based on a year is referred as the effective annual interest rate.

If  $i$  represents the nominal interest rate per year, and  $m$  the number of interest (compounding) periods per year, the effective annual interest rate  $i_e$  may be expressed as

$$i_e = \left(1 + \frac{i}{m}\right)^m - 1 \quad (14.2)$$

Now for 24% nominal interest rate, the effective interest rates are as follows

- For quarterly compounding ( $m=4$ )

$$i_e = \left(1 + \frac{0.24}{4}\right)^4 - 1 = 0.262 \text{ or } 26.2\% \text{ per annum}$$

- For monthly compounding ( $m=12$ )

$$i_e = \left(1 + \frac{0.24}{12}\right)^{12} - 1 = 0.268 \text{ or } 26.8\% \text{ per annum}$$

- For daily compounding ( $m=365$ )

$$i_e = \left(1 + \frac{0.24}{365}\right)^{365} - 1 = 0.27115 \text{ or } 27.115\% \text{ per annum}$$

- For continuous compounding ( $m=\infty$ )

When the interest is compounded continuously, i.e., an infinite number of times per year, the annual effective rate of interest will be given by

$$i_e = e^r - 1 \quad (14.3)$$

$$i_e = e^{0.24} - 1 = 0.27125 \text{ or } 27.125\% \text{ per annum}$$

Continuous compounding is very seldom used in engineering economic studies.

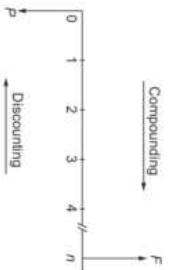
## 14.2 CALCULATIONS FOR THE CASE OF SINGLE PAYMENT (OR RECEIPT)

### 14.2.1 Single-payment Compound-amount Factor or Future-value Factor

When an amount  $P$  is invested for  $n$  equal interest periods with  $i$  as the interest rate, the future value of the investment obtained according to Eq. 14.1 is

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Non-conventional Energy Resources



**Fig. 14.2 Single payment and future value**

$$F = P (F/P, i, n)$$

### Example

What will be the amount of Rs 2,000 invested at 12% interest is compounded annually at the end of 6 years?

## 14.1

### Solution

Given,

$$P = 2,000, \quad i = 0.12, \quad n = 6$$

From Eq. 14.1,

$$F = 2,000 (1 + 0.12)^6 \approx \text{Rs } 3,948$$

### Example

Find the number of years in which an investment of Rs 10 lakhs will double in value, if the interest rate is 12.25%.

## 14.2

### Solution

Given,

$$P = 10 \text{ lakhs}, \quad F = 20 \text{ lakhs}, \quad i = 0.1225$$

From Eq. 14.1,

$$20 = 10 (1 + 0.1225)^n$$

$$2 = (1 + 0.1225)^n$$

$$\log 2 = n \log (1.1225)$$

$$n = \log 2 / \log (1.1225)$$

$$n = 6$$

### 14.2.2 Single-payment Present-worth Factor

If the future value of an investment (or payment) is known, we can derive its present value, given an interest rate and the number of compounding periods for  $P$  in Eq. 14.1, giving

The factor  $(1 + i)^n$ , which is used to multiply  $P$  in order to derive  $F$  is called 'single-payment compound-amount factor'. It is usually designated as  $(F/P, i, n)$ . Therefore, the above relationship can be written as

$$(14.4)$$

As shown in the cash-flow diagram, (Fig. 14.2), the present value  $P$  is an outlay and it is represented by a downward arrow at time zero '0', while its future value  $F$  is an inflow represented by an upward arrow.



$$P = F \left[ \frac{1}{(1+i)^n} \right] \quad (14.5)$$

The expression in brackets, which is used to multiply  $F$  to obtain  $P$  is called '**single-payment present-worth factor**', and is designated as  $(P/F, i, n)$ . Therefore, Eq. 14.5 can be written as

$$P = F (P/F, i, n) \quad (14.6)$$

The process used in converting the future value to its present value is called **discounting**, and has wide application in engineering economy. In the above expression, the present value is calculated by discounting the future value of a given amount. The term  $i$  is known as the discount rate.

**Example** What is the present value of a future payment of Rs 100,000 due 10 years from now, if the nominal interest rate is 6%?

## 14.3

### CALCULATIONS FOR UNIFORM SERIES OF PAYMENTS (OR RECEIPT)

#### 14.3.1 Uniform-series Compound-amount Factor

Business firms and individual investors, in order to meet their future capital investment requirements, set aside each year a certain amount of savings which over time accumulate to an amount that, hopefully will meet their expected needs. In this case the

#### Solution

Given,

$$F = 100,000,$$

From Eq. 14.5

$$P = F \left[ \frac{1}{(1+i)^n} \right]$$

$$P = 100,000 \left[ \frac{1}{(1+0.06)^{10}} \right]$$

$$= \text{Rs } 55,839$$

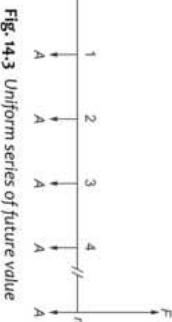


Fig. 14.3 Uniform series of future value

investment process involves investing an amount  $A$  each year. At the end of the  $n^{\text{th}}$  the year the principals plus the interest earned compounded annually becomes  $F$ , the future value of the investment as shown in Fig. 14.3.

The accumulated future amount  $F$  after  $n$  years may be calculated as:

$$F = A \left[ \frac{(1+i)^n - 1}{i} \right] \quad (14.7)$$

where  $A$  is the annual amount invested each year and compounded annually to accumulate  $F$ . The expression in the bracket is known as '**uniform series compound-amount factor**' and is designated as  $(F/A, i, n)$ . Therefore, Eq. 14.7 can be written as:

$$F = A (F/A, i, n) \quad (14.8)$$

### Example

What will be the future amount of a uniform payment of Rs 500 deposited at the end of each year with an interest rate of 9 per cent per annum, at the end of 6 years?

### 14.4

#### Solution

Given,

$$A = 500, \quad i = 0.09, \quad n = 6$$

From Eq. 14.7

$$F = 500 \left[ \frac{(1+0.09)^6 - 1}{0.09} \right] = \text{Rs. } 3,762$$

### 14.3.2 Uniform-Series Sinking-Fund Factor

When the future capital expenditure for a certain activity or project is known, the required amount  $A$  to be invested annually at a given interest rate can be determined from Eq. 14.7 as:

$$A = F \left[ \frac{i}{(1+i)^n - 1} \right] \quad (14.9)$$

The expression in the bracket is known as '**uniform series sinking fund factor**' and is designated as  $(A/F, i, n)$ . Therefore, Eq. 14.9 can be written as:

$$A = F (A/F, i, n) \quad (14.10)$$

**Example 14.5** The replacement of the tubular battery of a solar PV system at the end of four years is likely to cost Rs 12,000. What amount should a user deposit every year to accumulate the desired amount if he earns 9 per cent interest on his deposit?

**Solution**

$$\text{Given, } F = 12,000, \quad i = 0.09, \quad n = 4$$

From Eq. 14.9

$$A = 12,000 \left[ \frac{0.09}{(1 + 0.09)^4 - 1} \right] = \text{Rs } 2,624$$

### 14.3.3 Uniform-Series Present-Worth Factor

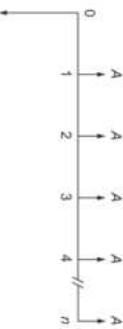


Fig. 14.4 Uniform series of present value

It is often required to know the present value  $P$  of a series of equal payments  $A$  (or receipts) over a number of years  $n$  at a given rate of interest  $i$ . Such a series is shown in Fig. 14.4.

The present worth  $P$  of a uniform series of cash flow can be determined using the following equation:

$$P = A \left[ \frac{(1 + i)^n - 1}{i(1 + i)^n} \right] \quad (14.11)$$

The expression in the bracket is known as 'uniform-series present-worth factor' and is designated as  $(P/A, i, n)$ . Therefore, Eq. 14.11 can be written as:

$$P = A (P/A, i, n) \quad (14.12)$$

### Example 14.6

In a major maintenance drive, replacing old machinery in a plant by more efficient one can reduce energy consumption leading to saving of Rs 30,000 at the end of each year for the next 8 years. Keeping the overall economy in mind, how much expenditure in the maintenance may be allowed if the interest rate is 10%.

**Solution**

$$\text{Given, } A = 30,000, \quad n = 8, \quad i = 0.1$$

Present worth of overall savings due to enhanced efficiency after maintenance from Eq. 14.11:

$$P = A \left[ \frac{(1 + i)^n - 1}{i(1 + i)^n} \right]$$



$$P = 30,000 \left[ \frac{(1 + 0.1)^6 - 1}{0.1(1 + 0.1)^6} \right] = \text{Rs. } 1,60,047$$

Therefore, at the most the above amount may be spent on the replacement at present.

### Example

A 100 litre-per-day domestic solar water heater saves consumption of electricity in an electric geyser on 100 days of the year by heating 100 litres of water from  $15^{\circ}\text{C}$  to  $60^{\circ}\text{C}$ . The useful life of the solar heater is estimated as 10 years. Determine the present worth of saving through the use of the solar water heater, if the efficiency of the electric geyser is 90% and the cost of electricity is Rs 4 per kWh. Assume interest rate as 12%.

#### Solution

Given,

$$n = 10, \quad i = 0.12$$

Electricity saved by the solar water heater in one day:

$$= \left( \frac{1}{0.9} \right) \times 100 \text{ kg} \times 4.2 \text{ kJ/kg } ^{\circ}\text{C} \times (60 - 15) ^{\circ}\text{C} \times \left( \frac{1 \text{ kWh}}{3,600 \text{ kJ}} \right)$$

$$= 5.83 \text{ kWh/day}$$

Monitory worth of electricity saved by solar water heater during one year:

$$= (5.83 \text{ kWh/day}) \times (100 \text{ days/year}) \times (\text{Rs. } 4/\text{kWh})$$

$$= \text{Rs. } 2,332$$

Therefore, annual saving,  $A = 2,332$

Present worth of overall savings during its lifetime of 10 years may be calculated from Eq. 14.11 as

$$P = A \left[ \frac{(1 + i)^n - 1}{i(1 + i)^n} \right]$$

$$P = 2332 \times \left[ \frac{(1 + 0.12)^{10} - 1}{0.12(1 + 0.12)^{10}} \right] = \text{Rs. } 13,176$$

### 14.3.4 Uniform-Series Capital-Recovery Factor

In engineering economy studies, the present value of an investment is frequently known, and what is to be found is the annual receipt (**annuity**) that



will be generated in the future over the life of the investment at a given rate of interest. Rearranging the terms in Eq. 14.11.:

$$A = P \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (14.13)$$

The expression in the bracket is known as uniform-series capital-recovery factor and is designated as  $(A/P, i, n)$ . Therefore, Eq. 14.13 can be written as

$$A = P(A/P, i, n) \quad (14.14)$$

**Example 14.8** A 2kW PV rooftop plant cost Rs.2,00,000 and has a useful life of 25 years. The annual average maintenance cost is 2% of the capital cost and the discount rate is 10%. Calculate the unit cost of a solar PV generated electricity if it supplies a load of 25% of its power rating for 10 hours daily.

**Solution** Given,

$$P = 200,000, \quad n = 25, \quad i = 0.1$$

The annualised capital cost is

$$A = P \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right]$$

$$A = 200,000 \left[ \frac{0.1(1 + 0.1)^{25}}{(1 + 0.1)^{25} - 1} \right]$$

$$A = 22,034$$

$$\text{Annual maintenance cost} = 0.05 \times 2,00,000 = 10,000$$

$$\text{Thus, total annual cost of a solar PV plant} = 22,034 + 10,000$$

$$= 32,034$$

$$\text{Annual electricity production} = 2 \times 0.25 \times 10 \times 365$$

$$= 1,825 \text{ kWh}$$

$$\text{Therefore, unit cost of electricity production} = \frac{32,034}{1,825}$$

$$= \text{Rs } 17.60$$

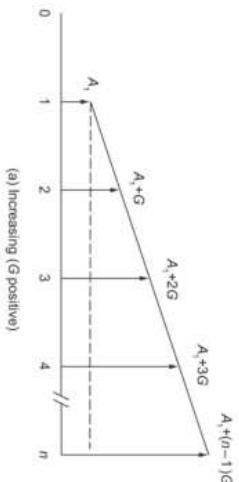
## CALCULATIONS FOR UNIFORM GRADIENT SERIES OF PAYMENTS (OR RECEIPT)

**14.4** Sometimes an investment generates a uniform series of payments that either increase or decrease by a constant amount as shown in Fig. 14.5. Such

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a series is known as **uniform (or arithmetic) gradient series** of payments. To evaluate such a series, an equivalent uniform series of payments with constant cash flows  $A_s$  is found and then  $P_s$  or  $F_s$  is computed for this equivalent series using Eq.14.7 through Eq. 14.14.



(a) increasing ( $G$  positive)

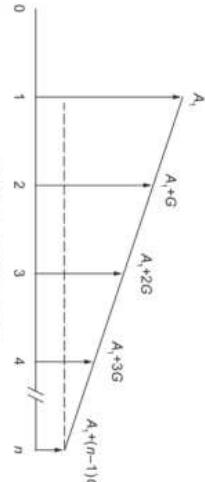


Fig. 14.5 Uniform gradient series

The equivalent cash flows of uniform series of payments may be obtained from

$$A_g = A_1 + G (A/G, i, n) \quad (14.15)$$

where  $G$  is the constant amount of change or gradient per period (which may be positive or negative),  $A_1$  is the payment at the end of the first year and  $n$  is the number of periods.  $(A/G, i, n)$  is known as 'uniform gradient annual series factor' or **gradient to uniform series conversion factor** and is given by

$$(A/G, i, n) = \left[ \frac{1}{i} - \frac{n}{(1+i)^n - 1} \right] \quad (14.16)$$

It may be noted that the first payment starts from the year 1 and continues up to the year  $n$  and grading starts from the year 2.

**Example**

A person wants to start a solar-lantern-manufacturing company and expects the sales revenues of Rs 10 lakhs at the end of first year. In subsequent 5 years, sales are expected to increase by Rs 1 lakh annually. The manufacturer has applied for a loan of Rs 40 lakhs from a bank to finance the project. The bank's policy requires that the loan must not exceed 85% of the expected revenues. If the discount rate is 12%, will the manufacturer get the loan?

**Solution**

Given,

$$A_1 = 10 \text{ lakhs}, \quad G = 1 \text{ lakh}, \quad i = 0.12, \quad n = 5$$

The gradient to uniform-series conversion factor from Eq. 14.16 is given by

$$(A/G, i, n) = \left[ \frac{1}{0.12} - \frac{5}{(1+0.12)^5 - 1} \right]$$

$$= 1.7745945$$

The equivalent cash flows of uniform series from Eq. 14.15

$$A_n = 10 + 1 \times 1.7745945$$

$$= 11.7745945 \text{ lakhs}$$

The present worth of the series of the cash flow may be obtained from Eq. 14.11

$$P_n = A_n \left[ \frac{(1+i)^n - 1}{i((1+i)^n - 1)} \right]$$

$$P_n = 11.7745945 \times \left[ \frac{(1+0.12)^5 - 1}{0.12 \times ((1+0.12)^5 - 1)} \right]$$

$$= 42.44 \text{ lakhs}$$

85% of the expected revenues =  $42.44 \times 0.85 = 36.07$  lakhs

This amount is less than the amount of loan (i.e., 40 lakhs).

Therefore, the manufacturer will not get the loan.

## CALCULATIONS FOR GEOMETRIC GRADIENT SERIES OF PAYMENTS (OR RECEIPT)

### 14.5

In many situations, periodic cash flows are expected to increase or decrease over time, not by a constant amount (gradient) but by a constant percentage rate, i.e., a geometric growth through time as shown in Fig. 14.6. Escalation in the prices of different fuels at a constant rate each year (known as inflation) is a typical situation that can be modeled with geometric sequence of cash flow.



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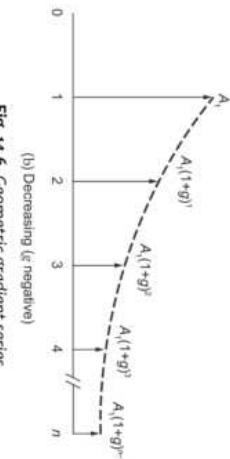
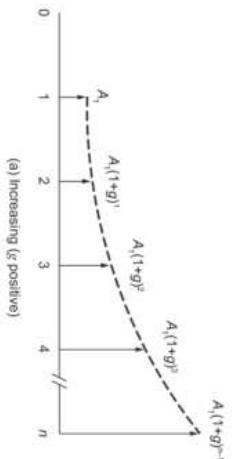


Fig. 14.6 Geometric gradient series

If  $g$  represents the change in cash flow from one period to the next (as the fraction of the cash flow of the first period), then the  $j^{\text{th}}$  cash flow  $A_j$  is related to the first cash flow as

$$A_j = A_1 (1 + g)^{j-1} \quad \text{for } j = 1, 2, \dots, n \quad (14.17)$$

The term  $g$  can be either positive or negative depending on the increasing or decreasing cash flow series. Each term of the series may be discounted or compounded at the interest rate  $i$  to obtain the value of  $P$  or  $F$  respectively. The present worth of the geometric gradient series is determined by summing all discounted terms:

$$P_{\text{gr}} = \sum_{j=1}^n A_1 (1 + g)^{j-1} \frac{1}{(1+i)} \quad (14.18)$$

$$\text{or } P_{\text{gr}} = \frac{A_1}{(1+g)} \sum_{j=1}^n \left( \frac{1+g}{1+i} \right)^j \quad (14.19)$$

This may be solved to give

$$P_{\text{gr}} = \frac{A_1}{(i-g)} \left[ 1 - \left( \frac{1+g}{1+i} \right)^n \right] \quad \text{when } i \neq g \quad (14.20)$$

$$\text{and } P_{\text{gr}} = \frac{nA_1}{(i+g)} \quad \text{when } i = g \quad (14.21)$$

Conversely, if  $C_n$  is the cost of a commodity in current currency, that has inflated by an average annual rate  $j$ , to obtain its cost in currency with worth that prevailed at the year 0 (real value, or constant value rupee), the current value is deflated, i.e., divided by a deflator:

$$C_o = C_n / (1 + j)^n \quad (14.25)$$

## COMPARATIVE ECONOMIC EVALUATION OF ALTERNATIVES

**14.7** Capital projects have differences in terms of costs, benefits, and timings, the basis of comparison must take into account these differences and the time value of money. A wide variety of appraisal criteria have been suggested. However, there is no one best appraisal method for all types of conditions. Each method has its own merits and limitations. The methods discussed here merely aid in the decision-making process, which may include several non-quantitative and non-economic criteria as well.

### 14.7.1 Payback Period

Sometimes business firms are concerned with the number of years required to recover the initial outlay of an investment. The payback period is found in two ways—conventionally and by discounting the cash flow.

**Simple (Conventional) Payback Period,  $n_p$**  Simple Payback period is obtained by counting the number of years it takes for cumulative cash receipts (benefits,  $B_n$ ) to equal the cash expenses (costs,  $C_n$ ).

$$\sum_{n=0}^{n_p} (B_n - C_n) = 0 \quad (14.26)$$

#### Example

A proposed solar PV street light will cost Rs 10,000 and last for 20 years. The savings of electricity bill is estimated as Rs 900 per year. What is the simple payback period of the proposal?

### 14.11

#### Solution

Given,

Initial investment,  $C_o = 10,000$   
Net annual savings =  $B = 900$  per year

Now,

simple payback period,  $n_p = \frac{10,000}{900} = 11.11$  years

This period is much less than the expected useful life of the street light. Hence the proposal may be accepted.

**Example**

The cash flows of three project proposals during their lifetime of 5 years are given in Table 14.1. Calculate the simple payback period for each of them.

**14.12****Table 14.1** Cash flows for projects A, B, C

<i>Year</i>	<i>Cash Flows (Rs.)</i>		
	<i>Project A</i>	<i>Project B</i>	<i>Project C</i>
0	-2400	-2400	-2400
1	600	800	500
2	600	800	700
3	600	800	900
4	600	800	1100
5	600	800	1300

**Solution**

The cumulative cash flows for the above problem are given in Table 14.2.

**Table 14.2** Cumulative cash flows for projects A, B, C

<i>Year</i>	<i>Cumulative Cash Flows (Rs.)</i>			
	<i>Project A</i>	<i>Project B</i>	<i>Project C</i>	
<i>Year</i>	<i>Current</i>	<i>Cumulative</i>	<i>Current</i>	<i>Cumulative</i>
0	-2,400	-2,400	-2,400	-2,400
1	600	-1800	800	-1600
2	600	-1200	800	-800
3	600	-600	800	0
4	600	0	800	800
5	600	600	800	1,600

Simple payback period as seen from Table 14.2,

For the project *A* = 4 years

For the project *B* = 3 years

For the project *C* the cumulative cash flow becomes zero somewhere during the year 4. If it is assumed that the cash flow of Rs 1,100 is uniformly distributed over the 4<sup>th</sup> year, the exact value of simple payback period can be determined as

Simple payback period for the project *C* =  $3 + \frac{300}{1100} \approx 3.27$  years

**Discounted Payback Period,  $n_{dp}$**  The simple payback period fails to consider the time value of money. The discounted payback period accounts for the changing value of money over time. Therefore, the discounted payback period,  $n_{dp}$ , is the smallest  $n$  that satisfies:

$$\sum_{n=0}^{n_p} (B_n - C_n) \frac{1}{(1+i)^n} = 0 \quad (14.27)$$

where  $i$  is the interest rate or the minimum rate of return.

**Example** For the cash flows of three project proposals given in Table 14.1, calculate the discounted payback period for each of them, considering the rate of interest as 12%. Comment on the results.

### 14.13

**Solution** The discounted cash flows corresponding to discounted periods are calculated and the results are tabulated in the following table.

Table 14.3 Discounted and cumulative cash flow calculations

Year	Cash Flows (Rs.)			Project C		
	Project A	Discounted Cumulative	Project B	Discounted Cumulative	Project C	Discounted Cumulative
0	-2,400	-2,400	-2,400	-2,400	-2,400	-2,400
1	536	-1864	714	-1686	446	-1954
2	478	-1386	638	-1048	558	-1396
3	427	-959	569	-479	641	-755
4	381	-578	509	30	699	-56
5	340	-238	454	484	738	683

Looking at the cumulative cash flow, it can be concluded that:

For the project A the investment is not paid back till the useful life of the project (5 years). Therefore, this is a net loss project and should be rejected.

For the project B: Discounted payback period,  $n_{dp} = 3 + \frac{479}{509} = 3.94$  years

For the project C: Discounted payback period,  $n_{dp} = 4 + \frac{56}{739} = 4.08$  years

From the discounted payback point of view, the project B is better as compared to project C as the investment is paid back earlier.



### 14.7.2 Net Present Value, NPV

The net present value method requires that all cash flows be discounted to their present value, using the firm's required rate of return  $i$ . It can be expressed as,

$$\text{NPV} = \sum_{j=0}^n \frac{B_j - C_i}{(1+i)^j} \quad (14.28)$$

where  $B_j$  stands for benefits at the end of the period  $j$ , and  $C_i$  for cost at the end of period  $j$ , and  $n$  is the useful life of the project.

If  $C_i$  is the initial capital investment in the project, and  $A$  is the uniform annual cash flow of the project, the above relation becomes:

$$\text{NPV} = C_i - A \left[ \frac{(1+i)^n - 1}{i(1+i)^n} \right] \quad (14.29)$$

#### Example

For the cash flows of three project proposals given in Table 14.1, calculate the net present worth for each of them, considering the rate of interest as 12%. Comment on the results.

### 14.14

#### Solution

The net present value of each project for the lifetime of the investment (5 years) is calculated. This is in fact the net cumulative discounted cash flows. Therefore:

NPV of the project  $A = -238$

NPV of the project  $B = 484$

NPV of the project  $C = 683$

*Comments* Project  $A$  has a negative NPV and, therefore, it should be rejected. As seen earlier, the project  $B$  is better than the project  $C$  from the point of view of discounted payback period.

However, the net present worth of the project  $C$  is higher due to higher cash flows in later years.

### 14.7.3 Internal Rate of Return, IRR

The internal rate of return for an investment expresses the profitability of a capital investment in percentage terms, a measure that is easily understood by experts and laymen alike. It is defined as the rate of return (i.e., interest rate) that makes the NPV of an investment equal to zero. Mathematically, the IRR is the interest rate  $r^*$  that satisfies the equation:



$$\text{NPV}(i^*) = \sum_{j=0}^n \frac{B_j - C_j}{(1+i^*)^j} = 0 \quad (14.30)$$

In other words, IRR is the interest rate  $i^*$  that causes the discounted present value of the benefits in a cash flow to be equal to the present value of the costs, i.e.

$$\sum_{j=0}^n \frac{B_j}{(1+i^*)^j} = \sum_{j=0}^n \frac{C_j}{(1+i^*)^j} \quad (14.31)$$

To find IRR (i.e.  $i^*$ ), Eq. 14.30 is solved using the trial and error (iterative) method. The following procedure may be followed.

1. Make an initial guess for  $i^*$ .
2. Calculate the value of  $\text{NPV}(i^*)$  at this value of  $i^*$ .
3. If the calculated value of  $\text{NPV}(i^*)$  is positive, it indicates that the actual value of  $i^*$  would be more than the trial value. Increment the value  $i^*$  by a small step for the next trial. If the value of  $\text{NPV}(i^*)$  is negative, it indicates that the actual value of  $i^*$  would be less than the trial rate. Decrement the value  $i^*$  by a small step for the next trial. Go to the step 2 for the next trial.
4. Repeat steps 2 and 3 until a situation is reached where a value  $i_1$  gives  $\text{NPV}(i_1)$  as positive and the next higher value  $i_2$  gives  $\text{NPV}(i_2)$  as negative.
5. Find the value of IRR by interpolation as follows:

$$\text{IRR} = i_1 + \left( \frac{i_2 - i_1}{\text{NPV}(i_1) - \text{NPV}(i_2)} \right) \text{NPV}(i_1) \quad (14.32)$$

When the IRR of an investment is greater than the 'cost of the capital' of the firm, the investment is accepted. The cost of the capital is the minimum acceptable rate of return or required rate of return of the firm as explained in Section 14.1.3.

#### Example

A small windmill for water pumping requires initial costs of Rs 20,000. It is expected to save Rs 3,000 per year. Calculate the IRR on this investment if the life of the windmill is 15 years and the salvage value of the windmill after its useful life is negligible.

#### 14.15

Solution  $C_o = 20,000$ , Annual benefit  $= B = 3,000$ ,  $n = 15$

$$\begin{aligned} \text{NPV}(i^*) &= \sum_{j=0}^n \frac{B_j - C_j}{(1+i^*)^j} = \sum_{j=0}^n \frac{B_j}{(1+i^*)^j} - C_o = 0 \\ &= 3000 \left[ \frac{(1+i^*)^{15} - 1}{i^* (1+i^*)^{15}} \right] - 20,000 \end{aligned}$$



**Example 14.17** The cost of a 100 litre solar water heater is Rs 12,000. During its useful life of 20 years its routine annual maintenance will cost Rs 200. The replacement of insulation in the 12<sup>th</sup> year will cost Rs 3000. If its salvage value is Rs 1000, determine the capital recovery cost for an interest rate of 11%.

**Solution**

Given:  
 $C_0 = 12,000, \quad C_i = 200, \quad C_{12} = 3000, \quad S = 1000,$   
 $n = 20, \quad i = 0.11$

In Eq. 14.36, adding a term for the discounted cost of Rs 3000 over a period of 12 years, we get

$$\begin{aligned} C_{\text{act}} &= 12000 - 1000 \times \left[ \frac{1}{(1+0.11)^{20}} \right] + 200 \times \left[ \frac{(1+0.11)^{20} - 1}{0.11(1+0.11)^{20}} \right] \\ &\quad + 3000 \times \left[ \frac{1}{(1+i)^{12}} \right] = 12000 - 124 + 1593 + 858 \\ &= 14,327 \end{aligned}$$

Now, from Eq. 14.31, capital recovery cost,

$$\text{CR} = 14327 \times \left[ \frac{0.11 \times (1+0.11)^{20}}{(1+0.11)^{20} - 1} \right] = \text{Rs } 1,799$$

**14.7.6 Annual Equivalent Amount (or Equivalent Uniform Annual Worth)**

In this method, all original cash flows are first converted to net present worth and then converted to a series of equal annual payments by multiplying this amount by the capital recovery factor.

If  $B_j$  and  $C_j$  represent the benefits and costs respectively in the  $j$ th year, the present worth of cumulative cash flows can be determined as

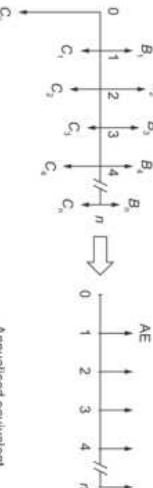
$$\sum_{j=0}^n \frac{(B_j - C_j)}{(1+i)^j} \quad (14.37)$$

where  $i$  represents the prevailing interest rate and  $n$  is the useful life of the investment/project. Now, the annual equivalent amount can be found as explained above:

$$\text{AE} = \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \times \sum_{j=0}^n \frac{(B_j - C_j)}{(1+i)^j} \quad (14.38)$$

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The situation is illustrated in Fig. 14.8.



**Fig. 14.8** Annual equivalent amount

An important advantage of the annual equivalent amount method is in resolving the dilemma faced by a firm which must choose between two investment alternatives of different useful lives. This method does not cancel the difference in the lives of the two projects. It simply removes the difference from the analysis. The following example will elaborate this point.

**Example**

**14.18** For a particular operation, two machines A and B having same capacity but different economic characteristics as shown below are available: The firm's cost of capital is 10%. Evaluate the profitability of both machines by the NPV method and by the AE (Annual Equivalent Amount) method and comment on the results.

**Table 14.6** Economic characteristics of two machines

Machine	Initial cost (Rs)	Annual cash flow (Rs)	Useful life (Year)
A	90,000	26,000	5
B	75,000	26,000	4

**Solution** The NPV and AE for the two machines are computed using Eqs. 14.37 and 14.38. The results are tabulated in the Table 14.7 below:

**Table 14.7** Computed results

Machine	Initial cost (Rs)	Annual cash flow (Rs)	Useful life (Year)	NPV (Rs)	AE (Rs)
A	90,000	26,000	5	8560	2258
B	75,000	26,000	4	7417	2339

Looking at the table above, we see that the machine A has higher NPV than the machine B. This higher profitability of the machine A is obtained by a longer life of 1 year over the machine B. However, this is misleading. A more accurate comparison of the two machines is obtained when the annual equivalent (AE) of

If a salvage value  $S$  is expected then the annual amount of depreciation is computed as follows:

$$D = (C_o - S)/N \quad (14.41)$$

The salvage value can be positive, zero or even negative. A negative salvage value is estimated if dismantling or carry-away costs are anticipated.

In this method, the annual rate of depreciation remains constant. Other methods for calculating the depreciation are beyond the scope of the present book and interested readers are advised to refer any standard book of economics for detailed treatment on this topic.

A term frequently used in the context of depreciation is **book value**. The book value of an asset is equal to the remaining investment after the total amount of depreciation has been charged to date. In other words, book value represents the current worth of an asset as shown by the books of account. The book value of an asset decreases every year by the amount of depreciation till it reaches the salvage value at the end of the lifetime of depreciating asset.

### Example 14.19

A commercial solar dryer costs a capital amount of Rs.1,20,000 to purchase and install and has negligible salvage value after a useful life of 5 years. Use straight-line depreciation and 40% tax on earnings. The discount rate is 9%. The yearwise earnings are given below:  
Calculate the net present value (NPV) of the solar dryer.

Table 14.8

Input data

In Rupee					
Year	1	2	3	4	5
Earnings, E	33,000	35,000	37,000	39,000	41,000

**Solution**

Given:

$C_o = 1,20,000$ , Useful life  $N = 5$ , Tax rate  $T = 40\%$

Discount rate  $i = 0.09$

Depreciation can be calculated as  $D = 1,20,000/5 = 24,000$

The steps of computation and intermediate values are tabulated in the Table 14.9 below:



### Review Questions

- Differentiate between nominal and effective interest rates. Explain continuous compounding.
- What do you understand by discounting? Explain with an example.
- With the help of a cash-flow diagram, explain the significance of annuity.
- What is inflation? How is the effect of inflation on annual cash flows taken care of?
- What is depreciation? What effect does it have on cash flows?
- What do you understand by tax shield?

### Problems

- What will be the amount of Rs 5000 invested at 6% interest compounded annually at the end of 12 years?  
**(Ans. Rs. 10,061)**
- How long will it take for Rs 15,000 invested at 8% interest compounded annually to double in value?  
**(Ans. 9 years)**
- A person inherits Rs 50,000 and invests it in a bank account that generates 9% interest (nominal) for 4 years. Calculate the future value of this investment if interest is compounded (a) annually; (b) quarterly; (c) daily; and (d) continuously.  
**(Ans. Rs 70,579, Rs 71,981, Rs 71,663, Rs 71,666)**
- What is the present value of a single payment of Rs 20,000 due 10 years from now, if the interest rate is 10% compounded annually?  
**(Ans. Rs 7711)**
- The estimated salvage value of a solar PV collector at the end of its useful life of 25 years is Rs 80,000. Determine its present worth for a discount rate of 10%.  
**(Ans. Rs 7384)**
- A person invests Rs 2000 a year into an 'individual retirement account' for 10 years. Calculate the accumulated value of the investment if the nominal interest rate is 10% compounded quarterly.  
**(Ans. Rs 32,463)**
- The replacement cost of the gas holder of a 2-m<sup>3</sup> biogas plant at the end of 6 years is likely to be Rs 4500. What amount should a user deposit every year to accumulate the desired amount if he earns 8 percent interest on his deposit?  
**(Ans. Rs 613)**
- A solar PV-power-based pump installed for a fishing pond gives maintenance-free service during its lifespan of 20 years and is expected to save Rs. 2400 worth of fuel each year. Determine the present worth of the lifecycle fuel saving assuming a discount rate of 12% per year.  
**(Ans. Rs 17,927)**

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## Non-conventional Energy Resources

16. A biomass-briquetting plant requires an initial investment of Rs 35,00,000. The average yearly income from the plant is estimated as Rs 6,00,000 during its lifetime of 10 years. Find the IRR of the project. Comment on the economic feasibility of the proposal if the specified cost of the capital is 12%.

(Ans. 11.23% which is less than the cost of capital, economically not feasible)

17. For the cash flows of two project proposals given in Problem 12, calculate the benefit-to-cost ratios for each of them, considering the rate of interest as 12%.

(Ans. 0.874, 1.407)

18. A floating drum type,  $2\text{-m}^3$  biogas plant costs Rs 8000. During its lifetime of 12 years, it requires a routine annual maintenance of Rs 300 and replacement of gas holder after 8 years costs Rs 2500. What is the capital recovery cost on this expenditure if the opportunity cost of the capital is 15%? The plant has no salvage value.

(Ans. Rs 1927)

19. A heat exchanger costs Rs 4,00,000 to purchase and install. During its useful life of 10 years it results in fuel saving of Rs 1,20,000 per year. The life of the heat exchanger may be extended by 4 years (i.e., total life of 14 years) if a major overhaul is carried out at the end of the 7th year at a cost of Rs 2,00,000. Compute the AE (annual equivalent amount) for the two cases: (i) the heat exchanger is used up to 10 years only, without going for an overhaul, and (ii) it is used for 14 years with overhaul. Give your recommendations regarding the economic feasibility of an overhaul on the basis of computations. Assume 10% interest rate and zero salvage value of the heat exchanger.

(Ans. Use it for 10 years only without going for overhaul)

20. A solar-heating system is proposed for an office to carry 60% of the annual heating load by solar energy. The solar equipment is purchased for Rs 6,00,000 with a 20% down payment and the balance borrowed on loan at 10% interest for 10 years. The discount rate is 8%. Calculate the savings accrued by the use of the solar heating system for the 10-year period with the following information.

- (i) A conventional non-solar heating system would have a fuel cost of Rs 1,20,000 for the first year.
- (ii) Fuel cost is expected to increase at 10% a year.
- (iii) Additional maintenance, insurance, and parasitic energy cost due to installation of the solar system are estimated to be Rs 5,000 for the first year, subject to an inflation rate of 3%.
- (iv) Additional property taxes are expected to be Rs 8,000 for the first year subject to an inflation rate of 4%.
- (v) 40% of the interest on mortgage and the extra property tax are deductible from income taxes.
- (vi) Taken the inflation of economy and the durability of the installation into account, it is estimated that the resale value of the solar system at the end of 10 years will be Rs 8,000.

(Ans. Rs 60,131)



21. A 2-m<sup>3</sup> biogas plant costs Rs 12,000 to install and another Rs 1000 per year (on average) to repair and maintain. It saves 300 litres of kerosene per year to the owner, as the biogas substitutes kerosene presently used for domestic cooking. Calculate the benefit-to-cost ratio (B/C) for the investment if the salvage value at the end of 25 years of its useful lifetime is negligibly small and the discount rate is 10%. The present market price of kerosene is Rs 10 per litre subject to an annual inflation of 8%.

(Ans. 2.62)

22. Determine the present value of the net benefits of investing Rs 2000 on a box-type solar cooker if the annual repair and maintenance cost is Rs 200 and the cooker is able to cook 400 meals in a year. The cooker has no salvage value after a useful lifetime of 10 years. Assume that the monetary worth of fuel saved per solar cooked meal is Rs 1.50 and that the discount rate is 10%. What if a 5% annual escalation in fuel prices is expected?

(Ans. Rs 458, Rs 1,235)

23. An investment is made in a biomass-energy system by borrowing Rs 1,70,000 at an interest rate such that the annual payments are Rs 27,000 for 10 years (principal plus interest). The biomass-energy system has a useful life of 15 years and it saves Rs 22,000 in the first year. Find the net present value and the discounted payback period if the annual discount rate is 10% and the conventional fuel prices are escalating at 5% per annum.

(Ans. Rs 51,021, 10.5037 years)

24. Two alternative investment opportunities are given below:

	<i>Alternative A</i>	<i>Alternative B</i>
Capital cost	Rs 1,50,000	Rs 225,000
Annual receipts	Rs 90,000	Rs 70,000
Annual expenses	Rs 12,000	Rs 17,000
Estimated salvage value	Rs 30,000	Rs 45,000
Useful life	8 years	10 years
Discount rate	15%	15%

On the basis of profitability, which alternative should be preferred?

(Ans. Alternative A)

### Objective-type Questions

- As per 'end-of-period convention', all cash flows are assumed to occur
  - at the start of an interest period
  - in the middle of an interest period
  - at the end of an interest period
  - none of the above
- An amount grows fastest with
  - yearly compounding
  - monthly compounding
  - continuous compounding

# Appendix A

## Conversions

- 1 Btu is the heat needed to raise the temperature of 1 pound of water by 1°F.
- 1 Btu = 252 calories =  $1054.35 \text{ joules}$
- 1 kWh =  $3412 \text{ Btu} = 3.6 \text{ MJ} = 860 \text{ kcal} = 0.86 \text{ KGOE}$
- 1 quad Btu = 1 quadrillion ( $10^{19}$ ) Btu =  $2.930 \times 10^{11} \text{ kWh} = 25 \times 10^9 \text{ KGOE}$
- 1 gallon = 3.785 litres
- 1 barrel (bbl) = 42 gallons = 158.98 litres = 58, 00, 000 Btu

## Important Physical Constants

- Mechanical equivalent of heat,  $J = 4.184 \text{ J / calorie}$
- Planck constant  $b = 6.626076 \times 10^{-34} \text{ J s}$
- Boltzmann constant  $k = 1.380658 \times 10^{-23} \text{ J / K}$  (or  $8.629112 \times 10^{-5} \text{ eV / K}$ )
- Gas constant  $R = 287 \text{ J / kg K}$  for air
- Specific heats for air,  $c_p = 1 \text{ kJ/kg K}$ ,  $c_v = 0.71128 \text{ kJ/kg K}$
- Atomic mass unit =  $1.660540 \times 10^{-27} \text{ kg}$
- Velocity of light  $c = 2.997925 \times 10^8 \text{ m / s}$
- Electron charge  $e = 1.602177 \times 10^{-19} \text{ C}$
- Gravitation (std.)  $g = 9.80665 \text{ m / s}^2$

## Units of Pressure and Their Inter-relations

- 1 Pa = 1 N / m<sup>2</sup>
- 1 Bar =  $10^5 \text{ Pa} = 1 \text{ kg / cm}^2 = 0.1 \text{ MPa} = 14.50777 \text{ psi}$
- 1 atm pressure = 760 mm of Hg = 14.7 psi = 1.01325 bar

## Number Conversions

- 1 lakh = 0.1 million
- 1 crore = 10 million
- 1 quad = 1 quadrillion =  $10^{15}$



## Appendix A

**Prefixes**

$10^{-24}$	yocto	y
$10^{-21}$	zepto	z
$10^{-18}$	atto	a
$10^{-15}$	femto	f
$10^{-12}$	pico	p
$10^{-9}$	nano	n
$10^{-6}$	micro	$\mu$
$10^{-3}$	milli	m
$10^{-2}$	centi	c
$10^{-1}$	deci	d
$10^0$	none	-
$10^{+1}$	deka	da
$10^{+2}$	hecto	h
$10^{+3}$	kilo	k
$10^{+6}$	mega	M
$10^{+9}$	giga	G
$10^{+12}$	tera	T
$10^{+15}$	peta	P
$10^{+18}$	exa	E
$10^{+21}$	zetta	Z
$10^{+24}$	yotta	Y

## Appendix B

Some public/ private sector undertakings / institutes for promotion of non-conventional energy sources in India:

1. **Solar Energy Centre (SEC)**  
Village Gwalpahari, Faridabad  
Gurgaon Road (Haryana)
2. **Sandat Swaran Singh National Institute of Renewable Energy (SSS-NIRE)**  
Adhikui Village (12 Km from Jalandhar)  
Jallandhar—Kapurthala Road (Punjab)
3. **Centre for Wind Energy Technology (C-WET)**  
275, School Road, Third Avenue, C-sector,  
Anna Nagar, West Extension  
Chennai (Tamil Nadu)
4. **Tata Energy Research Institute (TERI)**  
Darbari Seth Block  
IHC Complex  
Lodhi Road  
New Delhi

# Appendix C

**Table C1** Monthly average, daily and hourly global radiation in kWh/m<sup>2</sup> and sunshine hours on horizontal surface at New Delhi (latitude: 28° 35' N, Longitude: 77° 12' E)<sup>[48]</sup>.

Month	δ	7	8	9	10	11	12	13	14	15	16	17	18	19	Hour		Total kWh/ day	Sun- shine hours
															10	11	12	13
Jan	0.000	0.004	0.006	0.271	0.433	0.556	0.618	0.615	0.552	0.340	0.268	0.099	0.005	0.000	3.987	7.6		
Feb	0.000	0.020	0.163	0.364	0.540	0.670	0.727	0.728	0.659	0.534	0.358	0.165	0.021	0.000	5.901	9.0		
Mar	0.001	0.066	0.260	0.475	0.655	0.781	0.865	0.844	0.769	0.635	0.558	0.240	0.064	0.001	6.348	8.2		
Apr	0.010	0.130	0.359	0.554	0.727	0.848	0.910	0.903	0.833	0.699	0.523	0.318	0.122	0.010	6.935	8.6		
May	0.030	0.177	0.383	0.581	0.746	0.865	0.925	0.930	0.844	0.719	0.547	0.352	0.158	0.027	7.287	8.0		
Jun	0.036	0.164	0.399	0.510	0.657	0.757	0.809	0.813	0.750	0.639	0.583	0.318	0.159	0.036	6.544	5.9		
Jul	0.026	0.150	0.275	0.425	0.549	0.640	0.672	0.671	0.666	0.518	0.412	0.273	0.141	0.032	5.344	5.8		
Aug	0.012	0.101	0.245	0.392	0.522	0.607	0.640	0.659	0.595	0.510	0.592	0.355	0.107	0.013	5.053	5.6		
Sep	0.003	0.079	0.248	0.431	0.587	0.698	0.757	0.747	0.689	0.571	0.417	0.244	0.074	0.003	5.062	7.0		
Oct	0.000	0.056	0.202	0.406	0.581	0.701	0.754	0.758	0.692	0.560	0.491	0.333	0.060	0.000	5.355	8.8		
Nov	0.009	0.128	0.319	0.495	0.620	0.685	0.680	0.613	0.590	0.315	0.125	0.010	0.000	4.523	9.2			
Dec	0.000	0.003	0.085	0.250	0.425	0.543	0.605	0.605	0.538	0.418	0.255	0.086	0.003	0.000	3.843	8.0		

NB Time indicated is LMT.

Value given for a particular hour is the radiation incident during one hour preceding the time.

Multiply by 3600 to obtain an hourly value in J/m<sup>2</sup>/h.

**Table C2** Monthly average, daily and hourly diffuse radiation in kWh/m<sup>2</sup> on horizontal surface at New Delhi (Latitude: 28° 35' N, Longitude: 77° 12' E)<sup>[48]</sup>

Month	δ	7	8	9	10	11	12	13	14	15	16	17	18	19	Hour		Total kWh/ day	Sun- shine hours
															10	11	12	13
Jan	0.000	0.003	0.051	0.103	0.140	0.160	0.174	0.172	0.162	0.137	0.106	0.051	0.003	0.000	1.240			
Feb	0.000	0.013	0.076	0.126	0.159	0.183	0.191	0.190	0.180	0.166	0.125	0.075	0.013	0.000	1.474			
Mar	0.001	0.043	0.113	0.159	0.189	0.210	0.220	0.225	0.215	0.197	0.163	0.113	0.041	0.001	1.861			
Apr	0.009	0.085	0.153	0.202	0.236	0.262	0.274	0.279	0.274	0.250	0.212	0.166	0.079	0.008	2.473			
May	0.027	0.114	0.190	0.244	0.279	0.303	0.315	0.318	0.308	0.286	0.247	0.189	0.077	0.022	2.922			
Jun	0.033	0.124	0.215	0.286	0.342	0.382	0.399	0.399	0.377	0.340	0.279	0.235	0.114	0.028	3.540			
July	0.023	0.096	0.178	0.257	0.315	0.358	0.372	0.365	0.333	0.291	0.241	0.174	0.101	0.023	3.135			
Aug	0.009	0.074	0.153	0.224	0.277	0.317	0.334	0.331	0.302	0.265	0.210	0.149	0.075	0.010	2.727			

NB Time indicated is LMT.

Value given for a particular hour is the radiation incident during one hour preceding the time.

Multiply by 3600 to obtain an hourly value in J/m<sup>2</sup>/h.

**Table C3** Monthly average, daily irradiation (*global*) on tilted surface in kWh/m<sup>2</sup> at New Delhi (Latitude: 28°35' N, Longtitude: 77°12' E)[18]

# Appendix D

## Key to Objective-type Questions

### **Chapter 1**

1c, 2d, 3a, 4a, 5d, 6c, 7b, 8d, 9c, 10b, 11c, 12a, 13d, 14(a), 15c, 16d, 17b, 18a,  
19a, 20c

### **Chapter 2**

1d, 2c, 3b, 4d, 5b, 6d, 7b, 8d

### **Chapter 3**

1b, 2a, 3c, 4d, 5a, 6d, 7b, 8c, 9c, 10a, 11c, 12c, 13a, 14d, 15b, 16d, 17c, 18a,  
19d, 20c

### **Chapter 4**

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

### **Chapter 5**

1d, 2b, 3d, 4a, 5c, 6b, 7c, 8a, 9d, 10b, 11a, 12c, 13b, 14d, 15c, 16d, 17a, 18c,  
19b, 20a

### **Chapter 6**

1b, 2b, 3d, 4d, 5a, 6c, 7a, 8d, 9c, 10b, 11d, 12b, 13d, 14c, 15d, 16b, 17a, 18b

### **Chapter 7**

1b, 2b, 3c, 4a, 5d, 6a, 7a, 8d, 9b, 10d, 11c, 12b, 13b, 14a, 15a, 16d, 17d

### **Chapter 8**

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

### **Chapter 9**

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

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# Appendix F

## Internet sites for further reading

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