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Sustainable Energy and the Environment: A Clean Technology Approach

Springer

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Technology Approach

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Foreword

We are a scientific civilization whose health and wealth depend heavily on the power of knowledge. The key to the knowledge power lies with translational higher education. While science is a search for truth and is moral and ethics neutral, its applications through engineering and technology invariably have both positive and negative societal effects. As a result of very rapid exploitation of many of our natural resources, the world has nearly reached the limits of sustainability in several areas such as our environment. Today, it is generally recognized that human activities are significantly changing the composition of the earth's atmosphere, posing an imminent threat of catastrophic climate change globally. Critical contributors to this change are the concentrations of carbon dioxide (CO_2), methane (CH_4), short-lived trace gases like CO, NO_x, SO_2, and HCs; particulate material, both scattering aerosols (e.g., sulphates, nitrates, etc.) and absorbing aerosols (black carbon, organic carbon, etc.); etc. In many countries, emissions of these pollutants are already at a dangerous level. Consequently, the atmosphere is being increasingly loaded with undesirable pollutants. Energy in a variety of forms derived from non-renewable sources, being the major driver of global economic activities, is also a significant contributor to the pollution of our biosphere. Creative and transformational solutions for developing renewable and sustainable energy systems are already a central challenge for the world. This ambitious goal calls for substantial progress in the growth of energy production from renewable sources, judicious mix of various energy sources, and increased energy efficiency. Energy and environmental sustainability is, therefore, a central challenge for the whole world.

The book *Sustainable Energy and the Environment: A Clean Technology Approach,* authored by N.D. Kaushika, K.S. Reddy, and Kshitij Kaushik, introduces a unique approach to the concept of sustainability and energy conservation with emphasis on the relationship between scientific principles and those employed in engineering solutions. The authors have a wide experience in teaching and/or conducting research in the subject matter. This book is intended for professional

engineers and university students dealing with the effects of environmental degradation on ecological processes and climate change, energy-related environmental problems, energy efficiency, energy conservation, renewable energy, and technologies of pollution control.

Indian Institute of Technology   K.L. Chopra
Kharagpur, India
Nov 12, 2015

Preface

It is now widely recognized that human sustenance and developmental activities are not only provoking the imminent threat of catastrophic climate change but also threatening the security of energy and other resources and making complex changes in the entire earth system. Indeed, energy, environment, and ecosystems are dynamically and interactively connected. It, therefore, makes sense to consider the energy environment system in its totality and adopt sustainable solutions that balance economic growth and environment conservation. Furthermore, it is also almost certain that no single energy resource will be able to ensure energy security on a long-term basis, and the fossil fuels will remain an important part of energy mix for the next 20–40 years. The solution, therefore, needs diverse range of approaches and technologies. It includes making existing fossil fuel technologies cleaner and affordable with transition to greener power generation based on waste, water, and renewable resources. Furthermore, to cope up with the changing global energy scenario, we need transformational changes in how we use and how we deliver energy services.

This book titled *Sustainable Energy and the Environment* presents a wide spectrum of available knowledge on these topics. Chaps. 2 and 3 present an introduction to the physical and biological environment and the processes related to the existence and sustenance of life on earth. An outline of conventional energy and power systems and related environmental degradations are discussed in Chaps. 4 and 5. Clean coal technologies for power generation and sustainable energy and power technologies based on such renewable resources as solar, biomass, and wind are covered in Chaps. 6, 7, 8, 9, 10 and 11. Finally, topics on management of waste and water, pollution control schemes, and energy conservation are outlined in Chaps. 12, 13 and 14.

The book covers the material required for energy and environment courses currently being taught at engineering colleges and environmental sciences departments of various universities.

The authors, Prof. N.D. Kaushika and Prof. K.S. Reddy, have taught this subject in the Indian Institute of Technology (IITs) for over three decades and Mr. Kshitij Kaushik has on hand professional experience of working with the corporate sectors for over two decades. This has helped them in preparing the book which intends to serve scientists, engineers, policy experts, programme managers, and students.

Research scholars were involved in the writing of this book through extending their cooperation in proof checking and drawing of the figures. The contribution extended by IIT Madras has also been highly encouraging. We particularly thank Capital Publishing Company for bringing out this book in an expeditious manner.

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Contents

About the Authors

N.D. Kaushika former Professor, Centre for Energy Studies, Indian Institutes of Technology Delhi, subsequently Director of reputed engineering institutions in Delhi and National Capital Region, is a specialist in renewable energy and environment. He is a Recipient of the S.S. Bhatnagar Research Endowment Award (Hariom Ashram Prerit) for research in Energy Conservation in 1987. He is presently a Consultant at Innovation Centre, Ansal University, Gurgaon. He was earlier been author of two books and has contributed articles in several reputed journals and authored chapters in books by international publishers including Academic Press, USA, and Elsevier Science major reference work.

K.S. Reddy Professor of Mechanical Engineering at IIT Madras, Chennai, is a specialist in solar energy, energy efficiency, and environment. Presently, he is also an honorary Professor at the University of Exeter, UK, and Adjunct Professor at CEERI-CSIR. He has authored more than 150 research papers in reputed international journals and conferences. Dr. Reddy has executed several research projects on solar energy sponsored by various national and international agencies. He is actively involved in the development of concentrating solar power technologies in India. He has filed couple of patents on solar CPV and CSP systems. He is associated with several industries on power generation, process heat, energy efficiency and conservation and characterization of engineering materials. He has also organized several national and international workshops on advanced renewable energy technologies at IIT Madras.

Kshitij Kaushik Associate Vice-President in Sky Power in Canada, is specialized in energy efficiency and solar photovoltaic. He is a co-author of one book and has contributed research articles in reputed international journals.

Chapter 1
Introduction to Sustainable Energy and Environment

1.1 Energy and Development

All nations of the world envision having sustainable and equitable growth. The actualization of sustainable and equitable growth encompasses various securities including that of five key elements: livelihood, economy, energy, ecological balance, national defence and internal peace. Energy is the prime mover of all these securities and has now become the essential component of economic development and social transformation for all the developed and developing countries of the world. Simultaneously, the advances in human health care and local life support system have led to unprecedented reproductive success and growth of population. The world's growth rate peaked in the 1960s at 2 % and a doubling time of 35 years (US Census 2005). The world's current growth rate is about 1.3 % representing a doubling time of 54 years. Many Asian and African countries have relatively higher growth rates. Afghanistan has a current growth rate of 3.5 %, representing a doubling time of 20 years. According to a study by United Nations, Department of Economic and Social Affairs, one can expect the world's population to become 11 billion by 2050. This has resulted in the growing need for energy. Owing to the population growth and economic progress, energy demand will increase from 17.7 terawatts in 2011 to 30–60 terawatts (450–900 million barrels of oil/day) in 2050. Approximately 75 % of this growth in energy demand will occur in Organization of Economic Co-operation and Development (OECD) countries. OECD is an international organization of 34 countries founded in 1961 to stimulate economic progress and global trade.

Studies of annual global energy consumption patterns in terms of tons of oil equivalent (toe) corresponding to year 2000 are shown in Fig. 1.1 (Boyle et al. 2004) which indicates that the developing countries have a significantly lower consumption of energy per capita as compared to the affluent countries. For example, the developing countries of Asia, Africa and Latin America where about 70 % of the world population lives, consume energy less than that in Western Europe which has 9 % of the world's population. These developing countries consume about one tenth
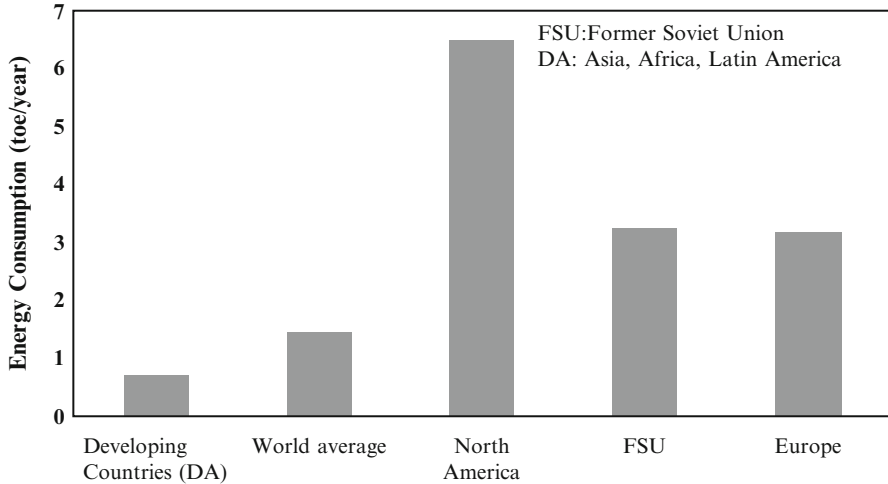
Fig. 1.1 Global per capita energy consumption patterns (Boyle et al. 2004)

of the energy consumed by North America. It is noticeable that all the developed countries have significantly higher energy consumption. The commercial energy consumed by the developing countries accounted for only 17.5 % of global energy consumption. This shows that the living standards are positively correlated with energy consumption. The high production levels of industry and agriculture in affluent countries may be attributed to mechanisation and higher energy consumption. It has been estimated that approximately three-fold increase in per capita energy consumption is required in developing countries to raise their standard of living to a reasonably acceptable level.

Over many years, the energy use pattern across the countries has changed. In Table 1.1, the industrialised and Asian nations are compared with respect to their per capita Gross Domestic Product (GDP) as well as energy use and Human Development Index (HDI). GDP is expressed in terms of Purchasing Power Parity (PPP) dollars. One can see a strong correlation between quality of life and energy consumption.

1.2   Energy Reserves and Resources

The terms 'Energy reserves' and 'resources' are intimately connected. 'Reserves' are quantities whose existence has been established and that are producible with existing technology under present economic conditions. 'Resources' include present reserves as well as deposits that have been identified but are not producible under present technological and economic conditions. However, the continual advances in extraction technology and higher acceptable prices keep on shifting the resource numerals into the reserve category. For example, U.S. oil reserves in

Table 1.1 GDP and Human Development Index across Countries (Power line 2000; HD Report 2004; UNDP; Masters 1994)

Country	GDP per capita (PPP $)	Energy use per capita (toe)	HDI (2010–2011)
Industrial			
Canada	21,916	7.854	0.908
USA	26,977	7.819	0.910
Sweden	19,297	5.723	0.904
Germany	20,370	4.128	0.905
France	21,176	4.042	0.884
Asian			
China	2935	0.664	0.898
India	1422	0.248	0.630
Pakistan	2209	0.254	0.504
Bangladesh	1382	0.064	0.515
Nepal	1145	0.028	0.463

1970 were estimated as 47 billion barrels (BB) and after a total consumption of 40 BB, the reserves were estimated as 35 BB in 1984 (Masters 1994). In mineral resource context it is, therefore, conventional to say that the resources being produced rather than being consumed.

The basic energy resources available as gifts of nature on earth include the following:

  (i) Fossil fuels (coal, oil and Natural gas)
 (ii) Fissionable and fertile isotopes (Nuclear) and fusionable isotopes
(iii) Renewable/Non-depletable sources (Solar, Wind, Biomass and Ocean)
(iv) Geothermal energy

Natural and manmade processes give rise to several usable energy resources (Chapman and Reiss 1995; Thorndike 1979; Kaushika and Kaushik 2005) as follows:

Fossil fuels are available in three forms, solid, liquid & gaseous. Most commonly used solid fossil fuels are coal, lignite, peat coke, wood, rice husk, sawdust and charcoal. These fuels have varying amounts of moisture, ash, volatile matter and fixed carbon. Yet another solid fuel, which could be used in coming times, is Oil Shale; these are shale (layered rocks) containing solid hydrocarbon (kerogen). The hydrocarbon content is about 65 gal of oil equivalent in 1 ton of shale. Huge deposits of oil shale exist in earth's crust. Besides the oil shale, in recent years, large deposits of sand impregnated with about 15 % oil have been reported to exist in Alberta (Canada). This is referred to as Tar Sand.

The liquid fossil fuel is mainly Crude Oil, which is a complex mixture of alkaline hydrocarbons with water salt and earth particles. Upon refining (fractional distillation), it yields several liquid fuels and other petroleum products. For example, crude oil boils at 400 °C and yields fuel oil at 350–400 °C, diesel oil at 250–300 °C, Kerosene oil at 170–250 °C, gasoline/petrol at 40–170 °C and

petroleum gas at 40 °C. Often the crude oil reservoir contains both oil and natural gas; the gas is predominantly methane (CH_4); gradually diminishing amounts of heavier members of hydrocarbon series represented by C_nH_{2n+2} are also present. The members with $n \geq 5$ are gaseous in the oil well but are liquid at STP (one atmosphere pressure and 293 K). The members ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}) are gaseous at STP but may be liquefied by the application of modest pressure. In general by the application of modest pressure, the natural gas separates into two parts; (i) Natural Gas Liquid or Liquefied Petroleum Gas (LPG) and (ii) Dry Natural Gas or Compressed Natural Gas (CNG). It has been estimated that in nature, the oil and gas existence is characterized as follows:

$$(CNG + LPG) : Oil : : 1.3 : 1$$

Energy may also be obtained from two nuclear phenomena: Fission and Fusion. Fission fuels include a rare isotope of Uranium U^{235} and U^{238} or Thorium Th^{232}. U ^{235} is commonly used whereas U^{238} or Th^{232} are usable only in breeder reactors. In natural ore, U^{235} is 0.7 % and U^{238} is 99.3 %. Deuterium and Lithium have been proposed as fusion fuels. The largest sources of Deuterium are oceans. There is one atom of deuterium for every 6500 atoms of hydrogen in nature.

1.3   Classification of Energy Resources

Fossil and nuclear fuels are the major suppliers of commercially available energy in the present day world; they are referred to as commercial resources of energy. Fuel wood, vegetable waste and cow dung etc. provide nearly half the total energy requirement of developing countries; these are called **non-commercial resources of energy.**

Yet another classification of resources of energy is based on the basic premise that fossil fuels reserves are finite in magnitude and their consumption is increasing at an escalated rate. These are referred to as conventional resources of energy. The escalating use of fossil fuels has adverse effects on land, air and water environment as well as on the ecological balance of earth. Environmentally benign energy alternatives are therefore very important and classified as alternate resources of energy.

Furthermore, all the resources of energy can also be broadly classified as follows: (a) Stored resources and (b) Continuous resources. The resources that are not replenished as fast as they are used are classified as *stored resources*. Fossil fuels and Uranium are the examples of stored resources. The time span of replenishment and use of fossil fuels are 10^8–10^3 years respectively. In contradistinction to these are the continuous resources of energy which are replenished at about the same rate as they are used like direct solar energy, tidal, hydro-potential and wind etc (Tiwari and Ghosal 2005). These are often referred to as Renewable resources of energy.

The fuel wood may be classified in either of the two categories. If the wood is used at the same rate as it is grown in energy forestry, it is regarded as continuous
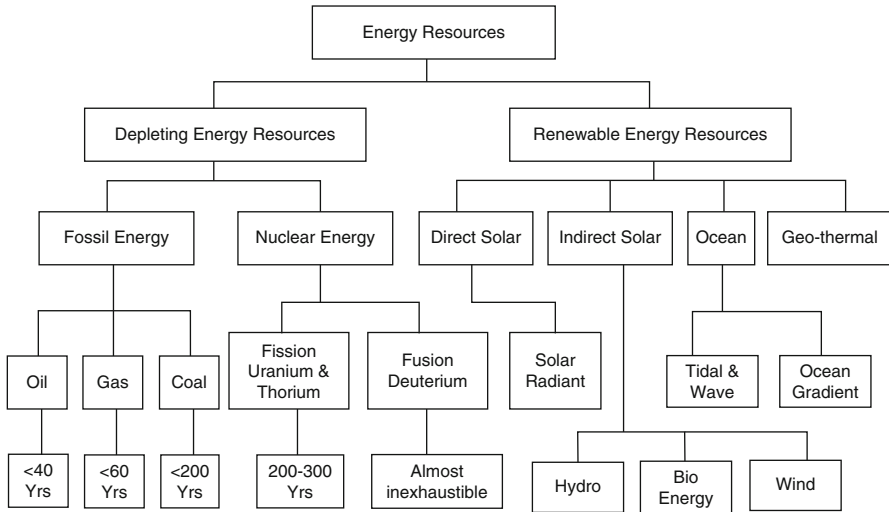
Fig. 1.2 Classification of energy resources. (*Source:* International Standardisation (ISO and IEC committee))

resource. If the utilization is faster than growth, it is referred to as stored resource. The energy resource classification based on above considerations and adopted by International Standardisation (ISO and IEC committees) is illustrated in Fig. 1.2 (Kaushika and Kaushik 2005). Corresponding expected life span (in years) of reserves at an assumed constant consumption rate (1996 exploration rate) is also shown therein.

1.4   Energy Security Aspects

In view of the fact that energy is the prime mover of all activities, it is imperative to develop a strategy for obtaining inflow of energy resources from whatever origin possible to secure us against energy shortage at global, national as well as regional levels. However, securing energy supply in the present day uncertain world would involve consideration of several factors such as energy reserves and resources, resource availability and access, technology advances, fuels for the future, role of nuclear energy, renewable energy, last but not the least implication of changing geopolitical environment and foreign trade as follows:

1.4.1   Energy Resource Availability

Total available supply of an energy resource will directly influence the cost as well as market price of energy required to maintain the living standards. The available

supply depends on the resource magnitude and the rate of resource consumption. At this stage, it may be noted that there is an important distinction between the *reserves* and *resources* of a mineral (such as coal etc.). Furthermore, in mineral resource context, it is conventional to say that the resource is being produced (rather than consumed). In what follows, we, therefore, explore to model the rate of production and the remaining lifetime for the energy resources (Masters 1994; Chapman and Reiss 1995; Kaushika and Kaushik 2005).

If $E(t)$ represents production rate of an energy resource at time, t, the total resource produced (Q) during the time interval between t_1 and t_2 can be determined as follows:

$$Q = \int_{t_1}^{t_2} E(t)dt \tag{1.1}$$

If the time interval of interest begins at $t = 0$, Eq. 1.1 reduces to:

$$Q = \int_{0}^{t} E(t)dt \tag{1.2}$$

Following cases are often of interest

Case I: Production rate remains constant:

$$\begin{aligned} E(t) &= E_0 \\ Q &= E_0 t \end{aligned} \tag{1.3}$$

Case II: Production rate has linear growth:

$$\begin{aligned} E(t) &= E_0 + f_0 t \\ Q &= E_0 t + \frac{f_0 t^2}{2} \end{aligned} \tag{1.4}$$

Case III: Production rate grows in exponential manner:

$$\begin{aligned} E(t) &= E_0 e^{rt} \\ Q &= \frac{E_0}{r}[e^{rt} - 1] \end{aligned} \tag{1.5}$$

where

Q = total resource produced by time t.
E_0 = the initial production rate
f_0 = rate of growth in E
r = rate of growth (fraction per year)

The Eq. (1.5) may also be expressed in terms of the length of time (say T) required using an amount Q as follows:

$$T = \frac{1}{r} \ln \left(\frac{rQ}{E_0} + 1 \right)$$ (1.6)

This equation may also be used to estimate the life span of the reserves of a particular resource as follows:

Example 1.1 World oil production in 1970 was equal to 30 billion barrels per year and the estimated total recoverable reserves were estimated at 2500 billion barrels. The production per year is doubling every 20 years. How long would it take to consume total reserves if the growth rate in production remains unchanged?

Solution The oil production rate is doubling every 20 years; so following the exponential growth formulation we have

$$2E_0 = E_0 \, e^{rt}$$

or

$$r = \frac{69.3}{20} = 3.465\%$$

and from Eq. (1.6) the life span (T) of the reserve is given by

$$T = \frac{1}{.03465} \ln \left[\frac{.03465 \times 2500}{30} + 1 \right]$$
$$T = 39.2 \, \text{years.}$$

For comparison, if there were no growth in production rate, the total oil reserve would last 83.3 years.

Example 1.2 (Thorndike 1979)**:** The world coal reserves in 1986 were estimated as 1.0 trillion (10^{12}) tons; the coal production in 1986 was 5.0×10^9 t per year and has since been doubling every 25.67 years. How long the reserves would last if the growth rate remains unchanged?

Solution As in Example 1.1, r is given by

$$r = \frac{0.693}{25.67} = 0.027$$

and the total life span of the reserves is given by

$$T = \frac{1}{0.027} \ln \left[\frac{.027 \times 1.0 \times 10^{12}}{5.0 \times 10^9} + 1 \right]$$
$$T = 68.75 \, \text{year}$$

For comparison, for constant production rate of 5.0×10^9 t/year the coal reserves would last for 200 years.

Example 1.3 In India coal was the first fossil fuel utilized in second half of nineteenth century. In 1984 its production (per year) and the total reserves were estimated as 140×10^6 and 1.56×10^{11} t respectively. With current rate of consumption the coal production in year 2004 is estimated to be 4.50×10^6 t. Calculate the life span of coal reserves in India.

Solution Using the exponential growth function formulation we have

$$450 \times 10^6 = 140 \times 10^6 = e^{r\,20}$$

or

$$r = \frac{1}{20} \ln \frac{450}{140} = 0.058$$

The total life span of coal reserves in India is given by:

$$T = \frac{1}{0.058} \ln \left[\frac{.058 \times 1.56 \times 10^{11}}{140 \times 10^6} + 1 \right]$$
$$T = 72.1 \, \text{year}$$

Example 1.4 Assuming the initial production of 5.0×10^9 t calculate the span of world coal resources in the range of 0.5–2.0 trillion (10^{12}) tons for various growth rates in the range of 0–6 % (Masters 1994).

Solution From Table 1.2 it may be noted that in the exponential growth function the total life span of a resource is quite insensitive to the magnitude of available resource. For example, at 5 % growth a total resource of 0.5×10^{12} t would last for 35 years whereas a four times larger resource would last for only 61 years which means another 26 years. Therefore, for practical situations the exponential growth for the production rate of any finite resource seems rather unlikely. Some authors (Masters 1994; Chapman and Reiss 1995) have argued that a resource production profile following a Gaussian function is more likely because initially the production might follow the exponential growth as the resource is abundant and cheap but subsequently as the availability decreases, consequently the prices go up and substitutions begin to appear. In this situation, the production profile tends to become S Shaped (or Sigmoidal) which in long term might become bell shaped. This aspect of production of resources is illustrated in Fig. 1.3.

Table 1.2 Life span of world coal resources with various growth rules

S. no.	Growth rate %	Life span (year) for coal resource (10^{12} t) 0.5 1.0 1.5 2.0			
1	0	100	200	300	400
2	1	69	110	138	160
3	2	55	80	97	109
4	3	46	65	78	85
5	4	40	55	64	71
6	5	35	48	55	61
7	6	32	43	49	54
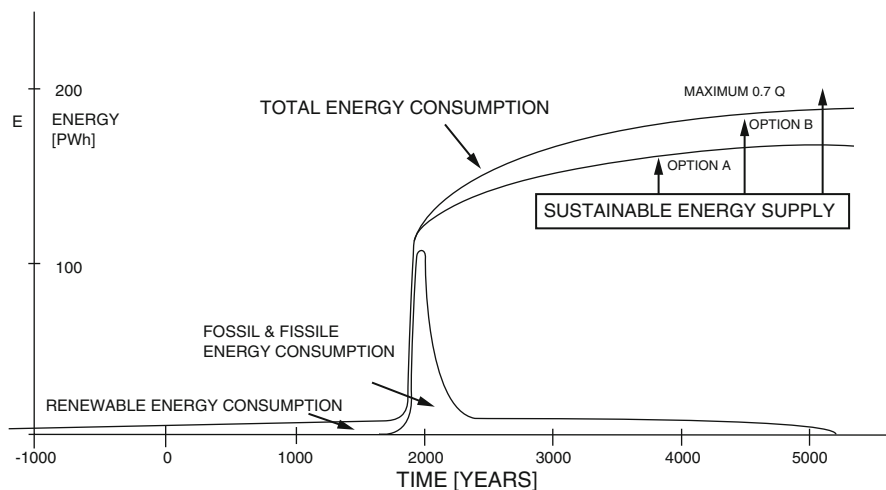
Fig. 1.3 S shaped curves for the production (consumption) of various resources usable on the Earth

1.4.2   Changing Resource Use Patterns

The energy resource use pattern has been continually changing since man appeared on earth. The primitive man used only muscular energy for transportation. With the advent of fire, the use of heat generated from the burning of wood became prevalent. Subsequently with the dawn of agriculture era the energy was used in three forms: human power, animal power and heat. The need for human power has been the cause of slavery for all the period of known history. The heat energy was obtained from fallen tree branches, charcoal and colza oil which were supplied each year by the growth of plants. The global energy consumption scenario was therefore based on renewable energy resources. From 1 to 1850 AD, global energy consumption per year is estimated to be about 0.004 Q. Energy policy and planning estimates use 'Q' as unit of energy $1Q = 1.05 \times 10^{21}$ J $= 293$ PWh (1 peta $= 10^{15}$).

With the passage of time and introduction of mechanization, the work of muscles has been transferred to machines (e.g. steam engine and internal combustion engine) driven by energy from coal, oil, gas as well as fissile materials (Uranium, Thorium), wind and water. Consequently the world energy consumption over the period 1850–1950 has increased to an yearly average value of 0.04 Q which is an order of magnitude higher than the value in previous 100 years. Subsequently the world energy consumption has increased at an accelerated rate and started depleting the resources of fossil and fissile energy; the use of these resources also proved to be environmentally hazardous. In recent years there has thus been growing realization on utilization of new energy resources like solar, tidal, geothermal, ocean thermal and ambient energy.

Fossil and nuclear fuels are the major suppliers of energy in industrial nations. In developing countries the contribution of biomass energy is also significant (35 %). Irony, however, is that fossil fuel reserves are finite and it has been estimated that all proven resources that are recoverable with today's technology will be exhausted in about 40–200 years. It is feared that in the beginning of twenty first Century world would face a serious lack of pace between the energy demand and supply. World, therefore, is faced with fossil fuel energy crisis. Furthermore, wood has been the oldest source of heat required for cooking and other applications in developing countries and its continual use has resulted in the felling of trees and serious deforestation. Consequently, in developing countries the fuel crisis would further aggravate the energy situation. Some authors refer to it as the dual energy crisis of developing countries. However, in the beginning of twenty first century when fossil energy resources are scarce the immediate available alternative with demonstrated technology might include the liquid and gaseous fuels obtained from coal, oil shale and/or tar sands. Nuclear energy is yet another option for twenty first century. The demonstrated technologies include fission and fusion. The fission technology is already commercial. Nuclear fission power in 2012 provides about 12.3 % of world's electricity out of which 13 countries relied on nuclear energy to supply at least one-quarter of their total electricity. In actual number the global nuclear power generation translates into 372,751 MWe as of January 2015 (World Statistics 2015). Nuclear power plants also do not emit large quantities of particulate that cause air pollution.

Most of the present day nuclear reactors use the rare isotope U-235 as fuel, which will not last for a very long period. The natural uranium ore contains 0.7 % U-235 and 99.3 % U-238 with breeder reactor technology U-238 and Thorium would be usable as fuels which could be available for about 200 years. In Table 1.3 potential of various resources for power generation in

Table 1.3 Potential of resources for power generation in India having total installed capacity of 124,000 MWe in 2007

Resource	Coal	Oil	Natural gas	Hydro	Nuclear
Potential (GWe × year)	41,000	300	250	84 (GW at 60 % PLF)	412,420

Source: Public awareness group, Nuclear Power Corporation of India Limited

Table 1.4 Resource wise global distribution of current and projected energy use

Resource %

	Oil	Coal	Gas	Fission	Biomass	Hydroelectric	Solar, wind, geothermal
Energy Use (2003) Total: 12 Terawatts	35	24	21	6.5	11	2.5	0.5
Projected Energy Use (2050) Total: 53 TW	10	6.5	14	14	2	2.2	50

Source: IEA

India are shown. Furthermore, the nuclear power generation does not involve the emission of greenhouse and acid rain gases. Therefore, it can be considered as the green power. There is a strong case for nuclear power as a green and economic resource in India.

1.4.3 Foreign Trade Constraints

The fossil fuel reserves are located only in specific regions of the globe. Only eight countries have 80 % of total world's crude oil reserves; six countries have all the natural gas reserves and eight countries have 90 % of the coal reserves. Other countries have to import their commercial energy. For example, India imports about 60 % of its oil requirements. Furthermore, developing nations have a tendency of using more and more fossil energy for their development whereas after the 1973 oil embargo, the developed nations have put a check on their fossil energy use. Resource wise use of energy is therefore influenced by foreign trade as well as development status of the nations. In such a situation, it is very difficult to formulate the future global energy scenario (Sayigh 1999). A range of possibilities exists; the scenarios are the images of alternative future and each can be interpreted of one particular image of how the future could unfold. However, for investigating alternative future developments and their implications in what follows the present, we present the distribution of global energy use for the year 2003 and projected for 2050 as illustrated in Table 1.4 (IEAE Stat).

1.5 Environmental Degradations

Energy undergoes variety of transformations in its flow from producer to consumer. Primary energy is available as gift of nature such as coal, oil, solar radiation, falling water etc. It flows through power plants, refineries, collectors etc. and yields secondary energy in the form of electricity and refined oil products. Secondary energy flows through transmission and distribution systems and is made available to consumers as final energy. The consumers make use of the energy utilization

equipment and systems like IC engines and stoves and obtain useful energy which sustains activity in several sectors (viz. transport, agriculture, household and industry) of socioeconomic system.

The above transformations generate residuals and toxins and tend to create a state of pollution in the environment. Consequently the residuals and toxins reach man in excess of normal natural concentrations and adversely affect healthy living as well as other pursuits of human benefit and enjoyment. The cost of dealing with hazards and assuring an acceptable environment must be regarded as part of the price of energy providing heat, light and power.

Each resource of energy has its special environmental problems. The proportion of adverse effects on constituents of the environment varies from one energy resource to another. Let us consider the case of electric power plant using coal as fuel. The coal is extracted by surface mining (strip mining) as well as underground mining (deep pit mining). Strip mining damages the land surface and end results are the ridges and valleys; top-soil is lost and plant growth suffers a setback. In underground mining the cavity is created by coal removal; its back filling is very costly so the over burden tends to collapse resulting in severe soil erosion. Waste material is brought to the surface during mining and forms huge refuge banks occupying hundreds and thousands of acres of land.

The combustion of coal at the power plant site adds fly ash, smoke, soot, gaseous oxides of sulphur, nitrogen and carbon to the atmospheric air. For each kiloWatt of electricity (kWe) generation about 2.5 t of coal is burnt annually and for a plant of 200 MWe capacity annual estimated release is shown in Table 1.5.

The typical conversion efficiency of a power plant is 40 %; thus 60 % of the heat of the combustion of coal goes to atmosphere and water bodies (sea, river, lakes etc.). The generated electricity is distributed to consumer points through transmission lines and cables. It is used for end use activities which eventually dump it as heat in the environment. Besides the power plants other major sources of pollution are the automobiles and industrial units. Even the hydropower sources are not free from environmental problems. For example, USA has already developed around 50 % of its hydro potential and further expansion is suffering a setback because of ecological considerations.

The carbon dioxide and heat added to the atmosphere has resulted in the increase of earth's planetary temperature which is often referred to as Global warming. This phenomena has been independently assessed by several research centres situated in USA, Germany and UK; earth's planetary temperature rise during the last 100 years is reported to be in the range of 1.0–1.3 °C and during the last two decades the temperature rises by about 0.3 °C per every 10 years. More recently, the U.N.'s Intergovernmental panel on Climate Change (IPCC) has reported that the rate of global warming over the period 1951–2012 stands at 0.12 °C per decade and over

Table 1.5 Release of 200 MWe coal fired thermal power plant

Toxin/Residue	SO_2	NO_x	CO	CO_2	Particulate
Emissions (tons)	10,000	4400	100	1.5 million	1000

the past 15 years (1998–2012) at 0.05 °C per decade (Source: National NEWS paper *The Hindu*, Vol. 136 No. 213 Sept 5 2013). The global warming is threatening the world in terms of reduction of polar snow cover and raising of the equatorial ocean level to flood the low-lying islands and coastal regions. During the last 100 years the rain has increased by 15 % and sea level has risen by 10.5 cm; it may continue to increase by 4 cm per decade in absence of preventive measures (Chapman and Reiss 1995; Sayigh 1999)

Oxides of nitrogen and sulphur are posing a threat to plants and vegetation kingdom through Acid rains; it has already resulted in the deaths of several lakes and forests. Atmospheric air pollution caused by high level suspended particulate matter (SPM) laden with toxic chemicals have turned several big cities of the world into 'killing fields'.

1.6   Concept of Sustainability

During twentieth century, the world has witnessed unprecedented population growth and the corresponding escalations in resource use associated with innumerable technological advances. The side effects of these activities have been recognised as environmental pollution such as accumulation of toxic waste, landfills above capacity, global warming, resource depletion (e.g. deforestation and thinning of ozone layer). These effects have constrained the limits of the earth's "carrying capacity"; its ability to provide the resources required to sustain life while retaining the capacity to regenerate. As the world's population continues to grow, the implementation of resource-efficient measures in all areas of human activity has received global attention. This circumstance has been discussed in various international forums for example, in 1970s; the Club of Rome proposed the concept of 'zero growth' in answer to the conflict between economic growth and environmental protection. This, in turn, generated a debate on whether economic growth should be allowed to continue or be reduced to zero. As a result of this debate, the concept of economic growth was redefined and a number of new terms such as 'depurative growth', 'quality growth' and 'moderate growth', were introduced and the name sustainable development was coined in this regard. Subsequently in 1972, the United Nations Conference entitled "Human Environment Conference" was held in Stockholm which declared that the protection of human environment for present and future generations is an imperative goal for mankind. As a follow up, the International Union for the Conservation of Nature and Natural Resources (IUCN) used the concept of 'sustainable development' in its World Conservation Strategy. In 1987, the World Commission on Environment and Development (WCED), chaired by Norwegian Prime Minister, Gro Harlem Brundtland, published a significant report – Our Common Future. This formally proposed the strategy of sustainable development as the development that meets the needs of present generation without compromising on the needs of future.

1.7 Energy Futures: Scope of the Book

In the preceding discussion, it is widely recognised that the increasing use of fossil fuels, in both developed and developing countries, is no longer a question of altering only the global environment, and through it, regional and global climate, but also threatening the security of energy and other resources and producing complex changes in the entire earth system. Indeed the energy, environment and ecosystems are dynamically and interactively coupled. It therefore makes sense to consider the energy environment system in its totality and adopt sustainable solutions that balance economic growth and environment conservation. Furthermore, it is also almost certain that no single energy resource will be able to ensure energy security on long-term basis and the fossil fuels will remain an important part of energy mix for the next 20–40 years. The solution therefore needs diverse range of approaches and technologies. It includes management of waste, water and renewable energies, making existing fossil fuel technologies cleaner and affordable and transition to greener power generation. Furthermore, to cope up with changing global energy scenario we need transformational changes in how we use and how we deliver energy services.

This book entitled "Sustainable Energy and Environment" covers a wide spectrum of available knowledge on these topics. The structure of the book is illustrated in Fig. 1.4.

Chapters 2 and 3 present an introduction to physical as well as biological environment and the processes related to the existence and sustenance of life on earth. An outline of conventional energy and power systems and related environmental degradations are discussed in Chaps. 4 and 5. The clean coal technologies for power generation and sustainable energy and power technologies based on such renewable resources as solar, biomass, wind are covered in Chaps. 6, 7, 8, 9, 10, and 11. Finally, the topics such as management of waste and water, pollution control schemes and energy conservation are outlined in Chaps. 12, 13, and 14.

Fig. 1.4 Architecture of sustainable energy and environment
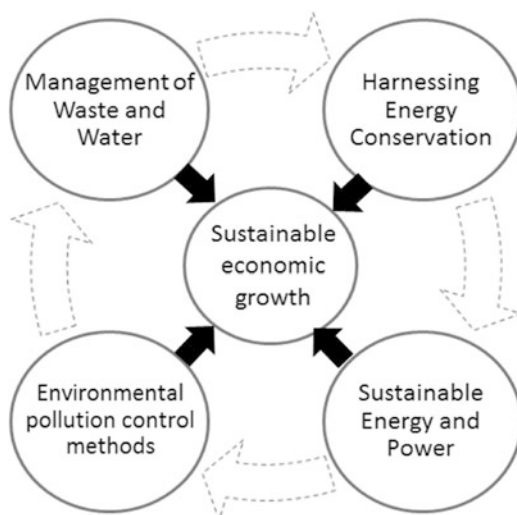
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Chapter 2
The Environment

2.1 Basic Constituents of the Environment

Earth is the third planet out from our nearest star – the Sun. It is the fifth largest of nine planets which go around the Sun. Earth is surrounded by a gaseous envelope called atmosphere and has invisible gravitational and magnetic field all around us. About 71 % of earth is covered with ocean. The Sun Earth system we live in is referred to as Environment. It is made up of two constituents:

(i) **Physical Environment:** It includes Land (Lithosphere – earth's solid and thin crust upto 60 km.), Water (Hydrosphere – oceans, lakes, rivers etc.) and **Air** (Atmosphere). The physical environment is responsible for the existence of life in various forms on earth.

(ii) **Biological Environment:** The biological environment provides such necessities of living beings as food and other materials for the sustenance of life. It includes the biosphere. All the living beings are dependent on each other and on the physical environment. This total pattern of relations between living organisms and the environment constitutes what is referred to as ecosystem. It is changing since time immemorial and the process of evolution of new species and extinction of old is continually taking place through the balance of various factors termed as ecological balance.

Ecology is the branch of science concerned with the interrelationship of living organisms and their environment.

2.2   Earth's Physical Environment

2.2.1   Earth's Differentiation

The oldest rock that has been found on earth is 3700 million years old, which indicates that the earth was in molten material form 3700 million years ago and has since cooled down. Simultaneously it has re-organized itself into different layers due to its own gravitation. The process by which the earth's mass got arranged into different layers (crust-mantle – outer core-inner core) is referred to as differentiation. Heavy materials like iron and nickel have settled deeper and formed the core; the lighter elements have formed the outer regions. The outermost layer (10–60 km) of earth has cooled and solidified; it is called the crust of the earth. The crust varies in depth. Under the ocean it is 5–10 km thick (with the ocean above) whereas under the main land mass it is 30–60 km thick. The temperature in the interior of the earth's crust increases with depth with an average gradient of 30 °C per km. Partially molten medium between the crust and outer core is called the mantle. At the interface of crust and mantle is a boundary called the Moho; its temperature is about 1500 °C. Quite often in context with crust and mantle interactive processes, the term lithosphere is used to refer to earth's surface layer up to the depth of 100 km. The mantle is about 2900 km thick and it has average temperature of 2000 °C. The next interior layer is outer core, which has temperatures in excess of 3000 °C. The temperature rises to about 7500 °C in the inner core which is a sphere of radius of about 2500 km.

2.2.2   Oceans and Continents

From outside, the earth appears as a hard and solid sphere but it is not a perfect sphere in shape. It is 12756 km across its equator and 12714 km from pole to pole. Three fourth surface of earth is covered by oceans and the rest is land mass made of six large pieces called lithospheric plates and about 12–15 smaller ones. The bottom portion of these plates is a thin slice of outer mantle which pushes the plates and makes them slide around due to enormous heat and pressure within the earth. As they do so they carry the continental land masses like giant rafts. The continental drifts are responsible for several such geo-environ phenomena as earthquakes and volcanoes. Earth's landscape features such as sea floor spreading, formation of folds and faults resulting in great mountains and narrow slits or wide valleys also owe their origin to continental drifts. It is now understood that 200 million years ago the present seven continents on earth were indeed united in a single land mass. Due to some geological events it was split in parts which have slowly drifted (15 cm per year) to take the present shape. Furthermore, the changes in temperature, rains, snow and frost have worn down the earth's surface in geological times by the process of weathering and erosion and formed glaciers (moving masses of ice), deserts, forests, lakes, caves, rivers and sea beaches.

Oceans are big reservoirs of resources such as fossil fuels, manganese, nickel and salts (sodium, magnesium, calcium and potassium). Owing to large heat capacity of water the oceans acts as temperature regulators on the earth. The oceans are the largest natural collectors of solar energy. The upper layers of Tropical Ocean are heated by absorption of solar radiation; the water at a depth of about 100–500 m is colder by about 25 °C due to flow from polar regions. This temperature gradient may be used for obtaining power from sea; the technology is popularly referred to as Ocean Thermal Energy Conversion (OTEC). Furthermore, the strong winds drag the water at sea surface and generate ocean currents and waves which besides being a renewable resource of energy also govern the climate and ecology of certain locations on earth.

The oceans contain about 97 % of world's total water stock. The remaining 2 % is in the form of ice in the Polar Regions, 0.009 % in lakes, 0.0009 % in rivers and the residue exists in atmosphere and ground water. The water from other natural sources like springs, glaciers etc. is often unpolluted however, when it comes in contact with foreign matters during industrial processes and domestic use it becomes polluted. It is then referred as waste water. The wastewater is available in enormous quantities. Furthermore, water from supply systems of major cites is often unsafe for drinking. It contains bacteria, viruses and other harmful microbes. Demand for water in India as well as in other countries is steadily increasing due to population growth, overuse, wastage and deterioration of quality of water due to industrialization. Urban population of India has grown almost five times in five decades from 62.44 million in 1951 to 288.08 million in 2001. Not long ago most of our cities were self-sufficient in meeting their water needs from the extensive urban water bodies. Today the water table is continually going down and scarcity of water is increasing day by day. To meet this ever-increasing demand, the use of water from rain and other natural resources is being considered as the rainwater is our ultimate resources and it can be easily harvested. Owing to some atmospheric contamination and catchment, the rain water has been observed to have some microbes in it. In this chapter, we investigate the technological feasibility of the utilization of water from various sources for drinking.

2.2.3   The Atmosphere

Earth is enveloped by a gaseous medium called the atmosphere. The existence of atmosphere on earth can be understood in terms of the concept of escape velocity as follows:

If on the surface of a planet a body is thrown vertically upwards with escape velocity (v_e), it will never return to the planet. The escape velocity is given by

$$(v_e) = \left(\frac{2GM}{R}\right)^{\frac{1}{2}} \tag{2.1}$$

where

G = Gravitational constant = 6.67×10^{-11} N m^2 kg^{-2}
M = Mass of the planet
R = Radius of the planet

and since the acceleration due to gravity (g) is given by

$$g = \frac{GM}{R^2}$$

so we have

$$v_e = (2g\,R)^{\frac{1}{2}} \tag{2.2}$$

for moon:

$$M \; = \; 7.36 \, \times \, 10^{22} \text{ kg; } R \; = \; 1.74 \, \times \, 10^6 \text{ m}$$

and

$$g_m = 0.1683\, g_e$$

Following the above formulations we have

escape velocity at earth = 11.2 km/s.
escape velocity at moon = 2.4 km/s.

Furthermore, according to kinetic theory of gaseous medium, the molecular velocity distribution is a function of the absolute temperature of the gas. The most probable velocity of various gas molecules in earth's atmosphere is as follows:

CO_2 (heaviest gas): 0.39 km/s.
N_2 (lightest gas): 0.49 km/s.
O_2 (oxygen): 0.46 km/s.
H_2 (hydrogen): 1.80 km/s.

These figures very clearly show the absence of atmosphere on the moon, rarity of light gases in earth's atmosphere and the presence of thin CO_2 atmosphere on Mars.

2.2.4   Atmospheric Composition

The knowledge of earth's atmospheric temperature, density and composition has been gained from observations as well as theoretical studies. The measurement techniques include density and pressure gauges, spectrometry, grenades and sodium clouds. The data has been collected with ground based as well as balloon, rocket

Table 2.1 Composition of air at earth's surface

Constituent	Percentage by volume	Percentage by mass
Major constituents		
Nitrogen (N_2)	78.084	75.51
Oxygen (O_2)	20.946	23.15
Argon (A)	0.934	–
Carbon dioxide (CO_2)	0.033	0.04
Sub total	**99.997**	**98.70**
Trace constituents		
Neon (N_e)	18.18×10^{-4}	Including Argon 1.30
Helium (H_e)	5.24×10^{-4}	
Krypton (K_r)	1.14×10^{-4}	
Xenon (X_e)	0.09×10^{-4}	
Radon (R_n)	6.0×10^{-18}	
Hydrogen (H_2)	0.5×10^{-4}	
Methane (CH_4)	2.0×10^{-4}	
Nitrous oxide (N_2O)	0.5×10^{-4}	
Sub total	**0.003**	**1.30**
Total	**100**	**100**

and satellite borne experiments. It is now well known that atmospheric air is a mixture of gases and not a compound. Widely accepted composition of air at earth's surface is outlined in Table 2.1.

Besides the above trace elements, atmospheric air has also been observed to consist of the traces of water vapour, ozone, Sulphur dioxide (SO_2), Nitrogen dioxide (NO_2), Carbon monoxide (CO) and particulate material (dust, salt). These constituents manifest themselves in highly variable proportions in the atmospheric air. The trace constituents and the highly variable constituents are collectively referred to as minor constituents of the atmosphere; these constituents contribute only a few hundred millionths to the total ground level pressure and so are measured in parts per million (ppm) units (Rajagopalan 2011).

2.2.5   Atmospheric Stratifications

The mixture of gases mainly nitrogen (N_2), oxygen (O_2), argon (A), carbon dioxide (CO_2) and water vapors (H_2O) provides a cover over earth's surface under the influence of gravitational field. The gas molecules are distributed in accordance with the hydrostatic equation as follows:

$$\frac{dp}{dh} = -\rho g$$

or,

$$dp = -\rho g\, dh \tag{2.3}$$

where dp represents change of atmospheric pressure through a vertical height, dh. If the atmospheric air obeys perfect gas equation, then its equation of state may be written as

$$p = n\, k\, T \tag{2.4}$$

So we have

$$\frac{dp}{p} = -\frac{\rho g}{nkT}\, dh$$

$$\frac{dp}{p} = -\frac{mng}{nkT}\, dh = \frac{1}{H}\, dh \tag{2.5}$$

$$H = \frac{kT}{mg} \tag{2.6}$$

where m is mean molecular weight of air and H is scale height.

Solving the Eq. (2.5) we have

$$p = p_0 \exp.\left\{ -\frac{mg}{k}\int\frac{dh}{T} \right\} \tag{2.7}$$

where p_0 is atmospheric pressure at earth's surface ($h = 0$).

Furthermore,

$$\frac{p}{p_0} = \frac{nkT}{n_0 k T_0} = \frac{mnT}{mn_0 T_0} = \frac{\rho}{\rho_0}\frac{T}{T_0} \tag{2.8}$$

The Eqs. (2.7) and (2.8) yield:

$$\rho = \frac{\rho_0 T_0}{T}\exp\left[-\frac{mg}{k}\int_0^h\frac{dh}{T} \right] \tag{2.9}$$

Following the Eq. (2.9) the ratio of densities of constituent gases at any height can be calculated; at higher heights the lighter gases predominate. Consequently, the mean molecular weight of air is reduced from 29 at earth's surface to 18 at 300 km.

In view of the above discussion, the atmosphere is most dense near earth's surface and becomes thinner at higher altitudes. The lowest and most dense region of earth's atmosphere is troposphere which extends up to about 10 km. This region of earth's atmosphere controls the weather and contains 80% of the total atmospheric gas. Above the troposphere are the other regions of atmosphere.

Stratosphere (11–30 km), mesosphere (31–100 km), thermosphere (100–400 km) and exosphere (above 400 km).

Both, the atmospheric air and the surface of the earth, are subjected to irradiation from the sun. The solar radiation spectrum on earth extends from 0.06 μm to 10 μm. The consequence of sun's radiation on the upper atmosphere is that certain radiation ($60 A^\circ – 2900 A^\circ$; $1 A^\circ = 10^{-10}$ m), is absorbed by the atmospheric gases leading to ionization and/or dissociation of gases. In lower mesosphere, the atmospheric oxygen gets dissociated and subsequently combines with molecular oxygen of upper stratosphere thereby yielding ozone. The reactions are:

$$O_2 + hv \rightarrow O + O$$
$$O + O_2 + M \rightarrow O_3 + M$$
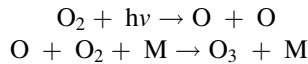
The vertical distribution of ozone extends roughly between 10 and 80 km with its peak concentration at 25 km. This region of the upper atmosphere is also called ozonosphere. The total atmospheric ozone contributes only a few millionth to the total ground level pressure. However, atmospheric ozone plays a very important role in biosphere. Ozone absorbs all the solar ultraviolet radiation of wavelength less than $2900 A^\circ$. Owing to this absorption, earth's biosphere is shielded from the lethal radiations and the stratospheric region of the atmosphere is heated; the stratospheric warming exerts profound influence on weather phenomena.

The extreme UV and X-ray radiations of solar spectrum ionize the atmospheric region above 50 km. The region between 50 km and 1000 km embodies electrons and ions in sufficient concentrations to affect the propagation of radio waves and is called the ionosphere. Atmospheric air density decreases vertically upwards and the intensity of ionizing radiation decreases downwards as they propagate into the atmosphere. Consequently the resultant ionization is maximum at a certain level forming what may be referred to as an ionospheric layer. The ionosphere consists of several horizontally stratified layers such as D, E, E_2, F_1 and F_2. These layers correspond to different constituents of the atmosphere and ionizing wavelength bands of solar radiation spectrum as shown in Table 2.2.

Besides the solar radiation, plasma also flows from the sun in the form of solar wind which interacts with top ionized regions above the ionosphere; these regions are referred to as plasmasphere. The structure and motions of some plasmaspheric

Table 2.2 Characteristics of ionospheric layers

Ionospheric layer	Level of maximum ionization	Active wavelength band (λ) A°	Absorbing gas
F_2	250	910–795	O
F_1	170	661–585	N_2
E_2	130	795–755	N_2
E	100	744–661	O_2
D	60	1012–910	O_2

regions are considerably governed by the geomagnetic field. These regions are therefore, referred to as magnetosphere.

2.3 The Biosphere

Life on earth exists in innumerable forms. The living organisms interact with the crust, the oceans and the atmosphere. The interactive sphere is often referred to as biosphere. The biosphere extends about 6–8 km into the atmosphere and 6–8 km deep into the depth of ocean. The biosphere supports life and sustains various human activities. It is a shallow layer compared to the total size of the Earth and extends to about 20 km from the bottom of the ocean. It is estimated that the biosphere contains at least 3.3×10^5 species of green plant, 9.3×10^5 species of animals, 8×10^4 species of bacteria and fungi. The essential requisites of life for all these species, namely, light, heat, water, food and habitats are supplied by the biosphere. The biosphere is very complex and large, it is usually divided into smaller units or ecosystems. All ecosystems can be divided into two parts known as the biotic (living) and the abiotic (non-living) components.

The biotic category can be subdivided into three functional groups:

Producers – autotrophic organisms (green plants and algae)
Consumers – heterotrophic organisms (all animal life)
Decomposers – heterotrophic organisms (bacteria and fungi)

The abiotic substances are the water, the nutrients, oxygen, CO_2, etc.

2.4 Natural Cycles

More than 100 chemical elements are known to occur in nature and over 30 are required by living organisms as nutrients. In nature, these elements are absorbed by plants from soil, water and air. From plants, they get transferred to other tropic level. Thus the nutrients flow from non-living things to living and then back to non-living through a cycle of processes involving decomposers – most important category of organisms. This exchange of elements necessary for living organisms as well nature is referred to as natural cycle.

Important cycles for the conservation of living and non-living components in nature are:

1. The hydrologic cycle
2. The biogeochemical cycle of

   • Carbon
   • Nitrogen
   • Phosphorus
   • Sulphur

In the unpolluted natural environment, the cycles operate in a balanced state with little variation thereby contributing to the stability of the whole biosphere.

2.4.1   The Hydrologic or Water Cycle

More than 97 % of biosphere water is in the oceans. The remaining 3 % is found on the continents and in the atmosphere. More than 70 % of this is locked in glaciers and icecaps. The water on which humans depends so heavily – lakes, streams and ground water – accounts for less than 1 % of the total supply. The hydrologic cycle of the biosphere depends on the reciprocity of evaporation and precipitation.

The entire Hydrologic cycle may be divided in to five parts as follows:

- Condensation
- Infiltration
- Runoff
- Evaporation
- Precipitation

The process begins with condensation, when water vapour condenses in the atmosphere to form clouds. Condensation occurs when the temperature of the air or earth changes. Infiltration, runoff, and evaporation occur simultaneously. Infiltration occurs when precipitation seeps into the ground. This depends a lot on the permeability of the ground. If precipitation occurs faster than it can infiltrate the ground, it becomes runoff. Runoff remains on the surface and flows into streams, rivers, and eventually large bodies such as lakes or the ocean. As both of these processes are happening, the power of the sun is driving this cycle by causing evaporation.

The vapour is returned to Earth as precipitation (rain and snow). The continents loose more than 50 % of the precipitation through evaporation and the remainder is temporarily stored in lakes and rivers or as ground water. The distribution of water in the biosphere is shown in Table 2.3.

2.4.2   Carbon Cycle

The biological systems receive their sustenance energy from the physical world (Sun-Earth system). Photosynthesis is the basic link between the physical and biological worlds to provide storable energy. Consequently, the power as well as the stored chemical energy of all living beings (plants and animals) ultimately comes from the sun through photosynthesis. It is accomplished by green plants and also by some species of bacteria as follows:

Table 2.3 Inventory of water in the biosphere

Reservoir	Volume (cubic km $\times 10^6$)	Percentage
Oceans	1370	97.25
Ice caps and glaciers	29	2.05
Ground water	9.5	0.68
Lakes	0.125	0.01
Soil moisture	0.065	0.005
Atmosphere	0.013	0.001
Streams and rivers	0.0017	0.0001
Biosphere	0.0006	0.00004

Source: Encyclopedia of Ecology, Vol. 1, p. 3732

$$\text{Water} + \text{CO}_2 + \text{Solar Radiant Energy} \rightarrow \text{Carbohydrate} + \text{Oxygen}$$
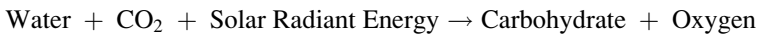
The chemical reaction is given by:

$$H_2O + CO_2 + h\nu \rightarrow CH_2O + O_2$$
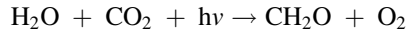
In the above reaction following two conversions of matter and energy takes place

1. **Carbon is fixed:** Inorganic form of carbon matter, the carbon dioxide (CO_2) is concerted into organic form, the carbohydrates ($C_nH_{2n}O_n$) which is the basic constituent of all living matters and carbon source for proteins and fats.
2. **Energy is Concentrated and Upgraded:** Solar radiant energy, which is a dilute form of energy, is concentrated and upgraded into chemical bond energy. This energy may be liberated by the reverse photosynthesis reaction as follows:

$$\text{Carbohydrate} + \text{Oxygen} \rightarrow CO_2 + H_2O + \text{Energy}$$
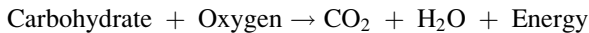
Thus, the biosphere contains a complex mixture of carbon compound in a dynamic equilibrium of formation, transformation, and decomposition. The producers, through photosynthesis, reduce CO_2 from the atmosphere to organic carbon. This then passes through consumers and decomposers, then usually re-enters the atmosphere through respiration and decomposition. Additional return from producers and consumers occurs through the non-biological process of combustion. Another major reservoir of carbon is the ocean, which stores more than 50 times as much as the atmosphere does. Interchange of CO_2 between the atmosphere and the ocean takes place through diffusion. Earth has significant reserves of bound carbon in the form of inorganic deposits such as limestone and organic fossil fuels.

2.4.3 Nitrogen Cycle

Nitrogen comprises 78–79 % of air. Through nitrogen fixation, it is assimilated by organism to form amino acids, urea, and other organic residues in the producer, consumer and decomposer cycles. Man has interfered with natural Nitrogen cycle by industrially fixing N_2. This includes production of nitrogen fertilizers and NO_x during fossil fuel combustion. Most of the excess N_2 is carried off into rivers and lakes and ultimately reaches the ocean. This is illustrated in Fig. 2.1.

2.4.4 Phosphorous Cycle

The main reservoirs of phosphorous on land are rock and natural phosphate deposits. Rain and other natural processes cause phosphorous to be released to the soil and much of it is fixed in the soil or absorbed on to soil particles. The land plants take the inorganic phosphate salts from the soil and convert them into Adenosine Triphosphate (ATP) and Adenosine Diphosphate (ADP). In the ocean, the cycle is similar to that of the fresh water systems. Phosphorus plays an important role in the growth of living tissue, for it is involved in the metabolic processes of energy transfer. It does not form gaseous compounds at normal temperature and pressures, and hence it cannot return to the atmosphere.
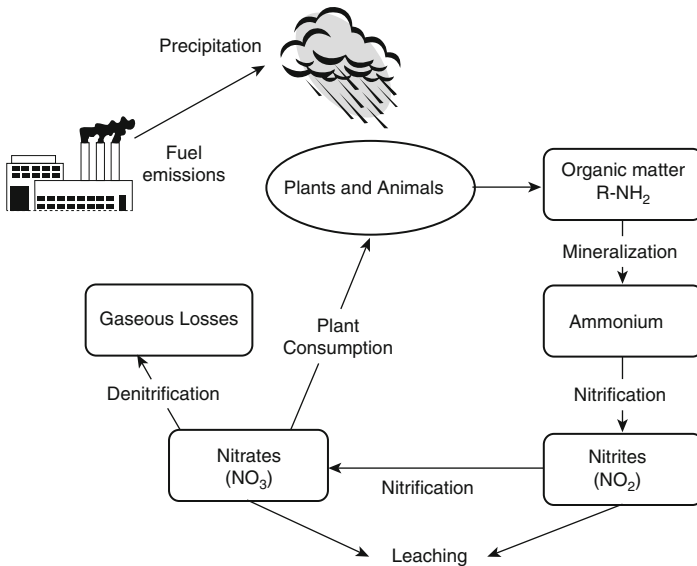
Fig. 2.1 Nitrogen cycle in the biosphere

2.4.5   Sulphur Cycle

Sulphur is found in the biosphere in a wide variety of forms. SO_2 and Hydrogen sulphide (H_2S) are the important gaseous forms, and sulphate ion (SO_4^{2-}) is the common form found in water and soil. Atmosphere receives sulphur through bacterial emission (H_2S), fossil fuel burning (SO_x), wind-blown sea salts (SO_4^{2-}) and volcanic emissions (H_2S, SO_2, SO_4^{2-}). Most of the sulphur in the form of SO_2 or H_2S is converted to sulphur trioxide (SO_3) which dissolves in water droplets to form sulphuric acid.

$$SO_3(g) \ + \ H_2O \rightarrow H_2SO_4 \ (g)$$
$$H_2SO_4(g) \rightleftarrows H_2SO_4 \ (l)$$
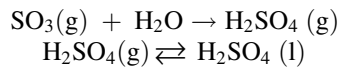
The sulphates and the acid then precipitate with rain. The S-cycle is over loaded due to burning of fossil fuels at an ever-increasing rate.

2.5   Ecological Balance and Biodiversity

For the sustenance of life, all living organisms are dependent on each other as well as on the physical environment. This total pattern of relations between living organisms and the environment constitutes what is referred to as ecosystem. In view of this, all the basic structural and operational units of nature are ecosystem. A typical summary of these inter-relationships between an organism and the physical and biological components of the environment is given in Fig. 2.2. The study of these relationships, distribution and abundance of organisms in an environment is called Ecology. The term ecology was first coined by Haeckel (1870) who defined ecology as the economy of nature. The study was classified into two categories; autoecology and synecology. When the study is devoted to the point of view of a single species it is referred to as autoecology whereas the study involving all the species living together as a community is called synecology. In recent times ecological studies have been referred to animals and plants thus dividing it into two: animal and plant ecology.

Energy has to be supplied to organisms for their survival, growth and reproduction. They also need to obtain the elements (carbon, nitrogen and phosphorous) of which they are composed. Therefore, the essential elements of ecosystem processes are energy transfer and nutrient transfer. The nutrient transfer is basically cyclical and ensures that the basic constituents of organisms are unaltered in nature. The ecosystem processes also include the different ways and means of interactions of different living organisms. For example, the life of an organism (say an animal in the forest) is affected by weather, time of the year, quality of nesting or sleeping sites, its ability to avoid predator, catch the prey, species and produce offspring. Consequently, the ecological balance is the result of many interactive processes
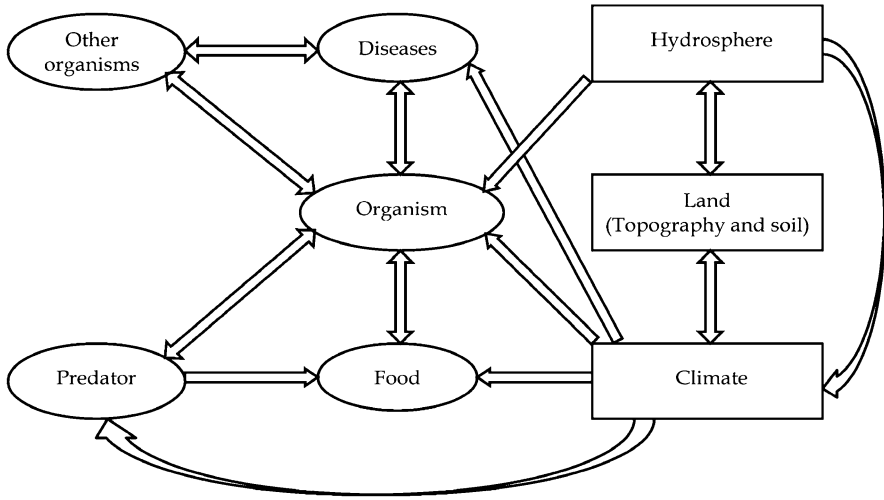
Fig. 2.2 Interactions between the organisms and the physical and biological environment

such as Energy Transfer and Photosynthesis, Trophic Levels and Food Chains, Habitats and Niches, and Population Dynamics. The above discussion follows the books Chapman and Reiss (1995) and Thorndike (1979) and is confined only to energy related topics. For further details readers are referred to these books.

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Chapter 3
Earth's Planetary Temperature

3.1 Simple Model of Earth's Planetary Temperature

Earth is the only planet in the solar system which may be characterized with the existence of living organisms (life) on it. In this context, it may be of interest to investigate its solar thermal equilibrium temperature often referred to as the planetary temperature of the earth. Solar radiant energy is intercepted by earth which absorbs it and gets heated and starts re-radiating the energy into space. In the state of thermal equilibrium, the absorbed solar energy and the re-radiated energy balance each other. The thermal equilibrium temperature of the earth is its planetary temperature (T_E). A simple model of earth's energy balance is illustrated in Fig. 3.1.

Following assumptions are made:

  (i) Earth is a solid sphere with no ocean and atmosphere.
 (ii) Earth is uniformly heated i.e., the variation of temperature with latitude and/or longitude is neglected.
(iii) Earth behaves like a black body which is defined to be a perfect emitter as well as a perfect absorber. This in turn means $\alpha = \varepsilon = 1$.

$$\text{The rate of solar energy absorbed by the earth } = \pi R^2{}_E S\alpha \qquad (3.1)$$

As a result of absorption of solar energy, the earth gets heated and emits thermal radiations. The rate at which radiant energy is emitted is given by the Stefan-Boltzmann law of radiation as follows:

$$\text{The rate of Energy re-radiated into space } = 4\pi R^2{}_E \sigma \varepsilon T^4{}_E \qquad (3.2)$$

where

R_E = Earth's radius
S = Solar constant (1360 W/m^2)

Fig. 3.1 Solar irradiance
on to the Earth and thermal
reradiation from the Earth
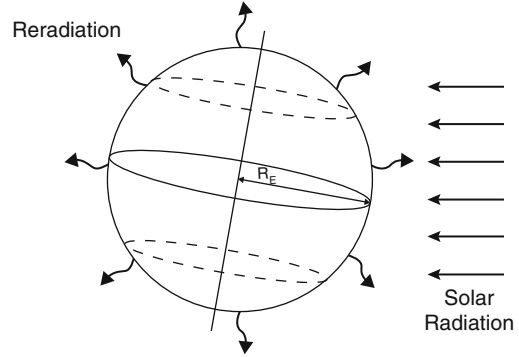
α = absorptance of earth's surface
ε = emmittance of earth's surface
σ = Stefan-Boltzmann constant (0.567×10^{-7} J m^{-2} deg^{-4} s^{-1})
T_E = Temperature of Earth

In steady state, the energy balance is given by:

$$\pi R_E^2 S\alpha = 4\pi R_E^2 \sigma\varepsilon T_E^4 \tag{3.3}$$

For the earth to be a black body, $\alpha = \varepsilon = 1$

$$T_E = \left[\frac{S}{4\sigma}\right]^{\frac{1}{4}} = \left[\frac{1360}{4 \times 0.567 \times 10^{-7}}\right]^{\frac{1}{4}} \tag{3.4}$$

$$T_E = 278.27$$

So,

$$TE = 278 \text{ K or } 5°C$$

The observed mean global temperature is 14 °C. This is interesting to note that a simple model gives results so close to observations.

3.2 Variation of Temperature with Latitude

It is well known that earth's temperature is higher in the equatorial region than in the polar region; it therefore makes sense to extend the model presented in Sect. 3.1 by relaxing the idealization of uniform heating of earth. For simplicity earth's axis of rotation is assumed to be perpendicular to ecliptic plane. Variation of solar irradiation on Earth with latitude can be seen in Fig. 3.2.

Fig. 3.2 Variation of solar irradiation on Earth with latitude
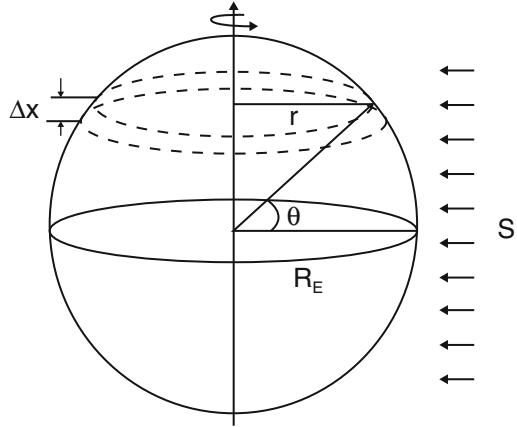
Let us consider the energy balance of a strip of width Δx located at the latitude, θ.

Projected area of strip on a plane perpendicular to sun rays
$$= 2r\,\Delta x\,\cos\theta$$
$$= 2R_E\,(\cos\,\theta)\,\Delta x\,\cos\theta$$

Rate of solar energy absorbed $= 2S\,\alpha\,R_E\,\Delta x\,\cos^2\theta$

The area of strip
$$= (\text{Circumference})\,\Delta x$$
$$= 2\pi\,r\,\Delta x$$
$$= 2\pi\,R_E\,\Delta x\,\cos\theta$$

The rate of re-radiated energy $\quad= 2\pi\,R_E\,\Delta x\,\cos\theta\,\sigma\,\varepsilon\,T_E^4(\theta)\qquad(3.5)$

where $T_E(\theta)$ is earth's temperature at a latitude θ

The energy balance is, therefore, expressed as follows:

$$2\pi R_E \Delta x\,\sigma\varepsilon(\theta)\,\cos\theta = 2S\,\alpha R_E\,\Delta x\cos^2\theta$$
$$T_E^4(\theta) = \frac{S\cos\theta\alpha}{\sigma\,\pi\varepsilon}\qquad(3.6)$$

For black body $\alpha = \varepsilon = 1$

So we have

$$T_E(\theta) = \left[\frac{S\cos\theta}{\sigma\,\pi}\right]^{\frac{1}{4}}\qquad(3.7)$$

$$T_E(\theta) = 296(\cos\theta)^{\frac{1}{4}}K\qquad(3.8)$$

Equation (3.8) represents the variation of earth's planetary temperature with latitude. Results of calculations are illustrated in Table 3.1.

Table 3.1 Variation of earth's planetary temperature $T(\theta)$ with latitude

Latiutde (θ) degrees	0	30	45	60	75	89
$T_E(\theta)$ K	296	285	271	249	211	17
$T_E(\theta)$ °C	23	12	−2	−24	−52	−166

3.3 Changing Global Temperature

Earth's planetary temperature is often referred to as global temperature. It has been continually changing since the inception of earth. The data on the past values of global temperature has been collected from several natural documents such as tree rings, changes in ice volumes as well as sea level, fossil pollen analysis and glacial movements. Seldom, if ever, the global temperature exceeds 15 °C, whose present value is 14 °C in the past two million years (period of man's appearance), there might have been about 20 glacial and interglacial periods indicating a glacial periodicity of 100,000 years. The glacial periodicities are due to changes in earth's orbit. The earth's orbit fluctuates from elliptical to nearly circular shape with a period of 100,000 years. The tilt of earth's axis of rotation fluctuates from 21.5° to 24.5° with a periodicity of 41,000 years; the earth's rotation as a rigid body also wobbles with a periodicity of 23,000 years. The variations in earth's orbit and the spin axis affect the amount of sunlight striking the planet and cause above variations in global temperature.

3.4 Radiations in the Atmosphere

The atmosphere receives the radiant energy in following forms:

- Incident solar radiation
- Solar radiation reflected from earth's surface and atmospheric constituents
- Re-radiation from earth's surface
- Re-radiation from other parts of the atmosphere

These radiations interact with clouds, particulate matter and gaseous constituents of the atmosphere which reflect, scatter, absorb (selectively as well as uniformly) and transmit the radiations. All these processes are wavelength dependent and manifest themselves in terms of host of atmospheric phenomena. Here we consider the basic features of these processes.

Satellite measurements made outside the earth's atmosphere indicate that solar radiant energy spectrum is spread over a wide range of wavelengths (0.06 µm–5.0 µm). It is characteristic of black body radiation at temperature 5762 K. However, it compares well with a black body at 6100 K in radiating the same amount of energy as the sun and has the wavelength 0.475 µm for maximum radiation (Fig. 3.3). It may be noted that the temperature in the core of the Sun is millions
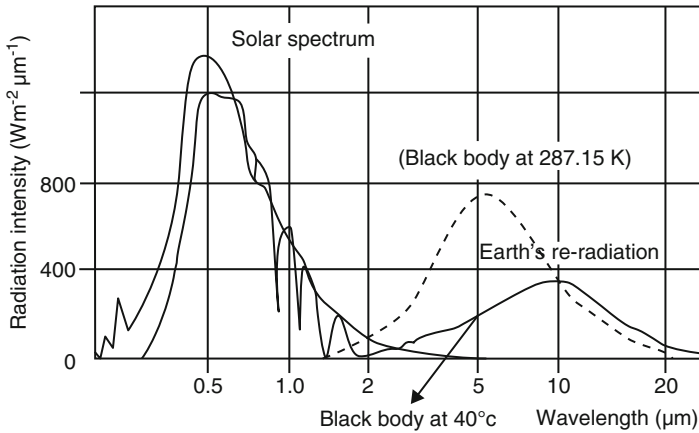
Fig. 3.3 Spectral distribution of solar and earth's radiations

Table 3.2 Various bands of solar energy

Wave-length band of solar energy		
Band	Wave-length (μm)	Interactive phenomena
X-ray and EUV	0.06–0.18	Ionizes Oxygen atoms above 250 km and Oxygen as well as Nitrogen molecules above 50 km
EUV	0.18–0.29	Dissociates Oxygen molecules between 5 and 50 km
UV	0.295–0.315	Absorbed by O_3
Visible	0.3–3.0	It contains 95 % of incident solar energy which is weakly absorbed (about 20 %) in the atmosphere
Near infrared	3.0–5.0	
Infrared	5.0–50	Atmosphere as a whole is opaque for this band

of degrees and 6100 K refers only to effective temperature of solar photosphere surface.

Various phenomena resulting from the interactions of atmosphere with various bands of solar energy are summarized in Table 3.2. The energy spectrum has sharp peaks at certain wavelengths in x-ray and UV region as follows:

- 30 A° Lyman α of ionized He
- 50 A°
- 1216 and 1026 A° respectively Lyman α and Lyman β of hydrogen
- 977 A° as C III line

The fraction of solar energy that is reflected back to space is called the albedo. Different parts of Earth's system such as clouds (0.35–0.4), snow (0.60–0.80), ocean (0.06–0.20), desert (0.25–0.40), agricultural land (0.10–0.20), forest (0.10–0.20) have different albedo values. Over the whole earth, about 28 % of

incoming solar energy is reflected back to space; therefore, typical value of planetary albedo A is 0.28.

The overall effect is that about 30 % of incident solar energy is reflected back into space and 20 % is absorbed at various levels in the atmosphere and the rest is absorbed at earth's surface.

3.5 Albedo and Earth's Planetary Temperature

Every object emits radiations characteristic of its temperature; the characteristics of these radiations are often described in terms of a theoretical concept called a black body; it is a perfect emitter as well as a perfect absorber. It means that it absorbs all radiation that falls on it; none is reflected and none is transmitted through it. The rate of radiant energy emitted by a black body (with emittance, $\varepsilon = 1$) is given by the Stefan-Boltzmann law of radiation. The wavelength at which the spectral distribution reaches its maximum is given by Wien's displacement rule as follows:

$$\lambda_{\max} = \frac{2898}{T_E}(\mu m) \tag{3.9}$$

where T is in Kelvin

Following the Eq. (3.9) $\lambda_{\max}$ values for the solar energy spectrum and earth's re-radiation spectral distribution ($T = 287.15$ K) are obtained as follows:

$$\lambda_{\max}(\text{solar spectrum}) = 0.475 \ \mu m$$
$$\lambda_{\max}(\text{Earth's re} - \text{radiation}) = 10.1 \ \mu m$$

In simple terms, earth is often assumed to be a black body in the consideration of absorption of solar energy and re-radiation by the earth which implies that $\alpha = \varepsilon = 1$ and $\frac{\alpha}{\varepsilon} = 1$ However, in reality, earth absorbs solar radiation (which is mostly in visible wavelength region) and re-radiates in the infrared and near infrared wavelength region (Fig. 3.3). So the black body assumption $\alpha(\lambda_1) = \varepsilon(\lambda_2) = 1$ must be applied carefully λ_1 and λ_2 are the representative wavelengths of solar and re-radiated energy spectrum.

The re-radiated energy is in the infrared and near infrared region of the spectrum and for this range of spectrum earth behaves like a black body; so it is logical to assume $\varepsilon(\lambda_2) = 1$. However, it is a common experience that the earth does not absorb the entire solar energy incident on it; a good fraction is reflected back into space; this fraction is called the albedo, A. The magnitude of albedo depends on the reflectivity of various constituents of earth's surface and its environment. The reflectivity of open water is 3–8 % and it increases to 25 % in polar region due to large angle of incidence; it is 20–70 % for clouds, 30 % for deserts and snowfields

and 10–15 % for arable land. A value of 30 % is often taken as representative for the albedo; recent satellite measurements have validated this value. So, we have:

$$\alpha(\lambda_1) = (1 - A)$$

For earth $A = 0.30$, so we have,

substitution of these values in earth's steady state energy balance Eq. (3.3) yields:

$$T_E = \left[\frac{S(1-A)}{4\sigma}\right]^{\frac{1}{4}} \tag{3.10}$$

$$T_E = 254.56 \text{ K} = 255 \text{ K}$$

Similarly Eq. (3.6) gives

$$T_E(\theta) = \left[\frac{S(1-A)\cos\theta}{\sigma\pi}\right]^{\frac{1}{4}} = 270.75(\cos\theta)^{\frac{1}{4}}\text{K} \tag{3.11}$$

For Venus the insolation and albedo are 2613 and 0.75 respectively; for Mars the insolation and albedo are 589 and 0.15. The planetary temperatures of Venus and Mars are, therefore, obtained as follows:

$$T_{venus} = \left[\frac{2613 \times (1 - 0.75)}{4 \times 0.567 \times 10^{-7}}\right]^{1/4} = 231.7\,K$$

$$T_{mars} = \left[\frac{589 \times (1 - 0.15)}{4 \times 0.567 \times 10^{-7}}\right]^{1/4} = 216.8\,K$$

The results of calculations of $T_E(\theta)$ based on Eq. (3.11) as a function of latitude (θ) are shown in Table 3.3. The values are much lower than the observed values of global temperature on earth.

3.6   Green House Effect

Earth's re-radiation energy is spread over the wavelength range of 3–50 μ. For an energy distribution characteristic of a black body at 14–40 °C the spectral maximal occurs at 9.3–10.1 μm. The atmosphere is almost black for this range of spectrum; this is due to the presence of carbon dioxide, water vapours and clouds whose absorption coefficients as a function of wavelength bands are summarized in Table 3.4.

Thus, the thermal energy re-radiated by the earth's surface does not totally escape into outer space but is partially absorbed by the atmosphere. The

Table 3.3 Calculations of $T_E(\theta)$

Latitude (θ) in degrees	T_E (θ) K	T_E (θ) °C
0	270.75	−2.25
30	261.2	−11.80
45	248.2	−24.70
60	227.6	−45.30
75	193.1	−79.90
89	98.4	−174.6

Table 3.4 Wavelenth bands and absorption coefficients of different constituents of atmosphere

Constituent	Absorption coefficient	Wavelength band
Carbon dioxide	>0.90	12–18 μ
Water vapours	>0.90	5–8 μ and 19–50 μ
Clouds	>0.90	5–50 μ

atmospheric regions absorbing the thermal radiations from the earth will be warmed and re-radiate the energy isotropically. The half of this energy will be back towards earth and heat the earth's surface; the resultant temperature of the earth would be higher than would be the case if the atmosphere were absent or transparent to infrared. This is referred to as the Greenhouse Effect.

The observed global average temperature of atmospheric air near the earth's surface is 288 K. It may be regarded as the actual temperature of the earth. If the earth did not have the greenhouse effect, its temperature as estimated from Eq. (3.10) was 255 K. It means that the greenhouse effect adds a warming of 33 °C to the surface of earth. Similarly, the actual planetary temperatures of Venus and Mars are 700 K and 220 K respectively (Masters 1994). The temperatures as estimated from Eq. (3.10) that does not consider the greenhouse effect are 232 K and 217 K. This shows that Mars has almost no greenhouse effect while the greenhouse effect is very pronounced on Venus.

The moon is approximately at the same distance from the sun as the earth; it receives the same amount of solar radiant flux. The diurnal temperature range of about 250 °C on the moon's surface is the consequence of the absence of an atmosphere and resultant greenhouse effect. Without the atmosphere, the earth's environment could be similarly intolerable.

3.6.1 Thin Spherical Shell Greenhouse Model

To quantify the greenhouse effect on earth's planetary temperature let us consider a simple shell model of earth wherein the earth land mass is considered to be surrounded by a spherical shell which is transparent to solar radiations but is opaque (total absorber) for earth's re-radiations. Energy balances can be expressed as follows:

The shell-earth system

$$S\pi(R+r)^2\alpha = 4\pi(R+r)^2\sigma\varepsilon T_S^4 \tag{3.12}$$

The earth system

$$S\pi R^2\alpha + 4\pi(R+r)^2\sigma\varepsilon T_S^4 = 4\pi R^2\sigma\varepsilon T_E^4 \tag{3.13}$$

where T_S and T_E are the equilibrium temperature of the shell and earth respectively.
Using the approximation $R+r\cong R$ Eqs. (3.12) and (3.13) reduce to

$$S\pi R^2\alpha = 4\pi R^2\sigma\varepsilon T_S^4 \tag{3.14}$$

$$S\pi R^2\alpha + 4\pi R^2\sigma\varepsilon T_S^4 = 4\pi R^2\sigma\varepsilon T_E^4 \tag{3.15}$$

$$8\pi R^2\sigma\varepsilon T_S^4 = 4\pi R^2\sigma\varepsilon T_E^4 \tag{3.16}$$

$$T_E = T_S 2^{\frac{1}{4}}$$

From Eq. (3.14)

$$T_S = \left[\frac{S}{4\sigma}\right]^{\frac{1}{4}}$$

And upon application of albedo correction as in Eq. (3.10)

$$T_S = \left[\frac{S(1-A)}{4\sigma}\right]^{\frac{1}{4}}$$

So, we have

$$T_E = \left[\frac{S(1-A)}{4\sigma}\right]^{\frac{1}{4}}2^{\frac{1}{4}} \tag{3.17}$$

$$T_E = (254.56)\,2^{1/4} = 302.72 = 303\ \text{K} \tag{3.18}$$

Seldom, if ever, global average temperature of atmospheric air near the earth's surface has exceeded 15 °C (288 K) and its present value is 287 K. The actual temperature of earth made up of both the land mass and oceans may be considered to be 1–2 °C higher, that is 288 K. The value, 303 K estimated from Eq. (3.17) is significantly higher than the value, 288 K based on observations. The discrepancy between the observed and estimated values could be due to the assumptions involved in the derivation of Eq. (3.17). In what follows we, therefore, investigate the rationale of these assumptions:

1. The atmosphere has been assumed to be a thin spherical shell totally opaque to earth's re-radiations. However, in the atmosphere IR absorbing materials (e.g. CO_2, water vapours and clouds) are distributed vertically in a continuous fashion rather than in a thin shell. The spatial distribution of these materials could result in the escape of some IR-energy in space. This could be taken into account by considering the thin spherical shell partially opaque to earth's re-radiations as follows:

If x represents the fraction of IR-energy that escapes into space then considering the energy balances of shell-earth system and earth system as in Eqs. (3.12) and (3.13) and using the approximation $R + r \cong R$ Eq. (3.18) modifies to:

$$T_E = 2^{1/4} \frac{1}{(1+x)^{1/4}} (255) \qquad (3.19)$$

Following two cases are of interest:

Case I: Thin shell, total absorber of IR-energy

$$x = 0$$
$$T_E = 2^{1/4} \times 255\,\text{K}$$

Case II: No absorber shell around earth

$$x = 1$$
$$T_E = 255\,\text{K}$$

Present global temperature value of 288 K in similitude with Eq. (3.18) may be expressed as:

$$288 = (1.627)^{1/4}(255) \qquad (3.20)$$

Also for present value (288 K) of global temperature Eq. (3.19) yields

$$T_E = 2^{1/4} \frac{1}{(1+x)^{1/4}} (255) \qquad (3.21)$$

Comparing Eqs. (3.20) and (3.21) we have:

$$x = 0.229$$

This gives us the present fraction of IR-energy that escapes into space. With greenhouse gaseous accumulation in the Shell x would tend to decrease and become zero. Thus $2^{1/4}$ 255 = 303 K may be regarded as the maximum theoretical value based thin spherical Shell model.

2. The underlying model of Eq. (3.17) does not take into account the sensitive and latent heat transfer due to convection and cloud ascendance from earth to the atmosphere. Furthermore, the model considers the spherical Shell as transparent to incident solar radiation; but in actual practice, 25 % of solar radiation is absorbed by O_2, O_3 and other constituents at various levels in the atmosphere.

Masters (1994) has estimated the global average temperature of the atmosphere as 288 K based on the work of Harte (1985). The corresponding energy flows as reported by these authors are as follows:

Total solar energy striking the earth $= S \pi R^2$
Earth's surface area $= 4 \pi R^2$

$$\text{Solar input per unit surface area} = \frac{S}{4} = \frac{1374}{4} = 343 \, W/m^2$$

Albedo $= 0.30 \times 343 = 102.9 = 103 \, W/m^2$
The radiation absorbed by the atmosphere $= 0.25 \times 343 = 86 \, W/m^2$
The solar radiation absorbed by earth $= 0.45 \times 343 = 154 \, W/m^2$
Incoming radiations absorbed by the earth and the atmosphere $= 0.7 \times 343 = 240 \, W/m^2$
The heat transfer due to convection and clouds from earth to the atmosphere $= 97 \, W/m^2$
Radiation from earth's surface at T $= 288$ K to atmosphere and space $= 401 \, W/m^2$

Of the 401 W/m², 20 W/m² escapes into space and the rest 381 W/m² is absorbed in the atmosphere. So from the consideration of thermal equilibrium we get:

Radiation from atmosphere to earth $= (401 + 97) - (155) = 343 \, W/m^2$

Similarly, from the consideration of thermal equilibrium of earth's atmospheric system we get:

Radiation from atmosphere to space $= (343 - (103 + 20)) = 220 \, W/m^2$

3.6.2   Greenhouse Model with Leakage

Suppose atmosphere has absorptivity (α) – a fraction α, of up welled IR is now absorbed by the atmosphere. α will depend on the concentration of Greenhouse gases. The atmosphere now absorbs only a fraction α, of the terrestrial radiation upwelling from the ground. See Fig. 3.4.

$$\text{Average Incoming Solar Flux} = \frac{\text{Intercepted Incoming Radiation}(S_0 \pi r^2)}{\text{Earth's Surface Area}(4\pi r^2)} = \frac{S_0}{4}$$

To solve for T_a and T_s,
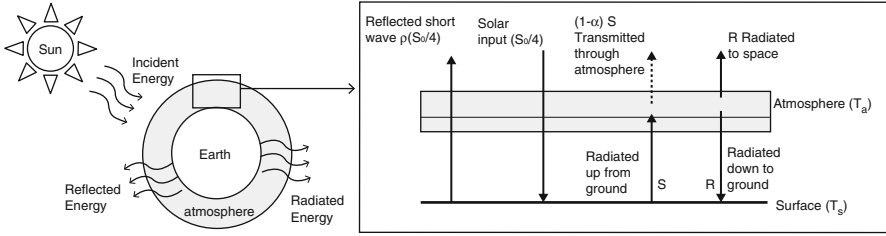
Fig. 3.4 Greenhouse model with leakage

$$\text{Surface :} \qquad \tfrac{1}{4}\,(1-\rho)\,S_0 + R = S \tag{3.22}$$

$$\text{Top of atmosphere :} \qquad \tfrac{1}{4}\,(1-\rho)\,S_0 = R + (1-\alpha)S \tag{3.23}$$

Here,

$$S = \sigma T_S^4 \quad R = \sigma T_a^4$$

Assuming that atmosphere radiates as a blackbody. Thus $T_a = T_e = \left(\dfrac{(1-\alpha)S_0}{4\sigma}\right)^{\frac{1}{4}}$

By adding the Eqs. 3.22 and 3.23, we get

$$T_S = \left(\frac{2}{2-\alpha}\right)^{\frac{1}{4}} T_e \tag{3.24}$$

If $\alpha = 1$ (opaque) $T_S = 2^{\frac{1}{4}} T_e$
If $= 0$ (transparent) $T_S = T_e$

By using Kirchhoff's law, T_a can be found out.

emissivity = absorptivity

By subtracting Eqs. $(3.23) - (3.22)^2$, we get

$$T_a = \left(\frac{1}{2}\right)^{\frac{1}{4}} T_S = \left(\frac{1}{2-\alpha}\right)^{\frac{1}{4}} T_e \tag{3.25}$$

It can be observed that the atmosphere is cooler than T_e since emission is only partly from the atmosphere.

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Chapter 4
Conventional Energy and Power System

4.1 Characteristics of Power Systems

Over the years it has been experienced that electricity is the most preferred form of usable energy for industrial, agricultural, commercial and domestic activities. It can be generated centrally in bulk and transmitted economically over long distances. Electrical energy consumption is presently about 30 % of total energy consumption on worldwide basis. The transportation sector around the world is going to be electric in the long run. The percentage of electricity demand with respect to total energy demand is, therefore, bound to grow at a high rate. For example, in India the power sector has passed through a phase of significant development. During the past 65 years of independence, the installed capacity of power has increased from 1700 MWe to 173,651 MWe in 2011. During this period the overall industrial production has increased ninefolds. However, in the power sector there is still a peak power capacity shortage of 12.5 % and approx. 8 % of total power demand has not yet been met. Therefore, it makes sense to survey conventional technologies in power sector for future developments.

Power systems consist of electricity generating units, transmission lines and distribution systems. Individual systems are connected through transmission lines to form electrically connected areas or regional grids feeding to the distribution system which supplies power to domestic, industrial and other consumers. The regional grids are interconnected to form a national grid, which connects the different regions in respect of generation and scheduling features. Electricity is generated at a voltage of 11–25 kV which is stepped up to transmission levels of 220–440 kV. For example, in India several 400 kV lines are in operation. Some countries do have 765 kV lines. At the supply end of the line the first step down of the voltage is in the range of 33–138 kV, which caters to large consumers. The next step down is at two levels as follows:

 (i) Feeder voltage of 11 kV.
(ii) Consumer voltage of 415 V (three phase) or 230 V (single phase).
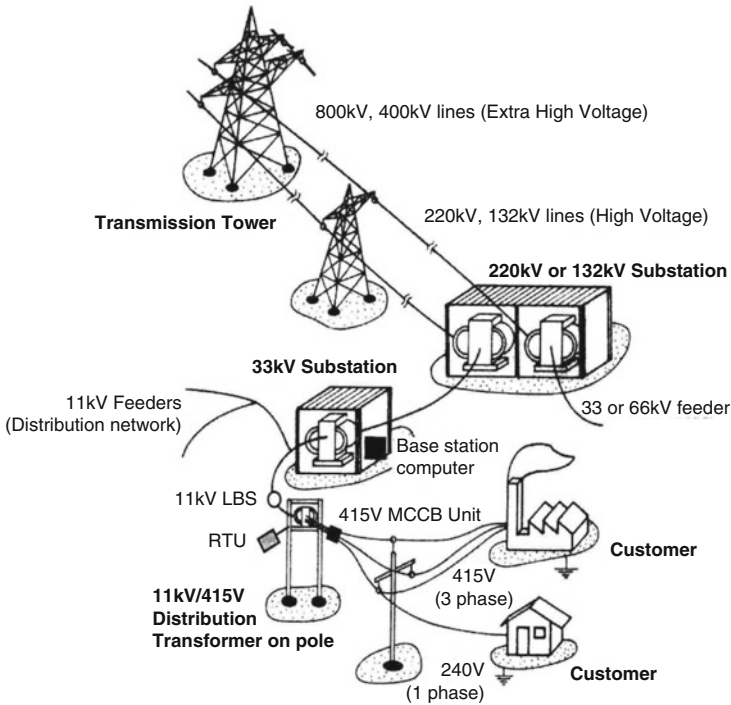
Fig. 4.1 Schematic of electrical power distribution system (*Source:* JERS/Vol. III/Issue II/April-June, 2012/82–84)

For more details the readers are referred to texts on electrical power systems.

In Delhi, distribution companies (discoms) including BEPL are in the business of distributing electricity and a schematic of the architecture of their distribution is illustrated in Fig. 4.1.

Conventional electricity generating systems include fossil fuel based power plants, nuclear power plants and hydro power plants. In what follows we survey the conventional techniques of electricity generation with a stress on future trends.

4.2   Fossil Fuel Based Power Plants

Bulk of electricity on global basis is generated by fossil fuel based power plants. In these plants, the chemical energy stored in the fuel (coal, oil, gas) is transformed into electricity. The entire process involves three energy conversion steps:

 (i) Chemical to thermal
 (ii) Thermal to mechanical
(iii) Mechanical to electrical

Chemical to thermal conversion involves fuel combustion; thermal to mechanical energy conversions are accomplished through a thermodynamic cycle of working substance. Water is used as a working substance (Culp 2000) in steam power plants and air and gas (like helium) are used in Gas turbine power plants. The electrical generators are used for mechanical to electrical conversion.

4.2.1   Steam Based Power Plants

In these plants the chemical to thermal conversion is accomplished in a fuel combustion chamber where heat is released to produce steam in the boiler. The steam at higher temperature and pressure is expanded through a turbine where some of its internal energy is converted into mechanical energy. The axial flow turbine is commonly used; it consists of appropriately shaped blades projecting radially outwards from the shaft which rotates on the principle of pin wheel and is mounted inside a stationary housing made up of several cylinders, steam is introduced at high pressure at one end and on leaving the turbine at the other end it condenses into water. The phase change creates partial vacuum and maintains pressure differential across the turbine. The spinning shaft acts as a prime mover and drives the electric generator, usually coaxial with the turbine. A simple schematic diagram of a coal fired thermal plant is shown in Fig. 4.2.

If η_1, η_2 and η_3 represent the efficiencies of above mentioned three conversion processes: chemical to heat, heat to mechanical and mechanical to electricity respectively.

The efficiency of overall conversion process is given by:

$$\eta = \eta_1 \eta_2 \eta_3 \tag{4.1}$$

The typical values for η_1 and η_3 in a coal based power plant are 0.88 and 0.90 respectively. η_2 may be obtained from thermodynamic considerations of the cycle of process that the working substance (water/steam) goes as it circulates through the system. Water from the condenser is at low temperature and pressure. It passes through pumps and pre heaters and enters the boilers at high pressure. In the boiler it absorbs heat and acquires higher temperature and undergoes phase change. Subsequently the steam is superheated and undergoes adiabatic expansion in the high pressure stage of the turbine. It is reheated and expanded through intermediate and low pressure stages of the turbine. The entire process may be approximated by a Rankine cycle modified to include superheating, feed water pre heating and steam reheating. Following Thorndike (1979) the process may be analyzed as follows.

The enthalpy gain (H_{in}) of the working substance takes place at a wide range of temperatures and is accompanied by the change in entropy (S_{in}) which may be expressed as
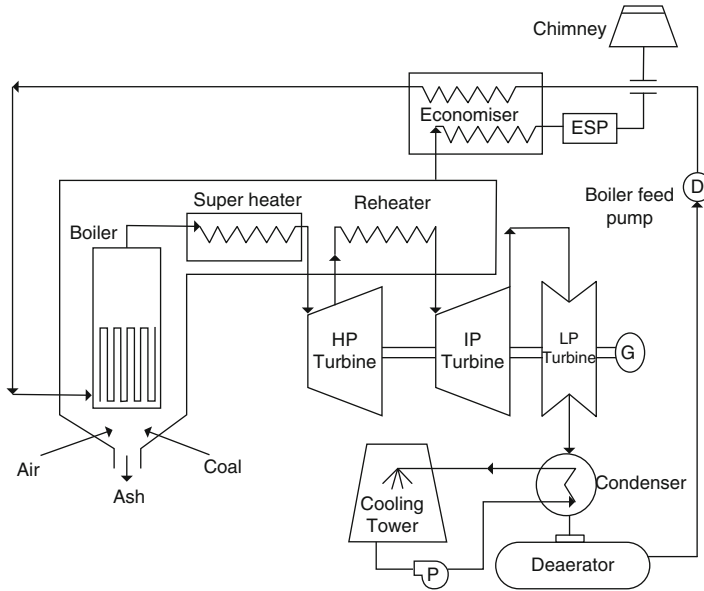
Fig. 4.2 Schematic diagram of thermal power plant

$$S_{in} = \int dS_{in} = \int^T \frac{dH_{in}}{T} \tag{4.2}$$

$$H_{in} = \int^T dH_{in} \tag{4.3}$$

$$\frac{H_{in}}{S_{in}} = \frac{\int^T dH_{in}}{\int \frac{dH_{in}}{T}} = T_{eff}(\text{say}) \tag{4.4}$$

Therefore, we have

$$H_{in} = S_{in} \times T_{eff} \tag{4.5}$$

Similarly, the enthalpy loss process may be expressed as:

$$S_{out} = \int dS_{out} = \int^T \frac{dH_{out}}{T} \tag{4.6}$$

$$H_{out} = \int^T dH_{out} \tag{4.7}$$

$$\frac{H_{out}}{S_{out}} = \frac{\int\limits^{T} dH_{out}}{\int \frac{dH_{out}}{T}} = T_0(\text{say}) \tag{4.8}$$

$$H_{out} = S_{out} \times T_0 \tag{4.9}$$

The entropy is a measure of randomness or chaos, and in a closed system it never decreases. So, we have

$$S_{out} \leq S_{in} \tag{4.10}$$

And maximum efficiency will correspond to

$$S_{out} = S_{in} \tag{4.11}$$

$$\eta_2 = \frac{H_{in} - H_{out}}{H_{out}} = 1 - \frac{T_0}{T_{eff}} \tag{4.12}$$

For a typical system,

$$T_{eff} = 645 \text{ K}$$

$$T_0 = 300 \text{ K}$$

$$\eta_2 = 1 - \frac{T_0}{T_{eff}} = 1 - \frac{300}{645} \tag{4.13}$$

$$\eta_2 = 0.534$$

The typical value of the overall conversion efficiency is therefore obtained as

$$\eta = 0.88 \times 0.534 \times 0.90 = 0.422$$

This efficiency of the overall conversion process is rather low and the second stage (η_2) seems responsible for it, which in turn is due to the lower value of T_{eff}. The fuel (coal) had a higher combustion temperature (10^4 K) but has been used to supply heat at relatively lower temperature, which has yielded low efficiency for the second stage. Thus higher exergy (available energy) loss in combustion chamber and large quantity of heat rejected to the condenser are the factors to be considered for the improvement of efficiency of thermal power plants. Superheating, feed water preheating using waste heat and steam reheating are based on these factors and are often used in thermal power plants for affecting the increase in efficiency.

4.2.2   Gas Turbine Power Generation

The gas turbine power generation is based on the expansion of high temperature air or gas (like He) as working substance in the turbine. Both open cycle as well as closed cycle systems have been proposed and tested. The simple open cycle gas turbine (GT) plant may be represented as in Fig. 4.3a. The working substance is generally air and its intake is from the atmosphere. The air is first compressed then heated in the combustion chamber and finally expanded in the turbine and let into the atmosphere. The GT plant uses approximately 70 % of its output power internally and, if all processes are not highly efficient, the losses easily consume the potential net output. The temperature of gas supplied to the turbine must, therefore, be as high as 1100–1200 °C in order to obtain good cycle efficiencies.

The closed cycle GT plant is illustrated in Fig. 4.3b, a gas (e.g. helium) is used as working substance. For heat addition and heat removal heat exchangers are used

Fig. 4.3 Schematics of (**a**) Simple open cycle gas turbine plant, (**b**) Closed cycle gas turbine plant, (**c**) The performance cycle for GT plant
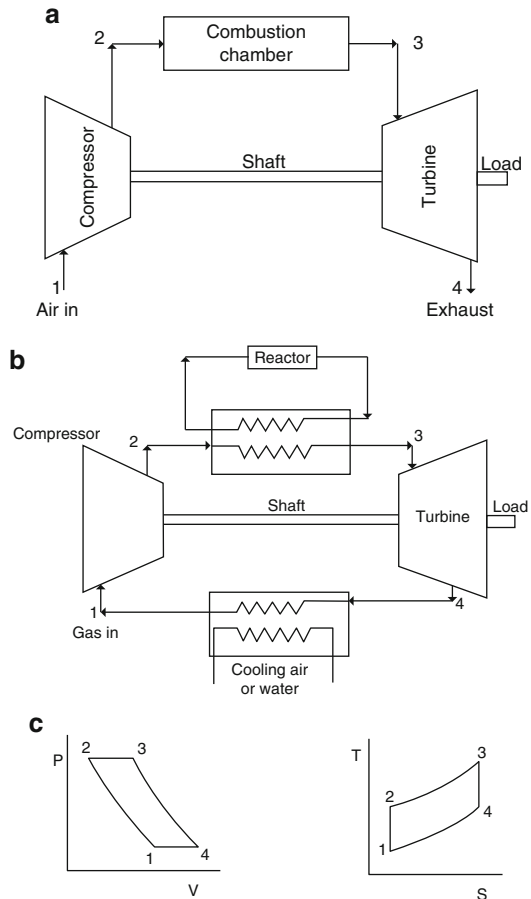
which add to the cost. However, the use of heat exchangers at higher temperatures is desirable for systems where environmental concerns are important. For example, from a nuclear reactor the radioactive releases may spread to the atmosphere.

The GT plant development has now reached a stage where good overall efficiencies are possible due to the higher performance levels of the components. The mechanical efficiencies of the compressor and turbine are in the range 90–96 %, and their isentropic (internal) efficiencies exceed 85 %.

The ideal cycle for the GT plant is the Brayton cycle shown in Fig. 4.3c. The gas is compressed isentropically, from point 1–2, heated at constant pressure from 2 to 3, and then expanded isentropically through the turbine from point 3–4. Cooling is affected in the heat exchanger (closed cycle) or in the open atmosphere (open cycle) to restore the gas to point 1.

The work output (W_T) of the turbine per unit time may be expressed as

$$W_T = m(H_3 - H_4) = m\,\Delta H \tag{4.14}$$

where m is the mass flow rate of the gas and ΔH is the change (decrease) in specific enthalpy which is given by

$$\Delta H = \int_{T_4}^{T_4} C_P\, dT \tag{4.15}$$

where C_P is the specific heat at constant pressure. In general, it is a function of the gas temperature. However, for a mono atomic gas like helium it may be taken as constant with respect to temperature. So, we have:

$$\Delta H = -C_P(T_3 - T_4) \tag{4.16}$$

Negative ΔH corresponds to decrease in enthalpy. The work output (W_T) is, therefore, given by

$$W_T = m\,C_P(T_3 - T_4) \tag{4.17}$$

Further, since

$$PV = RT \text{ (ideal gas equation)} \tag{4.18}$$

$$PV^{\gamma} = \text{constant (for adiabatic change)} \tag{4.19}$$

$$P\left(\frac{RT}{P}\right)^{\gamma} = \text{constant} \tag{4.20}$$

$$T \alpha P^{\gamma - 1} \tag{4.21}$$

$$T \alpha P^{\left(\frac{\gamma - 1}{\gamma}\right)} \tag{4.22}$$

So

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} = (r_T)^{\left(\frac{\gamma-1}{\gamma}\right)} \tag{4.23}$$

$$W_T = m C_P T_3 \left[1 - \frac{1}{(r_T)^{\left(\frac{\gamma-1}{\gamma}\right)}}\right] \tag{4.24}$$

Similarly, the compressor work rate,

$$|W_C| = m C_P T_2 \left[1 - \frac{1}{(r_C)^{\left(\frac{\gamma-1}{\gamma}\right)}}\right] \tag{4.25}$$

Ignoring pressure losses in the cycle, with $r_T = r_c = r$, we have for the complete cycle:

$$W_{net} = W_T - |W_C| = m C_P (T_3 - T_2) \left[1 - \frac{1}{r^{\left(\frac{\gamma-1}{\gamma}\right)}}\right] \tag{4.26}$$

Since $m C_P (T_3 - T_2)$ represents the heat added in the cycle, thermal efficiency is therefore, given by:

$$\eta_{th} = \frac{W_{net}}{m C_P (T_3 - T_2)} = 1 - \frac{1}{r^{\left(\frac{\gamma-1}{\gamma}\right)}} \tag{4.27}$$

It is often more advantageous to express the thermal efficiency or the net work output in terms of initial and maximum cycle temperature T_1 and T_3 respectively.

Simplifying Eq. (4.26) in terms of T_1 and T_2, the net work output per unit mass (specific work) is obtained as follows:

$$\frac{W_{net}}{m} = C_P \left[T_1 \left(1 - r^{\left(\frac{\gamma-1}{\gamma}\right)}\right) + T_3 \left(1 - \frac{1}{r^{\left(\frac{\gamma-1}{\gamma}\right)}}\right)\right] \tag{4.28}$$

The following conclusions can be drawn from Eqs. (4.26, 4.27, 4.28)

(i) From Eq. (4.26), η_{th} increases indefinitely with r
(ii) Following the Eq. (4.28) it can be shown that for an ideal cycle operating between the same temperatures T_1 and T_3 (and the same inlet and exhaust pressures), the net work output is maximum at an optimum value of γ.
(iii) For the same values of T_1, T_3, r and γ, the specific work is a direct function of C_p. Hence, helium can produce more than five times specific work (W_{net}/m) than air.

The fluid friction tends to increase the entropy in compression as well as expansion processes. Consequently, the Brayton cycle becomes non-ideal and involves mechanical losses of about 1 % in addition to the appropriate values of other losses. In practical systems as in steam cycles, regeneration is used to preheat the compressed gas at 2 by the exhaust heat at 4. Using the heat exchanger often referred to as regenerator or sometimes recuperator. Regeneration which is basically the internal exchange of heat within the cycle significantly shifts the optimum pressure ratio to lower values and improves the efficiency by reducing heat input. Turbine inlet temperature (TIT) is yet another important parameter for the escalation of GT cycle efficiency. Efforts are being made to boost TIT from its present value of 1100–1200 °C to 1500–1600 °C. It would involve solving a number of high temperature problems such as materials, cooling and fuels.

The gas turbine plants are compact, lightweight and low cost (El-Wakil 1985). They can be put on load in a fraction of an hour. They require limited cooling water, only for auxiliaries. Natural gas is the ideal fuel for gas turbines. This is not available everywhere. Blast furnace and producer gas or such liquid fuels of petroleum origin as distillate oils or residual oils are, therefore, commonly used in GT plants. Low capital cost and high fuel costs are the factors responsible for preferred application of GT plants as peak power units where they are expected to be online for about 1000–2000 h per year.

4.3   Nuclear Power

4.3.1   Nuclear Fusion and Fission Energy

In classical mechanics, mass, momentum and energy are conserved separately before and after interactions. However, nuclear energy has a different origin and at nuclear level mass and energy are not conserved separately but are related to each other. The theoretical foundations of this relationship were laid by Einstein in the special theory of relativity as follows:

The energy mass relation is

$$E = m c^2 \qquad (4.29)$$

where E is the total energy of the body and m, the mass of the body which is not constant but is related to its velocity v by

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad (4.30)$$

where m_0 is the rest mass of the body and c is speed of light in vacuum. Equation (4.29) reduces to

$$E = m_0 c^2 \left[1 - \frac{v^2}{c^2} \right]^{-\frac{1}{2}}$$

$$E = m_0 c^2 + \frac{1}{2} m_0 v^2 \tag{4.31}$$

In Eq. (4.31) first term is constant and is referred to as rest mass energy; the second term, as usual, is the kinetic energy of the body. The rest mass energy term indicates that energy and mass are not conserved separately but are related to each other. An energy $m_0 c^2$ must appear when rest mass m_0 disappears. 1 kg mass corresponds to 9×10^{16} J of energy. So in nuclear context decrease in nuclear mass would correspond to liberation of nuclear energy.

Half of the nuclear particles (neutrons) do not carry an electric charge, whereas the other half (protons) are all positively charged repelling one another and contributing to the tendency of nuclear disruption. For the nucleus to be stable it is essential that there exist some forces of some kind, attractive in nature, which act on uncharged neutrons as well as on positively charged protons in a similar manner. In similitude with the idea of surface tension that cause a mercury or a rain droplet to form a shape of sphere in order to make its surface as small as possible, assume that the forces acting between the nucleons are analogous to those acting between the molecules of any ordinary liquid which constitutes the basis of the liquid drop model of the nucleus. According to this model the nuclei of different chemical elements are considered as minute droplets of a universal nuclear fluid. One may, therefore, expect that these droplets will behave in the same manner as droplets of ordinary liquid wherein it has been observed that whenever two droplets closely meet they fuse together forming a larger droplet. The fusion of two droplets into one is due to the surface tension forces, which tend to reduce the total surface and surface energy of the liquid. It may be easily shown as follows.

If r and R are the radii of small and compound droplets respectively then we have the volume balance as:

$$4\pi R^3 = 4\pi r^3 + 4\pi r^3 \tag{4.32}$$

or

$$R = \sqrt[3]{2}\, r \tag{4.33}$$

$$\text{Surface area of compound droplet} \ = \ 4\pi R^2 \ = \ 4\pi r^2 2^{\frac{2}{3}}$$

$$\text{Surface area of two smaller droplets} = 4\pi r^2 + 4\pi r^2 = 8\pi r^2$$

$$\text{The ratio of surface areas before and after fusion} \ = \ \frac{8\pi r^2}{4\pi r^2 2^{\frac{2}{3}}} = \frac{2}{1.587}$$

Thus when two droplets fuse into one, the total surface is reduced in the ratio 2:1.59 or by about 20 %. This results in liberation of surface energy.

If the surface tension forces were the only forces acting in atomic nuclei, any two nuclei would fuse together, liberating nuclear energy. However, in contrast to ordinary liquids, a nuclear fluid is always electrically charged since about half of its constituent particles are protons. The electric repulsion between the nuclear charges acts in the opposite direction to the surface tension forces and would tend to disrupt larger droplets into smaller ones; this is referred to as fission. With both kinds of forces present, the liberation of nuclear energy through fusion or fission would depend on the relative strength of the two forces.

The nuclear volume is approximately proportional to number of nucleons i.e., mass number A; the radius of the nucleus is, therefore, proportional to $A^{1/3}$ and the total surface of the nucleus is proportional to 2/3 power of A the atomic weight mass number. On the other hand electrical energy increases approximately as the square of the nuclear charge. Therefore, for light nuclei, the surface tension energies (which give a release of energy by fusion) overshadow the effects of electric charge, so the fusion of two light nuclei will liberate excess energy as a by-product. However since electric energy increases with atomic weight much faster than the surface energy does, so for heavy nuclei the electric charge factor is of great importance; consequently the energy released by splitting the electric charge of the nucleus into two would be greater than the energy used up because of the greater surface area of the two fragments. This excess energy would be released when the large nucleus fissions or splits.

In Fission, a heavy nucleus splits into two or more lighter nuclei whereas in Fusion two or more light nuclei combine (fuse) to form a heavier nucleus. However, in both the processes the released heat energy (E) is due to the decrease in mass (Δm) and is given by

$$E = \Delta m c^2 \tag{4.34}$$

where c is velocity of light.

The technology of thermonuclear fusion is still at the R&D stage whereas the fission technology has reached the stage of commercial utilization. Presently 17 % of total global electricity production is from nuclear fission power systems. In what follows we present the current status of nuclear fission power generation technologies.

4.3.2 Nuclear Fission Power Generation

A nucleus is characterised by the surplus energy which the nucleons have by virtue of their mutual attractions when they become bound together to form the nucleus; this is referred to as the binding energy of the nucleus. In fact this is the energy releasable upon nuclear fission. The stable nucleus as such has a barrier that

prevents it from fissioning. So some energy must be added to the nucleus to affect the fission; this is referred to as excitation energy E_c. If E_r is the energy released in the fission, then:

$$\text{Net energy gain} = E_r - E_c$$

One well-documented method of providing the excitation energy to the nucleus is by the capture of neutrons is as follows:

$$^0n_1 + {}^A_Z X_N \rightarrow {}^{A+1}_Z X_{N+1} \tag{4.35}$$
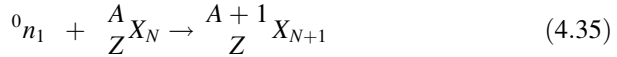
In this process (capture of neutron), energy acquired by the nucleus is sum of K.E. of neutron which it had before capture and the potential energy or the energy with which the neutron is bound, E_{bind}. If this energy is more than E_c, the nucleus will fission otherwise will stay in excited state and gradually tend to normalcy. This circumstance can be illustrated as follows.

The nucleus U^{236} can be formed as a result of the capture of one slow neutron (K.E. ~ 0) by U^{235}. The energies of U^{236} are:

$$E_c = 6.6\,\text{MeV}$$

$$E_{bind} = 6.8\,\text{MeV}$$

In this case $E_{bind} > E_c$ so the nucleus has the probability of fissioning as follows:

$$^{236}_{92}U \rightarrow {}^{133}_{51}Sb + {}^{99}_{41}Nb + 3\eta + \Delta E \tag{4.36}$$
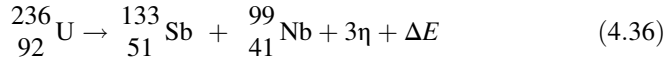
In contrast, the energies for U^{239} are as follows:

$$E_c = 7.0\,\text{MeV}$$

$$E_{bind} = 5.5\,\text{MeV}$$

So, the nucleus is not fissionable by slow neutron but would require neutrons of K. E. $= 1.5$ MeV.

The fission relation takes place in the following manner

$$n + U \rightarrow X + Y + (2 - 3)\,n \tag{4.37}$$
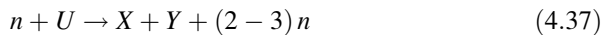
The availability of neutrons as reaction product is indicative of the chain reaction nature of the process. Following two cases may occur:

Case I: At least one emitted neutron is used in further reaction:

$$n + U \rightarrow X + Y + (2-3)\,n$$
$$\downarrow$$
$$n + U \rightarrow X + Y + (2-3)\,n$$
$$\downarrow$$

and so on
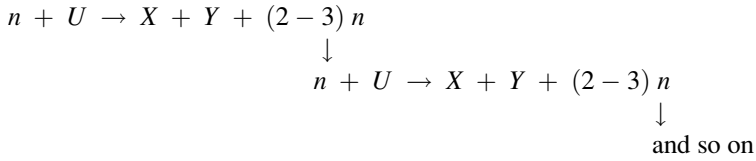
In this type of reactions the rate at which nuclear fission takes place remains constant. This is referred to as sustained chain reaction and is the basis of nuclear reactors.

Case II: More than one neutron is used in further reaction:

$$n + U \rightarrow X + Y + (2-3)\,n \begin{cases} \nearrow n + U \rightarrow X + Y + (2-3)\,n \nearrow \\ \searrow n + U \rightarrow X + Y + (2-3)\,n \nearrow \end{cases}$$
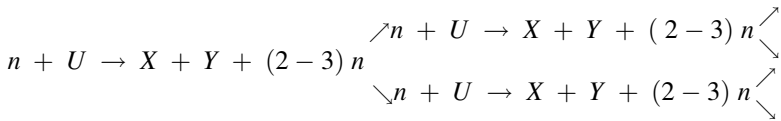
In this type of reaction the rate at which fission takes place grows. This is referred to as divergent chain reaction; it is relevant to such applications as nuclear explosions. Mathematically, the nuclear fission reaction rate is characterised by a parameter known as effective reproduction constant, Ke; it represents average number of neutrons that cause fission in the next generation resulting in following phenomena:

Ke < 1: number of fissions per generation shrinks and no chain reaction occurs.
Ke = 1: number of fissions per generation remains constant and sustained chain reaction occurs.
Ke > 1: number of fissions per generation increases and divergent chain reaction occurs.

In nuclear fission reactors one needs to have K = 1 to a very high degree of accuracy (say 10^{-7}). This is known as stability criteria because even if K = 1.001, the reactor will be in a state of divergent chain reaction and double its power level in 70 s.

The natural uranium ore consists of 99.3 % U^{238} and 0.7 % U^{235}. The slow neutrons are likely to cause fission in U^{235} and neutrons resulting from the fission are fast (1–2 MeV). Let us, therefore, consider the interaction of fast neutrons (1–2 MeV) with the natural uranium medium. High-energy (1–2 MeV) neutrons suffer inelastic scattering in the medium of natural uranium; the neutron energy is absorbed but does not yield fission.

$$n + U^{238} \rightarrow n^1 + {}^*U^{238} \rightarrow U^{238} + \gamma \text{ rays} \tag{4.38}$$
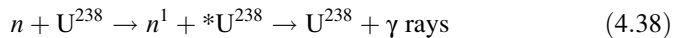
This process continues until the neutron energy is reduced down to the threshold of inelastic scattering. Then neutron starts loosing energy very slowly via elastic scattering. In this process, following two possibilities occur:

 (i) Since the loss of energy with each elastic collision is less; the neutrons may get lost due to diffusion out of the medium and no fission could occur.
(ii) The neutrons before getting lost may reach the energy range 1–100 eV which is the resonance capture region and there could be some probability of fission as follows:

$$n + U^{238} \rightarrow {}^*U^{239} \rightarrow U^{238} + \gamma \text{ rays} \qquad (4.39)$$

$$n + U^{239} \rightarrow n^1 + {}^*U^{239} \rightarrow X + Y + (2-3)n \qquad (4.40)$$
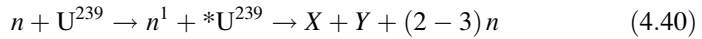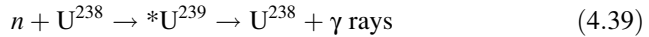
This shows that the interaction of fast neutrons with natural uranium would lead to fission with very little probability. Following measures are, therefore, taken to ameliorate the situation with respect to the occurrence of fission.

(a) Enrich uranium with U^{235} so that the amount of inelastic scattering on U^{238} is reduced.
(b) Interpose between the pieces of fuel a material of low atomic mass number to slow down the neutrons by elastic collision according to usual laws of motion. This material is referred to as moderator. Nuclei of ordinary hydrogen having almost the same mass as neutrons are very effective. But hydrogen can sometimes absorb neutrons inelastically. Second isotope of hydrogen, deuterium, is therefore a better choice. In practice, water (H_2O) heavy water (D_2O) and carbon have been used as moderators in fission reactors. Fully moderated neutrons will have energies corresponding to the temperature of their surroundings and are, therefore, called thermal.

In practice water as moderator and slightly enriched U^{235} fuel (2.5–3.5 %) can give Ke = 1. The precision of the stability criteria may be achieved by such control mechanisms as the negative feedback which involves automatic response that tends to cancel any perturbation such as unwanted change in power level. Doppler broadening of U^{238} capture cross-section and temperature variation of the density of moderator provides two such responses. Slow changes can be corrected by the control rods, but their mechanical inertia limits their response. Inherent negative feedback characteristic is, however, essential.

First nuclear reactor was built in Chicago in 1942 under the direction of great Italian scientist Enrico Fermi. Many types of reactors have since been built and operated around the world. These may be classified in several different ways depending on their application, type and arrangement of fuel moderator, coolant used and speed of neutron sustaining the fission reactor. The reactor types include (Hesketh 1996):

1. Reactors for material production
2. Power reactors – thermal
3. Power reactors – fast
4. Maritime reactors
5. Reactors in space

Future perspectives of reactors would involve

1. Plutonium fuelled thermal reactors
2. Passive-safety reactor designs
3. Thorium-based reactors

The technological emphasis is on power reactors in context with terrestrial power generation. Presently about 400 commercial power reactors are operational around the world. The majority of power reactors operating today fall into the category of thermal class. These reactors use moderators to reduce the kinetic energies of neutrons to about thermal motion. Various designs in the thermal category of power reactors are now known. These include (Hesketh 1996) Pressurised Water Reactor, Boiling Water Reactors, Gas Reactors (Magnox-magnesium alloy no oxidation) and advanced gas cooled reactors (AGR), High Temperature Gas Cooled Reactor (HTGR), Pressurised Heavy Water Reactor, Canadian System (CANDU) and Water Cooled Graphite-moderated Reactor (RBMK).

Many of the fundamental features are common to all these reactor types. They however, differ in their characteristics related to the moderator and transfer of fission heat to working substance (coolant). The basic technological objective is the effective transfer of heat in a controlled, protective, environmentally safe and cost effective manner. The heat energy obtained from the reactor is used to raise steam or heat a gas, which drives the turbine connected to generator to produce electricity. The whole system including the nuclear reactor, the turbine etc. is called nuclear power plant. Presently 60 % of the world's power plants use pressurized water reactors (PWR). Figure 4.4 (Hesketh 1996) shows the main parts of a nuclear power plant. It consists of a compact nuclear core placed inside a pressure vessel filled with water at high pressure (~100 atm). Water serves as both the moderator and heat transfer fluid. The high pressure prevents the boiling of water upto about 300 °C. The core consists of hundreds of fuel rods that allows cooling water to flow between them. The fuel assembly also consists of guide tubes inside which the neutron absorbing control rods can slide in and out of the core. The fuel rod is a stack of isotropically enriched uranium dioxide packed in a sealed tube of slightly alloyed zirconium (M.P. 2800 °C).

The control rods are made of such neutron absorbing materials as boron and hafnium. The control rods are used to shut the reactor down in normal operation or in the event of malfunctions. The boiling water reactor also uses the water as coolant (heat transfer fluid) as well as moderator. It uses lower operating pressure. Consequently the water passing through the core can boil and the steam is generated. The steam is then passed through drier plates to remove water droplets and expanded through turbine to produce mechanical/electrical power. This design does not need heat exchangers between the turbine and the reactor, but involves the risk of coolant being contaminated with radio nuclides. The turbine, therefore, must be shielded and radiological protection provided during maintenance.
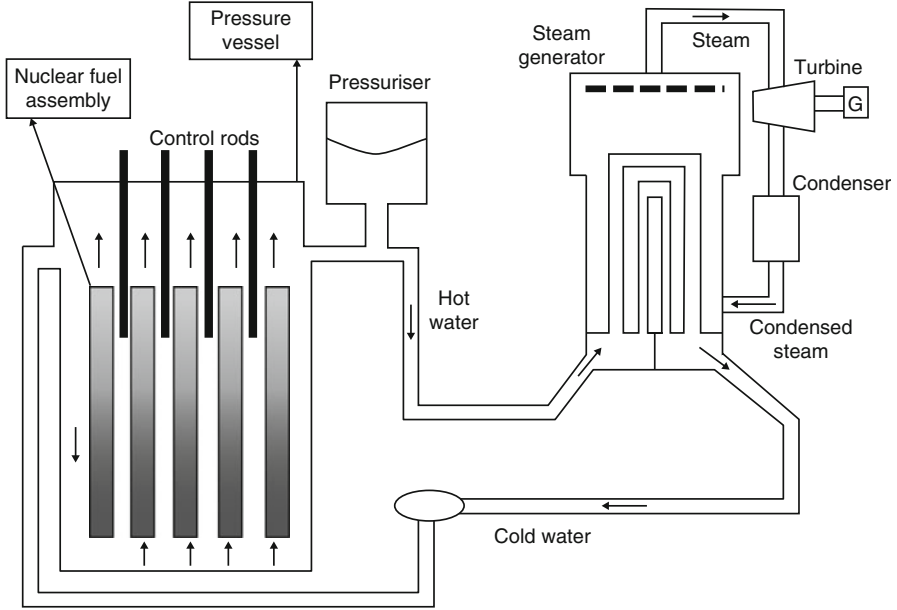
Fig. 4.4 Main parts of pressurized water reactor-based nuclear power plant (Hesketh 1996)

The gas reactors were developed in UK. They use graphite as moderator and pressurized carbon dioxide as coolant. They use natural uranium fuel encapsulated in corrosion resistant magnox (magnesium alloy, no oxidation). Advanced Gas Reactors use enriched (2.5–3.5 %) uranium oxide fuel encapsulated in stainless steel cans. Yet another development in gas reactions is HTGR where in as the name implies high heat surface temperatures are utilized. Ceramic coatings replace conventional cladding metals. It allows higher operating temperatures and improved thermal efficiency.

The term fast breeder reactor is used for the configuration which uses fast neutron in the energy range 0.1–1 MeV. This is possible as follows.

In a fission reactor using the natural uranium fuel, each neutron absorbed in U^{235} results in the release of more than two neutrons. One neutron is required for the sustained chain reaction. The spare neutrons may be used to convert U^{238} into new elements that are fissionable. The most important of these is the neutron capture by U^{238} to produce U^{239} followed by β-decay to produce neptunium-239 and then plutonium-239 as follows:

$$n \; + \; U^{238}_{146} \; \rightarrow \; U^{239}_{147} \; \xrightarrow{\beta-decay} \; Np^{239}_{146} \; \rightarrow Pu^{239}_{145} \qquad (4.41)$$
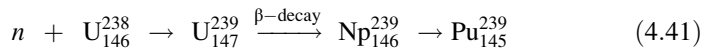
Thus the readily fissionable material (referred to as fissile) may be produced from one that is not so itself but it thus fertile. Some examples are:

$$\text{Fissile materials :} \quad U^{233}, \ U^{235}, \ Pu^{239}, \ Pu^{241}$$
$$\text{Fertile materials :} \quad Th^{232}, \ U^{238}, \ Pu^{240}$$

Conversion of fertile materials into useful fissile materials depends on the magnitude of reproduction factor η which represents the number of neutrons produced per neutron absorbed in the fuel.

$$\eta \ = \ \gamma \times \frac{\sigma_f}{\sigma_a} \qquad\qquad (4.42)$$

Where γ is number of neutrons produced in every fission reaction and $\frac{\sigma_f}{\sigma_a}$ is rate of fission to absorption.

If there are enough neutrons to compensate the consumption of every fissile nucleus by transmutation of at least one fertile nucleus, then the system becomes a breeder. The absolute minimum value for breeding is; obviously 2.0.

The η values for some fissile isotopes of uranium and plutonium in thermal and fast neutron energy distribution are given in Table 4.1 (Hesketh 1996).

The value of η in thermal neutron energy distribution is only around 2.0. It will therefore operate, if at all, the breeding cycle with low probability. However, at higher neutron energies η values are 2.4 and above this it will make the breeding cycle of plutonium fuel more probable. Furthermore, the fast neutrons can induce fission in all uranium and plutonium isotopes while thermal can do so only with odd mass numbers. So the fast breeder reactor term refers to a configuration which has following characteristics:

(a)   Involves two neutrons, one keeps the fission chain going and the other one replenishes the fuel
(b)   Produces more fissionable fuel than it consumes
(c)   Operates on uranium – plutonium fuel cycle
(d)   Plutonium as a fuel is surrounded by natural or depleted uranium
(e)   Fast neutron energy distribution is involved and consequently no moderator is used.

By converting U^{238} to plutonium, a breeder reactor can in theory produce over 50 times more energy per kg of uranium ore than a thermal system.

Liquid metal fast breeder reactor is an example of modern design for fast breeder reactor. It uses liquid sodium as a coolant which ensures excellent heat transfer properties and little neutron moderation.

Table 4.1 Values of reproduction factor, η for fissile isotopes

Isotope	η	
	Thermal	Fast
U^{235}	2.0	2.0
Pu^{239}	1.8	2.4
Pu^{241}	2.2	2.6

Since sodium melts at 98 ° C and boils at 881 ° C, reactor coolant loops can therefore, be operated at high temperature. The high coolant temperature allows the generation of high temperature, high pressure steam. Unlike water, sodium is not corrosive to structural materials. With such high melting point, pipes containing sodium must be thermally insulated to prevent freezing and heated electrically. This is achieved by winding a spiral of insulated heating wire along the coolant piping. Sodium absorbs neutrons, even fast neutrons, leading to the formation of Na–24. Great care must be taken to prevent contact between sodium and water or air which otherwise would result in a fire accompanied by spread of radioactivity. Hence the use of intermediate heat exchanger is essential to enable nonhazardous transfer of heat from radioactive sodium to non-radioactive sodium.

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Chapter 5
Energy Environment Interactions

5.1 Environmental Pollution

Energy flow from producer to consumer involves variety of transformations. For example, primary energy is available as a natural resource such as coal, oil, solar radiation, falling water etc. It is used in power plants, refineries, collectors etc. and yields secondary energy in the form of electricity and refined oil products. The secondary energy flows through transmission and distribution systems and is made available to consumers as final energy. The consumers make use of energy utilisation equipment and systems like IC engines and stoves and obtain useful energy that sustains activity in several sectors of socio-economic system.

The energy transformations generate residuals and toxins that are often thrown away to become a part of the environment which in turn cause an adverse change in the natural quality of environment brought about by physical, chemical or biological factors. Consequently, the residuals and toxins reach the living beings in excess of normal natural concentrations and adversely affect healthy living as well as other pursuits of human benefit and enjoyment. The resultant states of environment are, therefore, referred to as environmental pollution. Several types of pollutions are now known. The list includes air pollution, water pollution, thermal pollution, resource depletion, radioactivity, land use, oil spills etc. The cost of dealing with such hazards of life and assuring an acceptable environment must be regarded as part of the price of energy providing heat, light and power.

Each resource of energy has its special environmental problems. The proportion of adverse effects on the environmental constituents (land, air, water and biosphere) varies from one energy resource to another. The innumerable hazards of life resulting from energy processes and related human activities may be classified into four categories as follows (Thorndike 1979):

(a) **Threat to Life and Health of Living Beings**

It includes air pollution (cause of lung disease), radioactivity (as a cause for cancer and genetic damages), water pollution (typhoid fever to humans and

damage to plants and fish species) and oil spills (danger for marine life), thermal pollution (deadly heat waves and drought) and ozone depletion (skin cancer).

(b) **Loss of Economic Resources**

It includes air pollution (cause of damage to crops, timber and stones of buildings), water pollution (escalates the cost of water purification), soil erosion and refuge banks (escalates the cost of waste disposal).

(c) **Reduction in Aesthetic Enjoyment**

It includes visual pollution (e.g. pillars of transmission lines), noise pollution, waste disposal (odour) and wilderness degradation.

(d) **Damage to Nature**

It includes deforestation, wildlife reduction, solid waste disposal, pesticides etc. For example DDT is soluble in fat and propagates through food chain. It has caused extinction of raptorial birds and falcons.

In view of the above discussion the environmental pollution may be defined as an adverse change that may or will harmfully affect the nonhuman nature and/or the human health, safety, economic resources, material well beings, enjoyment of life in psychological and aesthetic terms. In what follows we discuss generation of pollutants from conventional energy processes and the mechanisms of the formation of various environmental hazards.

5.2   Mining and Transportation of Fossil Fuels

5.2.1   Soil Erosion and Land Use

Coal mining involves extraction, transportation and processing steps. Surface mining (strip mining) or underground mining (deep pit mining) are used for extraction of coal. Strip mining damages the surface; the end result is a series of ridges and valleys as a consequence of which following hazards are often observed:

(i) Top soil is lost and the plant growth suffers a setback

(ii) Pyrite (FeS_2) an impurity invariably found in coal refuge comes in contact with rain water and acidifies the nearby land water streams.

The underground mining results in the formation of underground cavity by coal removal and involves several environmental hazards such as:

(i) Back filling of the cavity is very costly and is often not accomplished. *Subsidence* of the overburden upsets the land surface resulting in severe soil erosion and causing serious damages to buildings and water flow systems.

(ii) Waste material is brought to the surface and forms huge refuge banks occupying hundreds and thousands of acres of land. The refuge bank interactions with such weather phenomena as rain and wind pollute the land, air and water environment.

(iii) Fire hazard in abandoned coal pits and refuge banks.
(iv) Health and safety menace.

The environmental hazards due to mining and transportation become exceedingly important when considered in context with shale oil and Tar sand where even with the richest deposits, about 85 % of the mined material is waste. This means that per unit of energy extracted from shale oil and tar sand requires five times more material to be mined and 17 times more material to be discarded.

5.2.2   Oil Spills

In general the oil spills (Thorndike 1979) occur due to leaks and blow outs at the extraction point. It includes the tanker discharges and leaks. The pipeline problems also occur during transportation and due to several assorted reasons at the refineries. These spills are not so serious in context with land based well but become a matter of great concern in connection with offshore wells. Oceanic oil spills may be classified into two categories:

 (i) Coastal oil spills
(ii) Oil build up in the ocean

The coastal oil spills are caused by normal well operations, dumping of crude oil and waste petroleum products and accidents connected with shipping. These spills give rise to environmental hazards such as:

 (i) Fouling in beaches
 (ii) Killing of marine birds and
(iii) Destruction of breeding ground of fish (e.g. shellfish) and other animals

The oil build up in the world's ocean water takes place due to controlled as well as normal operation of tankers and ships, wash away of refineries and automobiles carried by rivers. This low concentration of oil in the ocean could be dangerous in conjunction with chlorinated hydrocarbon pesticides (D.D.T). These pesticides are soluble in oil but are insoluble in water. Since the oil floats on the surface; it, therefore, causes damage to species spending part of their life cycle near the ocean surface. It includes plankton and larval stages of many fishes.

5.3   Combustion of Fossil Fuel

Combustion of fossil fuels is a widely known pollution generating process. It, therefore, makes sense to examine the mechanism of production of pollutants (residuals and toxins) in the combustion process.

5.3.1 Liquid and Gaseous Fuels

The petroleum fuels may be classified into three categories: gaseous, liquid and solid. In the gaseous fuel, hydrogen to carbon ratio is relatively higher; the sulphur and nitrogen contents are generally very low. When the fuel combustion takes place with sufficient supply of oxygen (air) it burns the fuel completely to produce CO_2 (nontoxic), greenhouse gas and water as follows:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + Q \text{ (heat)} \tag{5.1}$$
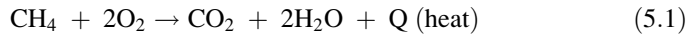
When the amount of air provided is insufficient then the combustion remains incomplete with formation of soot (black powdery substance), smoke (unburnt carbon) and carbon monoxide.

$$CH_4 + O_2 \rightarrow C + CO + H_2O \text{ (heat)} \tag{5.2}$$
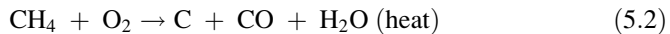
If sulphur is present in the gaseous fuel, sulphur oxide will be produced. At higher combustion temperatures, some oxides of nitrogen (NO_x) will also be formed. For example,

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O \tag{5.3}$$

$$N_2 + O_2 \Leftrightarrow 2NO \tag{5.4}$$
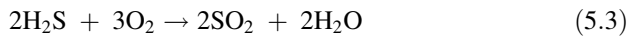
This reaction is far too left at ordinary temperature far too right at higher temperature ($>700\,^\circ C$).

The liquid fuels and their combustion may be discussed in two categories as follows:

(a) **The liquid fuels** like kerosene and petrol (gasoline) that vaporise easily can be heated up and subjected to combustion without any problem like gaseous fuels. These fuels are often used in cars, buses, trucks, aeroplane etc. These fuels are a mixture of liquid compounds of carbon and hydrogen called hydrocarbons. They burn very fast in the engine and incomplete combustion takes place which results in CO and unburnt carbon particles. The incomplete combustion also produces some alcohols and acids which escape into air. The combustion temperature is quite high and nitrogen and oxygen of air combine to form NO and NO_2 (a poisonous gas). Furthermore, tetraethylate lead Pb $(C_2H_5)_4$ is often added to petrol to slow down combustion. It gives rise to poisonous lead compounds in air. The corresponding chemical reactions are:

Complete combustion

$$C + O_2 \rightarrow CO_2 + Q \text{ (heat)} \tag{5.5}$$

Incomplete combustion

$$C + \frac{1}{2}O_2 \rightarrow CO \tag{5.6}$$
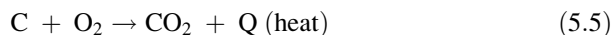
(b) **Heavy liquid fuels:** These fuels do not vaporise and, therefore, pose problems for their combustion. These fuels are, therefore, first atomised as a consequence of which some vapour is generated which upon providing some heat results in the initial ignition. Subsequently, heat from the flame cracks the fine oil droplets to produce gaseous hydrocarbons and fine carbon particles. During the combustion process the gaseous fuel provides the flame envelope in which the fine carbon particles burn similar to pulverized (powdered) coal burning. Incomplete combustion of the cracked products gives smoke containing soot (black powder), tar vapours, hydrocarbons and carbonmonoxides.

5.3.2 Solid Fuels

Commonly used solid fossil fuels include coal, lignite, peat coke, wood, saw dust and charcoal; the fuels contain varying amount of moisture, ash and volatile matter and the fixed carbon varies from sample to sample. These fuels are used in thermal power plants, steam engines, furnaces, ceramic kilns and in household cooking stoves. For the combustion of solid fuels grate-burning process is used. The process is illustrated in Fig. 5.1 for the case of a small boiler furnace. The sequence of operation is as follows:

(a) Initially, the fresh fuel bed (25–30 cm thick) is heated for devolatilization and setting ignition fire

Fig. 5.1 Grate burning process
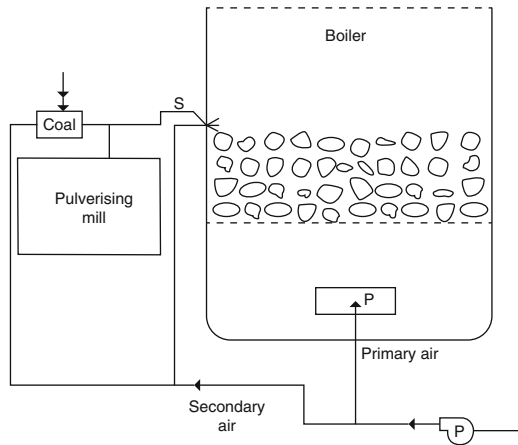
(b) Primary air entering at 'P' travels up and supplies oxygen for combustion in the bed. In the process, all the oxygen of air gets exhausted and only nitrogen and carbon dioxide reach the top of the bed. Some of the carbon dioxide produced in the combustion process reacts with carbon and produces carbon monoxide. The chemical reactions are as follows:

$$C + (O_2 + N_2)Air \rightarrow CO_2 + N_2 \tag{5.7}$$

and

$$CO_2 + C \rightarrow 2CO \tag{5.8}$$
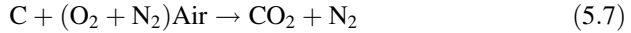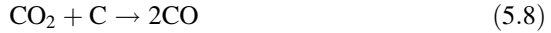
(c) Subsequently, the devolatilized coal, which is now coke burns on the grate as solid fuel in packed bed. The volatile matter released from fresh coal and the carbon monoxide generated from the interaction of carbon dioxide with hot coke bed burn in combustion flame using the secondary air supplied from 'S' on gas space above the fuel bed. The reactions are as follows:

$$\underset{\text{(Volatile matter)}}{C_nH_m+} \left(n + \frac{m}{4} \right) O_2 \rightarrow nCO_2 + \frac{m}{2}H_2O \tag{5.9}$$

$$\underset{\text{(Tar)}}{C_nH_m} \rightarrow \left(C_xH_y \right)_z + C + CH_4 + H_2 \tag{5.10}$$
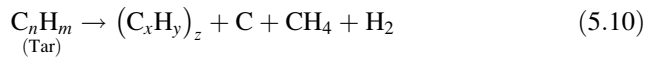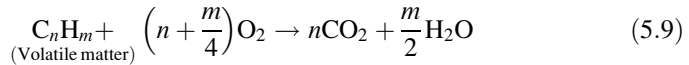
The combustion process also generates particulate material and the non-combustible material (ash), which is flown upward in the atmosphere with combustion, gases and subsequently appears as nitrates and sulphates resulting from NO_2 and SO_2.

5.4   Waste Heat Generation: Thermal Pollution

In Chap. 4, it was noted that typical conversion efficiency of a coal based power plant is 40 % which means that only a small fraction of the fuel energy contained in coal is converted to the desired electrical output and rather a large amount of fuel energy goes as waste heat to the environment. This is in accordance with the laws of thermodynamics. All the processes that convert fuel energy into electricity involve some inefficiency and generate waste heat. For example, according to the second law of thermodynamics related to conversion of heat into work it is impossible to devise a machine that can convert heat to work with 100 % efficiency; there will always be some waste heat rejected to the sink. The steam turbine may be viewed as a machine that takes heat from a high temperature source and converts it into work (electrical output) and rejects the remaining into low temperature sink, which is

often river or lake or the atmosphere. The maximum efficiency that such a machine can have is the Carnot efficiency (η_c) given as follows:

$$\eta_c = 1 - \frac{T_C}{T_H} \qquad (5.11)$$

where, T_H and T_C are the absolute temperatures of high temperature heat source and relatively colder heat sink respectively. Furthermore, the electricity generated at the power plant site is distributed to consumer points through transmission lines and cables where it is used for end use activities and is eventually converted into heat. Similar energy conversion processes take place in energy generation and utilization activities of automobiles, industrial and other units. These energy conversion processes also involve some inefficiency. Consequently, some portion of energy put into the process will end up as waste heat. However, according to first law of thermodynamics the energy is not lost (law of conservation of energy). It is merely converted into less useful form of low temperature heat. The waste heat addition to the environment is often referred to as Thermal Pollution and it is important consideration in the study of Environmental Science and Engineering. The waste heat addition in conjunction with carbondioxide builds up in the atmosphere, due to fossil fuel burning. It has resulted in the increase of earth's planetary temperature which is referred to as global warming which in turn is threatening the world in terms of such assorted manifestations as global climate change, rise in ocean level and frequent occurrence of deadly heat waves and droughts. The waste heat addition to natural water reservoirs: rivers, lakes etc. results in water pollution and is discussed in Sect. 5.6.

5.5 Atmospheric Air Pollution

5.5.1 Primary and Secondary Pollutants

Fossil fuel combustion processes add various pollutants in air. These pollutants are in the form of gases and particulate. Common primary air pollutants are as follows:

Particulate Matter Dusts, mists, soot (black powdery substance in smoke; unburnt carbon), lead and other substances such as sulphates, nitrates and fluorides. The particles of size larger than 10 μm are settleable in the atmosphere where as the smaller particles are able to remain suspended for relatively longer period of time in air. These are referred to as Suspended Particulate Matter (SPM), which are further classified in two types:

 (i) Aerosols having size less than 1 μm,
(ii) Particles of size more than 1 μm are called dust if solid and mist if liquid.

Gases Carbon dioxide (CO_2), carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), sulphur dioxide, H_2S, hydrocarbons (they result from evaporation of hydrocarbon fuels or from engine blow ups and include methane, ethane, propane, acetylene, ethylene, butane and isopentane).

Once in air these pollutants interact among themselves as well as with other atmospheric constituents and take part in wide range of chemical reactions resulting in new products called secondary pollutants. Some of secondary pollutant formation reactions are as follows:

Sulphur trioxide gas and mist:

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O \qquad (5.12)$$

$$2SO_2 + O_2 \rightarrow 2SO_3 \ (g) \qquad (5.13)$$

$$SO_3 \ (g) \rightarrow SO_3 \ (l) \qquad (5.14)$$

Sulphuric acid mist:

$$SO_3 \ (g) + H_2O \rightarrow H_2SO_4(g) \qquad (5.15)$$

$$H_2SO_4(g) \Leftrightarrow H_2SO_4(l) \qquad (5.16)$$

Ozone (at ground level):

$$NO_2 + sunlight \rightarrow NO + O \qquad (5.17)$$

$$O_2 + O \rightarrow O_3 \qquad (5.18)$$
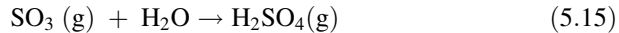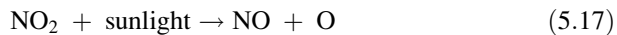
Smog (smoke + fog):

Hydrocarbon + NO_2 + sunlight → several   intermediate   steps → peroxyacyl nitrates (PAN) + formaldehyde + other

It has been often observed that secondary pollutants are more toxic and cause more severe damage than primary pollutants. So, in evaluating the hazards of primary pollutants one must also consider its secondary effects and the factor causing them. For example, an evaluation of the ill effects of hydrocarbons must consider the presence of NO_2 (another pollutant) and sunlight for smog formation (Thorndike 1979; Subrahmanyam and Sambamurty 2000).

5.5.2 Dispersion of Pollutants

The interaction of pollutants with the atmosphere can also result in dilution or accumulation of pollutants at a given site. In this regard, thermohydrodynamic stability of the atmosphere is an important factor. Stable air discourages the dispersion and accumulates pollutants. In contrast if the air is unstable, it encourages the pollutant dispersal and increases air quality. The atmospheric stability in

turn is a sensitive function of vertical temperature profile and the winds in the atmosphere. The role of vertical temperature profile on the stability of the atmosphere may be understood from the consideration of thermohydrodynamics of a small vertical perturbation (movement) of an air parcel in the atmosphere stratified by earth's gravitational field. Assuming the perturbation to be fast enough that the heat exchange between the parcel and the surrounding can be ignored. The air parcel experiences less pressure and expands in its upward movement; the expansion corresponds to the work done by the air parcel on the environment; consequently the internal energy of the air parcel will be reduced and its temperature will decrease. The parcel, colder and hence denser than the surrounding will obviously tend to come to its original position. Thus the initial perturbation tends to die with time. The atmosphere is said to be stable in this state. In contradistinction to this, is the state when raising the parcel keeps its temperature to be greater than the surrounding air. It will be less dense than the surrounding air and keep moving upward due to buoyancy forces. In this situation initial perturbation grows. This is an unstable state of the atmosphere. This circumstance may be quantified in terms of an atmospheric parameter referred to as adiabatic lapse rate as follows (Masters 1994).

In real terms the air parcel, during its vertical motion in the atmosphere, will experience a change in its temperature (T) pressure (P) and volume (V) as well as exchange heat with the surrounding environment. Following the first law of thermodynamics its energy balance may be expressed as

$$dQ = dU + dW \tag{5.19}$$

Assuming the volume of air parcel to remain constant and the air parcel obeying the ideal gas laws $(PV = RT)$. The energy balance of the air parcel of unit mass is written as

$$dQ = C_P dT - V dP \tag{5.20}$$

If the air parcel movement is fast enough to prevent its heat exchange with the surrounding, then $dQ = 0$, which yields

$$0 = C_P dT - V dP \tag{5.21}$$

Or,

$$\frac{dT}{dP} = \frac{V}{C_P} \tag{5.22}$$

Furthermore in the atmosphere stratified by gravitational field:

$$\frac{dP}{dZ} = -\rho g \tag{5.23}$$

Therefore, we have

$$\frac{dT}{dZ} = \frac{dT}{dP}\frac{dP}{dZ} = \frac{-V\rho g}{C_P} = \frac{-g}{C_P} \tag{5.24}$$
$$\text{(Since for an air parcel of unit mass } V\rho = 1)$$

The negative sign indicates that the temperature decreases with altitude. The rate of change of temperature with altitude is referred to as adiabatic lapse rate (Γ).

For dry air at temperature of 25 °C:

$$C_P = 1005\,\text{J/kg\,K}$$
$$\Gamma = \frac{-dT}{dZ} = \frac{9.8}{1005} = 0.00976°\text{C per metre}$$
$$= 9.76°\text{C per km}$$
$$\cong 1°\text{C per 100 meter}$$

In view of the above discussion, if the actual ambient air temperature gradient is more than the adiabatic lapse rate the atmosphere is unstable (Fig. 5.2). Conversely, if actual ambient air temperature gradient is less than the adiabatic laps rate, the atmospheric air will be stable. An extreme case is one in which the temperature increases with height (temperature inversion). It will render the atmospheric air highly stable and may create vital lid on the lower regions. Such a situation occurs in the atmosphere, for example, at stratospheric heights where the absorption of solar radiation by ozone creates an atmospheric air temperature inversion. This temperature inversion in turn renders the stratosphere to be highly stable and creates a lid on troposphere. Similar temperature inversion occurs in troposphere and also the pollutants are trapped in this region.

The presence of primary and secondary pollutants in atmospheric air has been observed to produce many deleterious effects on man and nature. On the basis of these effects, the pollutants may be classified into two categories as follows:

(a) **Greenhouse gases:** They have the ability to trap IR radiations and include CO_2, H_2O, methane, nitrous oxide (N_2O), chlorofluorocarbon and ozone.
(b) **Chemically active pollutants:** Chemically active pollutants in atmospheric air include Carbon monoxide (47 %), sulphur dioxide (15 %), hydrocarbons (15 %), nitrogen oxides (10 %) and particulate (13 %). These pollutants affect the living as well as nonliving components of nature directly causing damage
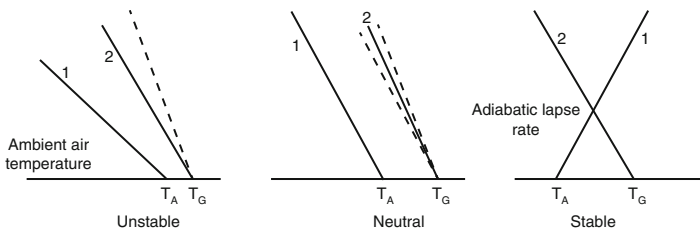

Fig. 5.2 Variation of atmosphere stability with ambient air temperature profile

to vegetation and the built structures etc. as well as indirectly forming acid and smog.

In what follows we present a discussion on the manifestations of hazards of life due to these pollutants.

5.5.3   Enhancement of Greenhouse Effect

The continual addition of green house gases in the atmosphere results in their building up at different levels in the atmosphere. It, therefore, causes an enhancement in greenhouse effect. CO_2 contributes largest to the greenhouse effect in earth's atmosphere because it is more uniformly distributed. Its contribution is nearly half of total greenhouse effect. Other gases together contribute the remaining 50 %. Methane contribution is largest (18 %) in this category; next is CFC about 14 %; ozone contribution is very less where as water vapours affect only in the immediate neighbourhood of earth's surface and their contribution is variable. The enhancement in greenhouse effect may adversely affect the earth's planetary temperature and cause global warming which is threatening the world in terms of frequent occurrence of deadly heat waves and droughts etc.

5.5.4   Damage to Vegetation

The atmospheric air pollutants, which directly affect the plants include SO_2, fluorides, ozone and nitrogen oxides (Chapman and Reiss 1995; Subrahmanyam and Sambamurty, 2000). In general, these pollutants bring about such changes in plants as frequency of occurrence, density, coverage and abundance. Low concentration of pollutants (e.g. SO_2) cause general chlorosis necrosis. At higher concentrations, bleaching and bronzing of leaves and plants and the formation of dark areas on flowers and fruits are observed. The mechanism of damage essentially involves the photosynthetic apparatus; different pollutants affect different components of photosynthetic process with variable degree of damage dependent upon their toxicity and concentrations. For example, SO_2 is toxic at 0.3–0.5 ppm and its action on vegetation results in chlorophyll 'a' destruction with release of Mg; the damage is a function of humidity.

$$SO_2 \; + \; H_2O \rightarrow H_2SO_3 \tag{5.25}$$

$$H_2SO_3 \rightarrow H_2SO_3 \; + \; H^+ \tag{5.26}$$

$$2\,H \; + \; \text{chlorophyll 'a'} \rightarrow \text{phaeophytin 'a'} \; + \; Mg^{++} \tag{5.27}$$
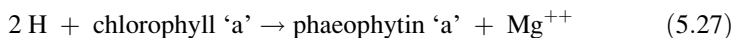
The lichen species are very sensitive to SO_2; it may also damage such crops as alfalfa and trees such as pine. Hydrogen fluoride and nitrogen dioxide have been observed to be harmful to corn, pitch, citrus trees and ornamental plants. Leaves of tobacco, bean, cereals and alfalfa are susceptible to ozone at concentrations of only 0.02 ppm since ozone destroys chlorenchyma cells and produces necrotic areas. Other pollutants become injurious at concentrations in excess of 0.1 ppm. This shows that O_3 is more toxic to vegetation than the primary pollutants.

Carbon monoxide is deadly poisonous in higher concentration. It quickly combines with hemoglobin in the blood and lessens its oxygen carrying capacity proving lethal for the target. In recent years some authors (Subrahmanyam and Sambamurty 2000; Colinvaux 1986) have reported that leaves of several plants such as phaseolus vulgaris, coleus blumei, Daucuscarota and Ficusvariegatus have been found to be capable of fixing carbon monoxide. These plants may, therefore be used to combat carbon monoxide pollution.

5.5.5 Damage to Built Structures

Colour fading of fabrics, leather and paper directly from SO_2 or through its highly reactive H_2SO_4 is well known and is advantageously used in several industries. However, the formation of coloured spots and physical deterioration of building structures and sculptures of materials like marble, limestone, slate and mortar etc. is relatively a more recent identification. The mechanism of deterioration is often referred to stone leprosy and may be described as follows:

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2O + CO_2 \tag{5.28}$$
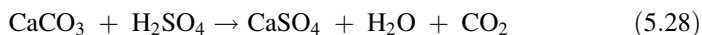
Many historical buildings in Greece, Italy and India including the Taj Mahal in Agra are the example of such deterioration.

5.5.6 Smog

Smog (smoke + fog) represents the state of atmosphere resulting from the mixture of the smoke and moisture in the air. The word smog was coined by H.A. Voeux (Subrahmanyam and Sambamurty 2000) and has since been known to cause serious health hazards episodes in several countries. Notable of these episodes happened in 1930 in Belgium, 1944 in Los Angles (USA), 1952 in London, 1970 in Tokyo, New York, Rome and Sydney. Over the years mechanism of smog formation has been continually studied (Thorndike 1979; Subrahmanyam and Sambamurty 2000). The complete repertoire of processes is still unfolding; however, it has come to be understood that the smog is of two types: it may be reducing and/or oxidising in its chemical composition.

The reducing smog results from the mixture of sulphur dioxide, particulate such as soot, ammonium sulphate etc. and the water from fog. The chemical reaction may involve following steps:

- Photochemical oxidisation of SO_2 into sulphur trioxide (SO_3). This reaction takes place in presence of sunlight and is most probable at times of temperature inversion (e.g. following sunrise in the morning).
- SO_3 combines with moisture in presence of metal salts to form acidic (H_2SO_3 and H_2SO_4) aerosols. In this reaction, particulates provide the condensation nucleation.
- Simultaneously, SO_2 combines with NH_3 in moist air to form $(NH_4)_2SO_4$ which may synergise the effect.

The deleterious effect of reducing smog was observed in London in 1952 when 5000 people were killed in a single year due to pneumonia, bronchitis and related respiratory troubles. The reducing smog is, therefore, sometimes called as London smog. The excessive coal burning in humid cold climate may provide all the basic ingredients of reducing smog.

The oxidising smog results from the action of sunlight on automobile exhaust gases. It is often referred to as Photochemical smog. The basic reactants in photochemical smog are the hydrocarbons, nitrogen oxides (NO_x), some sulphites and the sunlight. The products in the reactions are phytotoxic components mainly ozone (O_3) and peroxyacetyl nitrate (PAN). Right conditions of photochemical reactions during smog formation are initiated by solar UV radiations; consequently photochemical smog formation peaks in the afternoon unlike the reducing smog which peaks early in the day. The photochemical smog is characterised by eye irritation and poor visibility. Hot climate and low humidity often favours the formation of photochemical smog.

5.5.7 Acid Rain

The term 'acid rain' represents the presence of excessive acids in rainwater. Generally, H_2SO_4 and HNO_3 are the major acid constituents, seldom, if ever traces of HCl are also present. The formation of acids in the rain is illustrated in Fig. 5.3; the oxides of sulphur and nitrogen produced by combustion of fossil fuels in stationary and mobile sources are swept up by wind into the atmosphere where they may travel thousands of kilometres before their final deposition as acidic rain on earth.

The deposition could be dry or wet. Dry deposition would include dust particles containing sulphates and nitrates while the acidic water rain, snow dew and fog represent the wet form of deposition. Pure rainwater has pH value of 5.5–5.7, which may drop to as, low as 2.0 and acidify the lakes and soil on earth. The acidity in turn may affect the aquatic biota and terrestrial ecosystem. Acidic rain has been found to be very dangerous to the living organisms as it can destroy life.
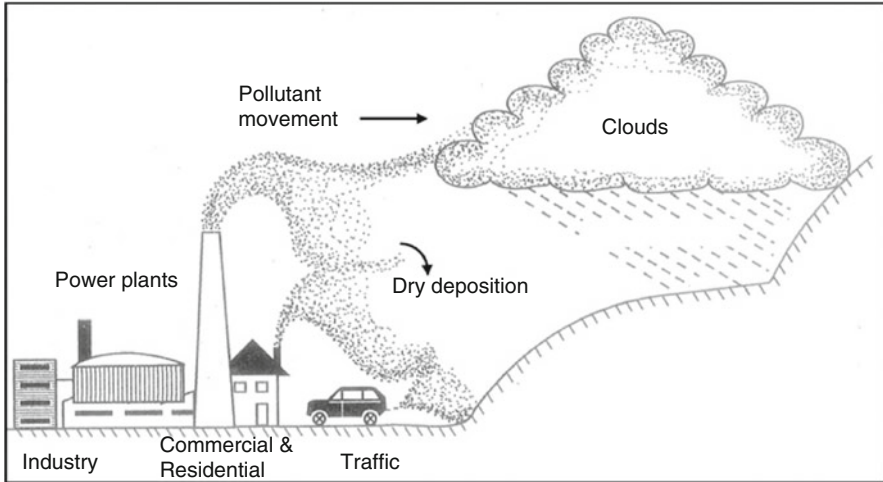
Fig. 5.3 Dry and wet deposition of pollutants in terrestrial ecosystems

5.6 Water Contamination

When natural water comes in contact with manmade energy processes, its characteristics such as colour, clearness, odour, temperature, pH value and dissolved oxygen are adversely affected and it is said to be polluted. The water pollution due to energy processes is an important problem faced by both developed and developing countries. For example, a steam-electric power plant requires enormous amount of cooling water to dump its waste heat at condenser end of the turbine. A typical nuclear power plant warms the cooling water by about 10 °C. It has been estimated that per unit (1 kWh) of electricity generated modern fossil fuel based plants contribute 1.2 unit of waste heat while the nuclear plants contribute 2.0 units. The heat is often released into a local river or lake; the resulting rise in temperature affects the local aquatic ecosystem in two ways:

 (i) It affects the water consumption by enhanced evaporation. The water is said to be consumed when it is evaporated, transpired, consumed by people and used for irrigation etc.
(ii) It affects the aquatic life in the vicinity of thermal plume. The aquatic life may be affected adversely as well as beneficially in variety of ways as follows:

   (a) *Temperature Moderation:* Addition of waste heat within certain limits can be used to bring the aquatic temperature to comfort level and promote the fish growth in the water reservoir.
   (b) *Large Temperature Excursions:* Abrupt changes in temperature caused by periodic plant outages, both planned and unanticipated can directly kill many aquatic species such as trout and salmon. The abrupt changes have been observed as more hazardous than gradual ones.

(c) *Permanent Rise in Water Temperature:* One of the most important water quality parameter is amount of dissolved oxygen (D.O) in it. The saturated value of dissolved oxygen is 8–15 mg/l and its value decreases with increase in temperature and salinity. The minimum desirable value for aquatic species is 5–8 mg/l. As the temperature of the water increases the aquatic life is affected by two factors. First, the metabolic rate tends to increase with temperature, doubling for each 10 °C rise in temperature. This causes an increase in the Biological Oxygen Demand (BOD) of the organism which when not met results in reduction of life span and resistance to diseases of many aquatic species. The second factor, causing the reduction of dissolved oxygen in water at elevated temperature further aggravates the situation.

Besides the waste heat, some other energy related water pollutants are (i) Heavy metals discharged directly into water by certain mining operations, (ii) Radioactive substances from nuclear energy processes.

Usually a temperature rise of 10 °C in condenser cooling water and 2–3 °C in river water is tolerated for the safety of aquatic life. This criterion may be used to estimate the size of a lake connected to a power plant as follows (Thorndike 1979):

When no waste heat is added to the lake its thermal energy balance may be expressed in terms of heat flux as follows:

$$E_L = E_R + E_C + E_e - E_S \qquad (5.29)$$

where,

E_L = Net heat loss flux from the lake.
E_R = Radiative loss flux = $\sigma\,[T_S{}^4 - T_a{}^4]$
E_C = Convective loss flux = $K f(w)\,[T_C - T_A]$
E_e = Evaporating loss flux = $f(w)\,[P_S - P_a]$

Substitution of these expressions in Eq. (5.27) yields

$$\frac{dE_L}{dT_S} = 4\sigma T_S^3 + \left[\frac{dP_S}{dT_S} + K\right]f(w) \qquad (5.30)$$

If the waste heat flux is E_w then according to safety criterion $\frac{dE_L}{dT_S}\Delta T_S \geq E_W$ Maximum allowable value of E_w is given by

$$E_w = \left\{4\sigma T_S^3 + \left(\frac{dP_S}{dT_S} + k\right)f(w)\right\}\Delta T_S \qquad (5.31)$$

Thorndike has reported the results of calculations made by Asbury for lake Michigan as follows.

The term dE_L/dT_S exhibits a factor of two seasonal variation due to variation in water temperature and wind speed. The annual mean value of E_L is estimated to be

22 W/m^2 k; the contribution of evaporative, radiative and convective loss terms is 50 %, 20 % and 30 % respectively. An E_L value of 2.5 W/m^2 k (1 % of solar energy flux) would escalate annual mean temperature of lake water by 1.1 °C. This value of E_L indicates that nearly 12 acres of lake surface would be required for 1 MW$_e$ capacity of power plant.

From the above discussion, it may be noted that the pollution resulting from the heat discharge of power plants in a water body may be reasonably controlled by using an appropriate size of cooling water reservoir. As far as possible, single pass cooling must be used in the cooling process and heat must be uniformly distributed in the water reservoir area. However, seldom if ever the water bodies are located where it is needed. The alternative cooling schemes such as cooling using oceans wet (evaporative) cooling towers and dry cooling towers must also be considered for application in suitable situations.

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Chapter 6
Clean Coal Technologies for Power Generation

6.1 Importance

In present day world fossil fuels are the major resource for power generation. For example, in India coal makes up 55 %, natural gas 10 %, hydroelectric 26 %, renewable 5 % and nuclear 3 % of total installed capacity. In UK almost half of the nation's electricity is generated from gas with a further 28 % coming from coal. In fact, coal is the most abundant fossil fuel and has long lasting reserves. Its availability is domestic in several countries and has exhibited stable prices. The world coal reserves of approximately 1040 billion tonnes may last for more than 200 years. In view of discussion in Chap. 5, coal is considered the most polluting fuel in the countries' energy mix. It has more than 40 % mineral matter (ash) content posing problems in handling, transporting and using the fuel in power plants. Some 20 % of the power plants in UK and India are old and below the margin of environmental safety and they are due for technology amelioration. Present day researchers are working to make existing coal technologies cleaner and affordable to enable a transition to green power generation. In what follows we present an outline of clean coal technologies.

6.2 Environmental Issues

Health related problems were the earliest documented hazard due to coal-based power plants. The tall stack concept was implemented to dilute the concentration. It was followed by the identification of several phenomena and related local and global environmental concerns which may be classified into three categories as follows:

1. Enhanced greenhouse effect due to carbon dioxide (CO_2) and Nitrous oxide (N_2O).

2. Smoke and acid rain effects of SO_x and NO_x.
3. Health related problems due to suspended or respirable particulate matter, SO_x, NO_x and trace elements like arsenic and mercury.

Greenhouse effect has received increased attention since 1980s. Coal's contribution to enhance greenhouse effect is about 20 %. The contribution is much less due to methane CH_4 (7 %) and N_2O (5 %) which have accumulated in the atmosphere due to various agricultural activities like wet paddy fields, decomposition of vegetation, agro waste disposal, biomass burning and leakages from coal mining and gas pipelines. However, it may be noted that the global warming potential of CH_4 is about 15–17 times, N_2O is 280–310 times and of chlorofloro carbons (CFC) about 7900–8500 times that of CO_2 (Kolar and Reddy 2004).

6.3 Emission Control in Power Plants

Several devices and techniques for the control of pollution resulting from coal utilisation in power plants have been proposed and tested and are presently in use. These include pre-combustion controls, combustion control, post combustion control and atmospheric dilution. These are summarised as follows:

6.3.1 Pre-combustion Controls

Coal is predominantly aromatic and is one of the most carbon intensive amongst the fossil fuels. Coal from different mines has different ash, moisture and mineral contents. Pre-combustion control of pollution involves measures to obtain better and less polluting coal fuel. According to New Source Performance Standard (NSPS), emission of SO_2 in coal plants is restricted to 1.2 lb/Mbtu (520 $g/10^6$ kJ). The coal which meets this emission rate without controls is referred to as compliance coal or low sulphur coal. An obviously effective technique could be homogenisation and blending to obtain relatively better and cleaner fuel. To control sulphur emissions high sulphur content coal may be substituted with low sulphur content coal or with the blend of two. The approach is referred to as fuel switching and can reduce SO_2 emission from 30 to 90 %. The other pre-combustion approach currently used is beneficiation of coal to get rid of unwanted mineral matter contents and other micro constituents. It involves the removal of sulphur in which the coal is either bound into organic coal molecules or in the form of inorganic pyrite (FeS_2). The physical coal washing may be used to wash away FeS_2 having 3.6 times greater specific gravity than coal. Desulphurisation of coal may also be carried out by organo-solvo refining. This technology is still at the research stage.

The coal washing process also reduces the ash contents and increases the calorific value of the fuel which in turn reduces the coal transportation and

pulverization costs. The sulphur bound in organic molecules of the coal may be removed by chemical and biological methods and is referred to as refining of coal. For example, organo-solvo refining wherein solvent extraction of impurities yields super clean coal with low ash. This technique is also in the research stage.

6.3.2   Combustion Control Techniques

Diverse range of approaches and technologies are needed to minimise emissions of carbon dioxide from the use of coal in power plants. The obvious approach is to improve the method of energy extraction from coal in its combustion in a furnace cum boiler of a power plant. In the conventional system coal is used in the pulverised form, its size being less than 100 μm. The approach is referred to as Pulverised Combustion (PC) Firing or PC Technology. The combustion efficiency of PC boiler is about 99 % and the thermal efficiency (boiler efficiency) is of the order of 80–90 %. The major drawback of PC technology based power plants is that it has very low energy efficiency ($<40\%$) and enormous amounts of undesirable gases (SO_x, NO_x, CO_x and N_2O) are exhausted. Fluidized Bed Combustion (FBC) is a promising technology in this regard. The basic characteristics of this technology are as follows:

- Combustion chamber contains finely divided particles such as sand.
- Combustion air entering from below lifts these particles until they form a bubbling bed.
- Start-up burners heat the bed to 800–950 °C. Subsequently, combustible material (crushed fuel top size is 6 mm) is fed into the bed. It ignites almost immediately.
- FBC can burn large varieties of fuels from high rank commercial fuels to low grade and waste fuels.
- For small scale power generation generally bubbling FBC are used. However, for large scale FBC due to deeper fluidized bed circulating FBC boilers are used. These are the conventional boilers. They operate at atmospheric pressure and therefore are often referred to as atmospheric FBC (AFBC) boilers.
- Yet another variant of FBC is based on pressurised 15 atm operation and is referred to as Pressurized FBC (PFBC).
- Both AFBC and PFBC work on two fundamental gas-solid dynamics: the bubbling or circulating as illustrated in Fig. 6.1a, b.
- All the four variants of FBC family are efficient and clean. However, the AFBC based circulating bed system exhibits cleaner performance than the bubbling bed.
- Pressurised FBC (PFBC) are used to heat gas which can be expanded through a gas turbine and can be used in a combined cycle based plant. Both the AFBC and PFBC can yield high overall plant efficiency of about 43 % as compared to 33–37 % of conventional CFBC and AFBC based power plants.
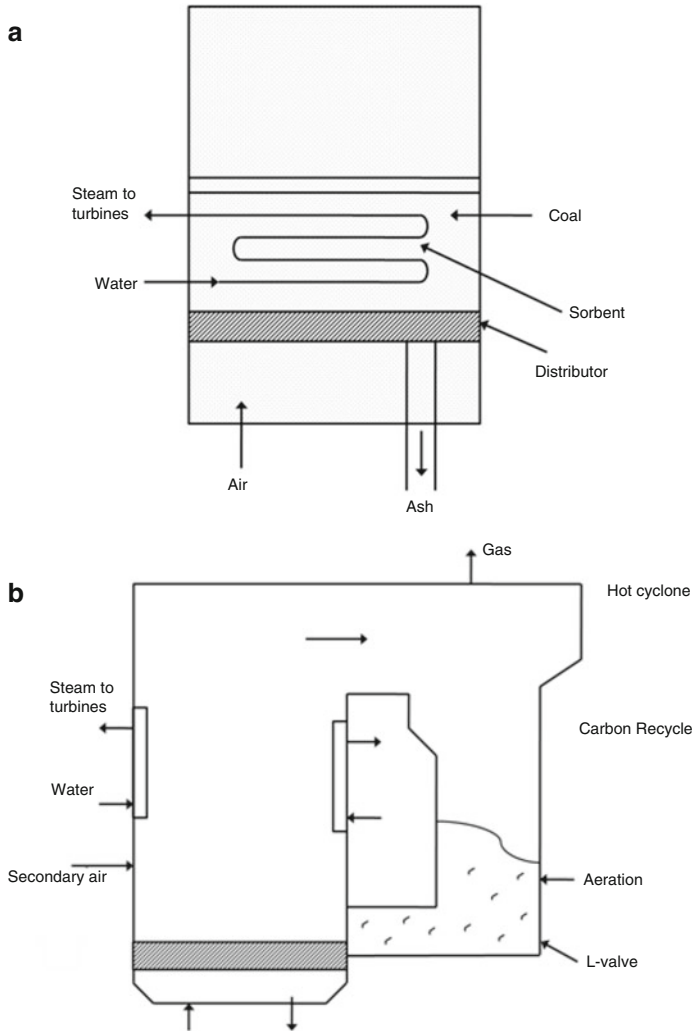
Fig. 6.1 (**a**) Bubbling fluidised bed boiler. (**b**) Circulating fluidised bed boiler

- In view of the above discussion Pressurized Circulating Fluidized Bed Combustion (PCFBC) based power plants are ultimate in terms of efficiency and environmental considerations.
- Yet another alternative to direct coal combustion is coal gasification wherein coal is reacted with steam and air/oxygen in a reactor at suitable pressure and temperature to produce a gaseous mixture of carbon monoxide, hydrogen, methane and CO_2 known as syngas (synthetic gas) which can be burnt in a gas combustor.
- For sulphur removal FBC boiler fuel is mixed with limestone ($CaCO_3$) or dolomite ($MgCO_3.CaCO_3$); ($MgCO_3$ does not take part in the reaction).

Generally 3.15 kg of $CaCO_3$ is mixed for 1 kg of sulphur removal. The crushed mixture is held in suspension (fluidized) by the air stream injected from the bottom of the bed. Sulphur oxide released during combustion reacts with the limestone to form solid calcium sulphate as follows:

$$CaCO_3 + SO_2 + \frac{1}{2}O_2 \rightarrow CaSO_4 + CO_2 \qquad (6.1)$$
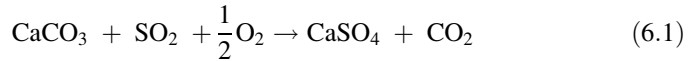
If the temperature exceeds the equilibrium value, the endothermic reaction proceeds as follows:

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (6.2)$$

$$CaO + SO_2 + \frac{1}{2}O_2 \rightarrow CaSO_4 \qquad (6.3)$$
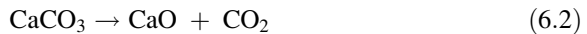
Thus, sulphur of the fuel is removed in the form of solid calcium sulphate, which falls to the bottom of the furnace and is removed. There are processes for regeneration of lime for reuse as the additive. However, the present economics often indicate a preference for once – through limestone system.

In FBC boilers, sulphur removal rates can be higher than 90 %. The heat transfer from the combustion region to the boiler tubes is also more efficient because fluidized particles are in direct contact with boiler tube and heat is transferred by conduction rather than by less efficient convection and radiation. The higher heat transfer efficiency enables the boiler to operate at about half the temperature ($\approx$700–800 °C) of conventional boilers temperature (1400–1600 °C). This greatly reduces the formation of NO_x. In FBC boilers, coal with higher ash content can also be burned without fouling the heat exchanger, since the operational temperature may be kept below the melting point of ash.

Operating experience with the FBC systems has shown that their emissions often show values lower than the stringent present-day world over norms of 650 mg/Nm^3. However, further reduction of NO_x is possible through the techniques as follows:

(i) *Low Excess Air Technology:* Wherein the amount of air made available for combustion is controlled to the minimum amount required for complete combustion.

(ii) *Second Generation Low NO_x Burner:* It involves two stages of air feed: In step 1 due to starvation of air, CO is formed, N_2 is released and in the other stage complete combustion takes place.

6.3.3 Post Combustion Technologies

Stack emissions from a coal-based power plant consists of fly ash as a particulate matter and oxides of nitrogen, carbon and sulphur as gaseous pollutants. The emissions from oil and gas fired plants consists of only gaseous pollutants. In

older power plants cyclone type mechanical dust collectors were used. Presently, electrostatic precipitator (ESP) is the main choice as fly ash collector. As electrostatic precipitator is basically a system wherein gaseous particles which are charged to saturation and collected on electrodes. ESP is available for both horizontal as well as vertical gas flows. Yet another device used for post-combustion pollution control is fabric filter, it is by far the most efficient collector of fly ash and is used in industries. In fabric filter the dust laden gas is passed through a suitably shaped fabric resulting in the deposition of dust on the fabric. The quality of fabric now determines the performance of bag filters. Fabrics like fibre, glass and teflon are capable of withstanding higher temperatures (up to 250) and resist chemical erosion and are therefore, often used in fabric filters.

6.4   Clean Power Plant Configurations

The above techniques used individually or in tandem evolve several power plant configurations as follows:

  (i) Plant with conventional PC firing in Rankine cycle power plant with Fuel Gas Desulphurisation (FGD), and particulate control.
 (ii) Plants with Atmospheric Fluidised Bed (AFBC) boiler in Rankine cycle.
 (iii) Circulating Fluidised Bed (CFBC) boiler with Rankine cycle.
 (iv) Combined cycle power plant with Pressurised Fluidised Bed (PFBC).
  (v) Integrated Gasifier Combined Cycle Power plant with steam based heat recovery system.

   The configurations 1, 2, 3 are commercially well proven. The configuration 4 is in the initial stages of commercialisation and 5 is at R&D demonstration stage.

6.4.1   Integrated Gasification Combined Cycle (IGCC) Power Plant

As the name implies, this power plant consists of a coal gasifier whose product gas $(CO + H_2 + CH_4)$ with a calorific value of 4–7 MJ/Nm^3 is cooled in the gas cooler and then cleaned (to remove H_2S, COS and particulate matter) in a Gas Clean Up (GCU) system before being introduced into the combustor of a gas turbine. The hot gases from a combustor at a temperature of up to 1250 K are expanded in the gas turbine to generate electrical energy. The exhaust gases from the gas turbine which are still at a considerably high temperature are made to generate steam in a Heat Recovery Steam Generator (HRSG). The high temperature high pressure steam is sent to turbo generator for the production of electricity. The exhaust gases from HRSG are let out to the atmosphere with additional heat recovery in an economiser.

Fig. 6.2 Flow diagram of conceptual 600 MW IGCC plant (Kolar and Reddy 2004)

The combined cycle operation of using the gas turbine and the steam turbine results in an overall plant efficiency between 39 and 45 % and has potential of achieving close to 50 % in the future. Further as the gas is cleaned before it is combusted the amount of gaseous and particulate pollutants in the exhaust gases is very low. In fact it has been well established that presently this is the most environmental-friendly technology for coal utilisation. In India, the Indian Institute of Chemical Technology, Hyderabad has been developing coal gasification technology since 1983. It has a 24 tonnes/day pilot plant on which various Indian coals have been studied. Based on this experience, IICT has developed a conceptual design of 600 MWe IGCC plant which has been illustrated in the Fig. 6.2 (Kolar and Reddy 2004).

Reference

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Chapter 7
Solar Thermal Energy and Power Systems

7.1 Solar Thermal Conversion

The use of solar energy has been known for centuries: early man used the sun based and natural sources, namely, wood, wind and waterfall for cooking, pumping, drying, transportation and other applications. With the advent of steam and internal combustion engines, use of above energy sources was taken over by fossil fuels, which were living matter millions of years ago and trapped solar energy through the process of photosynthesis. The global reserves of fossil fuels are finite and their accelerated use is hazardous to the environment and ecosystem. Public awareness of these limitations has revitalized the worldwide interest in solar energy utilization.

Solar energy is received as radiant energy that can be converted into thermal, electrical, chemical or any other usable form utilizing modern methods of conversion, which may be broadly classified into three categories: Solar thermal conversions, Solar photovoltaic and Solar bioconversion. Of the above three solar radiant energy conversion processes, thermal conversion is the simplest, most cost-effective and most technically convenient for most regions of the world. In solar thermal conversion process, the radiant energy is first converted into heat, which may be used as such or be converted into some other form for utilization. Solar radiant energy is characterized with low energy density; the average solar radiation falling on the earth is about 200 W/m^2 in a diluted form; which means that energy equivalent to one barrel of oil (6GJ) is spread over an area of few hundred square meters. Thus, concentrating collectors are essentially needed to obtain a good thermodynamic efficiency. An ideal solar collector should combine in itself the characteristics of good absorption of solar energy with low loss of heat and should be inexpensive. Furthermore, availability of solar energy is intermittent due to night and clouds. Therefore, a storage system is needed if the energy supply is to be made more reliable. Solar energy cannot be stored in its electromagnetic form. It must first be converted into some other form such as thermal energy, hydraulic energy,
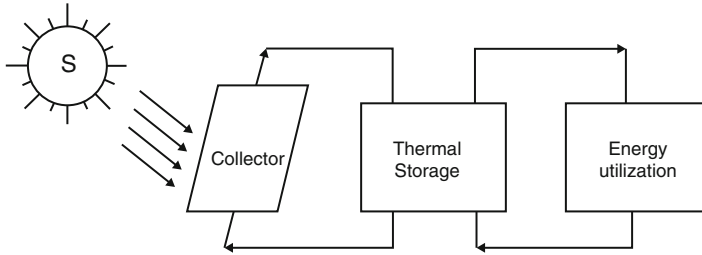
Fig. 7.1 Block diagram of a solar thermal system

mechanical energy, electrical energy, etc. In general, thermal energy storage is normally included in solar systems. Conventional solar energy system may therefore, be schematically represented as in Fig. 7.1.

Conventional solar systems involves solar collectors and separate thermal storage. Energy is transported from collectors to storage and subsequently from storage to the utilization unit and control device. Flow of energy has to be regulated. These functions are performed by using pumps and/or blower to transport heat. Such systems are known as solar active systems. In contradistinction to these there are many methods and devices for solar energy utilization that do not use mechanical power. The systems based on these methods are referred to as 'passive systems'. In these systems the energy flow is accomplished by natural convection, conduction or radiation. Besides, there are systems that utilize a gainful combination of active and passive components. For example, a passive system whose performance is significantly enhanced by the use of a fan or pump may be referred to as a hybrid system. The difference between an active system and a passive system may be made clear by considering the case of solar water heater which consists of the collector and storage units. Heat transfer from collector plate to store may be achieved by natural convection or thermosyphon principle. Alternatively, it may be accomplished by the forced flow of fluid using an electrically operated pump. Obviously, the former is an example of passive solar system and latter belongs to active systems.

Many designs of solar collectors are now available. These may be broadly classified into three categories: non-focussing collectors, focussing collectors and non-imaging collectors.

7.1.1 Non-Focussing Collectors

An example of a simple non-focusing collector is the 'flat plate collector'. The collector consists of black absorption plate in good thermal contact (two bodies are said to be in good thermal contact when heat can pass easily from one to another) with a heat carrying fluid (water/air) flowing through tubes. The base and sides of the plate are insulated and the upper surface is covered with transparent glazing at about 2.5–5 cm above the plate. Solar radiation (direct as well as diffuse) falls on

the cover and suffers partial reflection at air-glass interface. The transmitted radiation suffers one or more partial reflection at the other surface of glass. The remaining radiation reaches the blackened surface of the plate where it is largely absorbed. A small portion is reflected at the blackened surface, which subsequently suffers internal reflections between the plate, the glass cover until it is fully absorbed. The plate is heated due to absorption of radiation. A portion of the heat is transferred to the heat removal fluid and the rest is lost to environment through the base, sides and cover. Heat transfer in the collector system depends on the nature of the bonding between plate and tubes; the physical configuration and the material of the plate, tubes, cover, insulation etc. Some typical choices of materials and design considerations are given below. The absorber and tubes should have high thermal conductivity; should be non-corrosive and should be temperature stable. The most commonly used materials are copper (thermal conductivity $= 376 \text{ W/m}^2\text{K}$), aluminium ($205 \text{ W/m}^2\text{K}$) galvanized iron ($50 \text{ W/m}^2$ K), stainless steel ($25 \text{ W/m}^2\text{K}$) and some plastics like acrylic ($0.20 \text{ W/m}^2\text{K}$) and polyethylene ($0.30 \text{ W/m}^2\text{K}$) etc. Copper is thus the best material but its cost is prohibitive in certain parts of world. Aluminium is equally good in so far as its heat transfer characteristics are concerned but it will get corroded easily when in contact with water. Galvanized iron too becomes corroded in a hot (>50 °C) aqueous environment. Stainless steel and plastics are less readily corroded but are poor conductors of heat. A combination of copper (as tubes) and aluminium (as plate) is currently commonly used in practice. The plate is blackened to increase the absorption of radiation using black paint that can absorb up to about 96 % of solar radiation. Selective coatings have also been developed, these are good absorbers of solar radiation and poor radiators of heat and so are suitable for high temperature collectors. The thermal contact between the riser tubes and the plate is ensured by bonding the tubes to the lower surface (in some cases to the upper surface) of the absorber plate. Some bonding methods are as follows. Bonding can be accomplished by soldering with brass (brazing); soldering with thermal paste; using a tie or using a clamp. In some designs, the tube is made integral with the plate where dissimilar metals, such as copper and aluminium are used. The copper tubes are inserted in channels of aluminium and are metallurgically joined together by a pressure temperature technique.

In a flat plate collector, major heat losses are through the transparent cover system; these are essentially radiative and convective. Selective coating considerably reduces the radiation losses; double glazing further reduces the radiation losses and cuts convection losses. However, the effect on convective heat losses is marginal and at the expense of $(\tau\alpha)_{\text{eff}}$. Magnitude wise convective heat losses are about (a) one third of total loss in case of black painted collector, (b) three quarters of total loss from a selective absorber collector. One approach to reduce convective losses is to use a honeycomb convection suppression device (Hollands 1965).

An alternative approach for reducing the convective heat loss of flat plate collector is to have vacuum in the air space between the glazing and absorber plate. Evacuation in conventional flat plate collector would involve problems caused by tensile stresses in glass under one-sided vacuum. Cylindrically shaped

glass tubes are, therefore, used to maintain vacuum around the absorber; and are referred to as evacuated tubular collector.

7.1.2 Focussing Type Solar Collector

Focussing solar collectors concentrate the solar energy incident over a larger surface on to a smaller surface and accomplish that the area of absorber losing heat is smaller than the area collecting solar radiations. These collectors use reflecting or refracting elements to produce high density of radiation at a line or point focus. They generally utilize only beam radiation and hence require an arrangement for tracking sun's virtual motion. Thus, the focussing collector consists of a focussing device, a receiver and a tracking arrangement. Current technologies include: (i) one axis tracking concentrators like linear Fresnel lens/reflector, cylindrical parabolic collector; (ii) two-axis tracking concentrators like paraboloid dish, central tower receiver, conical concentrator, circular Fresnel lens; as well as (iii) fixed mirror concentrator with tracking receiver like hemispherical bowl mirror. These concentrators are expensive owing to the exacting requirement like optical perfection, precise tracking, and efficient heat transfer to the working fluid. Some options in focussing Solar Collectors are given in Fig. 7.2.

7.1.2.1 Characteristic Parameters of Solar Concentrators

The geometric and performance characteristic parameters of solar concentrators are very important in development of an effective solar energy system. Some of these parameters are listed below (refer Fig. 7.3).
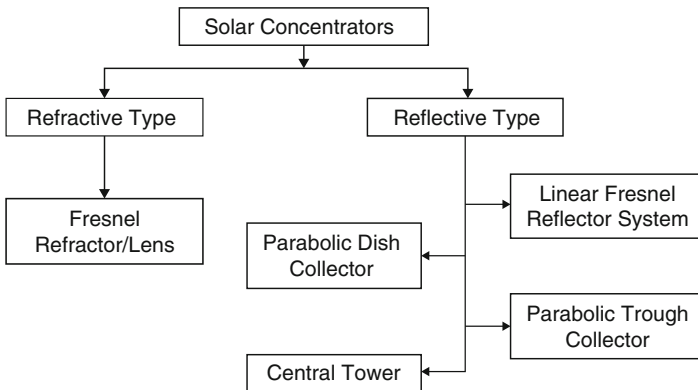

Fig. 7.2 Options in solar focussing collector systems
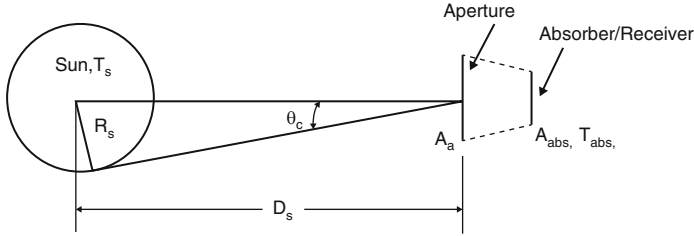
Fig. 7.3 Radiation incident on the aperture of the concentrator (Duffie and Beckman 1980)

(a) Aperture area (A_a) is the plane area of the concentrator normal to the incident solar radiation
(b) Absorber area (A_{abs})is the area receiving the reflected/concentrated solar radiation
(c) Half Acceptance angle (θ_c) is the limiting angle over which the path of incident solar ray reaching the absorber may deviate from normal to the aperture plane
(d) Intercept factor (γ)is the fraction of concentrated energy intercepted by the specified absorber/receiver
(e) Optical Efficiency (η_{opt}) is the ratio of the energy absorbed by the absorber to that incident on the collector
(f) Geometric Concentration Ratio (C_R) is the ratio of the aperture area (A_a) to the area of the absorber (A_{abs})

Theoretically, temperature as high as limited by the temperature of sun's photosphere may be attained. However, in practice these units are capable of heat delivery at many hundreds or even thousands degrees Celsius.

For a perfect concentrator, the radiation from the sun incident on the aperture of the concentrator is a fraction of the radiation emitted by the sun as shown in the Fig. 7.3 (Duffie and Beckman 1980).

$$Q_{a-abs} = A_a \frac{R_s^2}{D_s^2} \sigma T_a^4 \tag{7.1}$$

An absorber (assume perfect black body) at temperature T_{abs} radiates energy equal to $A_{abs} \, \sigma \, T_{abs}^4$ and a fraction E_{abs-a} of this reaches the sun

$$Q_{abs-a} = A_{abs} \sigma T^4_{abs} E_{abs-a} \tag{7.2}$$

where E_{abs-a} = Exchange View Factor, always less than unity.

If the Sun and absorber are at the same temperature under steady state condition, which results in no net heat transfer between them:

$$Q_{abs-a} = Q_{a-abs} \tag{7.3}$$

By Equating (7.1) and (7.2)

The concentration ratio (C_R) is given by

$$C_R = \frac{A_a}{A_{abs}} = \frac{D_s^2}{R_s^2} E_{abs-a} \qquad (7.4)$$

$$C_R = \frac{E_{abs-a}}{\sin^2\theta_c} \qquad (7.5)$$

By substituting, $\theta_C = 16'$ and $E_{abs-a} = 1$
 Max. concentration ratio for,

(a)   three dimensional collector, $C_{R3D} = 1/(\sin^2\theta_c) = 1/(\sin^2(16')) \approx 45{,}000$
(b)   two dimensional collector, $C_{R2D} = 1/(\sin\theta_c) = 1/(\sin(16')) \approx 212$

7.1.2.2   Classification of Solar Concentrators

Solar Concentrating collectors may be classified according to various parameters such as collector geometry, concentration ratio, optics and tracking axis. Various concentrating solar collectors are shown in Fig. 7.4. Classification of collectors referred as (i) Based on the tracking, the solar concentrators may be classified as continuous and intermittent tracking as well as one axis and two axis tracking,
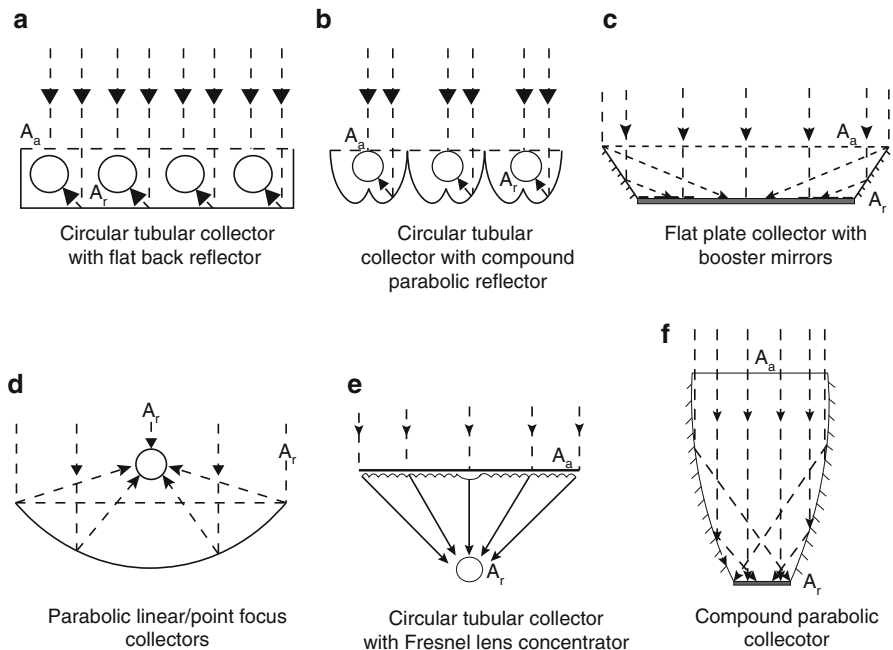

Fig. 7.4 Various types of concentrating solar collectors

(ii) Based on concentration ratio: low concentration ratio and high concentration ratio type of concentrators, (iii) Based on optical components: imaging and non-imaging type, line focussing and point focussing types and reflecting and refracting type. Following configurations are based on concentrating collector geometry:

(a) Circular tubular collector with flat back reflector
(b) Circular tubular collector with compound parabolic reflector
(c) Flat plate collector with booster mirror
(d) Parabolic linear/point focus collectors
(e) Compound parabolic collector
(f) Circular tubular collector with Fresnel lens concentrator

7.1.3 Non-imaging Collectors

An intermediate position between non-focussing collectors and focussing collectors is occupied by non-tracking concentrators, often referred to as non-imaging concentrating collectors. Since they do not require tracking, they are less expensive. Simple version includes a flat plate collector with plane booster reflectors at its edges to reflect solar radiation onto the absorber surface. In case of an array only two reflectors are used, one of which faces north and the other south. They collect and concentrate beam and a fraction of diffuse components of solar radiation. Concentration ratios up to 4 ($C_R < 4$) and the collected heat is in medium temperature range (100–200 °C). In the above system, maximum concentration is achieved around noon and the mirror become less effective as solar incidence angle increases.

7.1.4 Solar Thermal Applications

Solar thermal energy can be used for various purposes such as hot water production for commercial as well as domestic applications; heating and cooling of buildings; drying of crops, grain and fishery products; desalination of water; cooking; irrigation; refrigeration and electricity generation. In Table 7.1 a summary of the characteristics of various solar thermal application systems is presented. In what follows we consider solar thermal energy applications in sustainable building and power sector. Solar active as well as passive technologies could be used for building applications. In this chapter, we consider only the solar thermal power generation and solar active technologies for building applications. Solar passive technologies are discussed in a later chapter.

Table 7.1 Summary of solar thermal applications

Collector type/ application	Temperature range		
	Low temperature (<100 °C)	Medium temperature (100–200 °C)	High temperature (>200 °C)
Solar collector types	Flat plate	Advanced flat plate collector	Paraboloids
	Solar pond	Compound parabolic concentrator	Hemispherical bowl
	Ground/sand collector	Cylindrical parabolic concentrator	Mirror arrays
Applications	Agricultural drying	Industrial process heating	Steam engines and turbines
	Water distillation	Refrigeration	Industrial process steam
	Heating/cooling of buildings	Cooling	Stirling engines
	Domestic hot water and cooling	Vapour engines and turbines	Thermo electric generator etc.

7.2   Solar Active Systems for Buildings

7.2.1   Basic Components of Solar Active Systems

A solar active system employs pumps or blowers/fans to transport heat. It consists of a collector; heat transport fluid; a thermal storage unit; a heat distribution device, an auxiliary energy source and a means of control as well as protection arrangements. Only systems suitable for space heating/cooling applications and hot water production (up to 90 °C) for domestic and industrial processes are considered here.

7.2.2   Collector Array

The systems described above usually involve non-concentrating collectors. The simplest is the flat plate collector. Air and water are the common fluids used for heat transport. Common absorber plate configurations of liquid-based as well as air-based flat plate collectors have been discussed in several solar energy books (e.g. Kaushika 1988). Usually the collector is inclined at some angle to the horizontal. The fluid flow through the collector should be in the opposite direction to gravity. This means that the water inlet is at the bottom and the outlet is at top of the collector. Care must be taken to ensure that the flow is uniform through all the tubes. In large installations, an array of collectors is used. In the simplest configuration, all collectors are connected in parallel. If the array is made up of m collectors of area A_{c1}, A_{c2}-A_{cm} respectively, then total heat gain obtainable from the array may be written as:

$$Q_{uT} = A_{CT} F_{CRM} \left[(\alpha\tau)_{lm} S - U_{nm} \left(T_{fl} - T_A \right) \right] \tag{7.6}$$

where $A_{CT} = A_{C1} + A_{C2} + \ldots + A_{Cm}$. Also,

$$F_{CRM} = \frac{\dot{m}_{WR} C_W}{A_{CT} U_{Lm}} \left[1 - \exp\left(-\frac{A_{CT} U_{Tm} F'_{Cm}}{\dot{m}_{WR} C_W} \right) \right] \tag{7.7}$$

Duffie and Beckman (1980) m_{WRT} is total mass flow rate of water; if the mass flow rate is same, through all the collectors, then $m_{WRT} = m_{WR}$. Thus in a parallel connection arrangement, the largest mass of water per collector area is heated. An array can also be made from collectors connected in series. In such an arrangement the inlet temperature of the Nth collector will be that at the outlet from $(N-1)$th collector. Following the discussion, due to Duffie and Beckman (1980) and Sodha et al. (1983), the outlet fluid temperature from the Nth collector can be expressed in terms of the inlet temperature of the first collector:

$$T_{fCN} = \left(\frac{S}{U_{Lm}} + T_A \right) \left\{ 1 - \exp\left(-\frac{N A_C U_L F'}{\dot{m}_{WR} C_W} \right) \right\} + T_{fl} \exp\left(-\frac{N A_C U_L F'}{\dot{m}_{WR} C_W} \right) \tag{7.8}$$

Hence higher temperatures may be obtained in this arrangement than in the parallel connection arrangement. Heating of a given mass of water to a required temperature may be achieved by a mixed combination of series and parallel collector modules.

7.2.3   Thermal Storage and Utilisation

For heat storage, an insulated water tank is used in conjunction with liquid (water) based systems and a rock bed store with air-based systems. Heat distribution systems vary with the nature of the application. Direct transport of hot water to the user through connecting pipes is common in hot water systems. Alternatives such as fan coil, radiator coil and ducting network are used for other applications.

7.2.4   Heat Exchangers

In some cases when an antifreeze solution or corrosion inhibiting liquid is used in the collector circuit, it is desirable to use a heat exchanger to transfer heat from the collectors to storage tank. A heat exchanger consists of a surface which separates the two fluids but allows the transfer of heat from one fluid to the other. In solar systems the majority of heat exchangers are shell and tube type. This consists of a cylindrical shell filled with one of the fluids. The other fluid flows through tubes

submerged in the shell. The two fluids may have their flows parallel, counter or cross to each other. A combination of parallel and counter flows is often advantageous. A plate heat exchanger is used when high efficiency is required. It consists of a series of plates fitted in a frame. The two fluids pass through alternate passages. The temperature of colder fluid increases rapidly at first and then at a decreasing rate as it travels through the heat exchanger (Charters 1982a).

7.2.5   Auxiliary Heat and Protection

An auxiliary energy source is often used with active solar systems. This may be located in series or in parallel with the load. Controls are used to regulate the operation of devices like pumps and blowers. In addition, controls are used to prevent freezing or boiling of fluid in the collector.

7.3   Solar Space and Water Heating

Both air and water systems have been designed and tested for water heating as well as space heating applications. The most costly component of these systems is the collector field. Concentrating thermal collectors are required if the system is designed on stand alone mode, making the system cost prohibitively high. Therefore, in such systems an auxiliary energy source is required to make them more reliable. The air-based system has an advantage over the water-based system in relation to factors such as corrosion, leakage and damage due to freezing and boiling. However, the requirements of power for pumps and fans and the storage volume are relatively larger in air-based systems. Thus the choice between air-based and water-based systems is greatly influenced by the local availability and costs of material and components. A schematic of a typical space and water heating system is shown in Fig. 7.5. Sizing the collector for cost effectiveness is an essential step in system design. For this purpose, solar energy available per unit area of collector and the heating load must be known. A design procedure often referred to as the f-chart method is due to Klein et al. (1974, 1976) and is outlined in Beckman et al. (1974) and Charters (1982a). In this approach, the system is characterized by three dimensionless parameters:

(a)   f – fraction of monthly load met by solar energy
(b)   X – ratio of monthly mean collector loss to total load
(c)   Y – ratio of energy absorbed by collector to total load

First, typical correlation curves of these parameters are drawn. Then, from these curves, the annual solar fraction corresponding to an area of collector array may be calculated and its payback period is determined. The most viable area for the
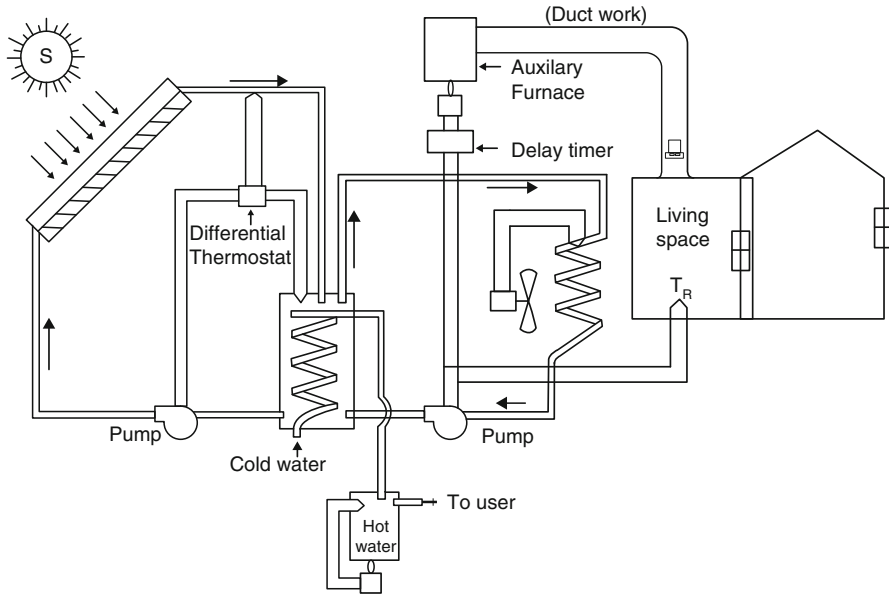
Fig. 7.5 Schematic of a typical space and water heating system (Beck and Field 1977)

collector array may then be obtained by repeating the above procedure for various collector areas.

7.4   Solar Heat Pumps

A heat pump is a device intended to upgrade heat. It raises the temperature of heat in excess of source temperature. This process may be regarded as the reverse of refrigeration. Thermodynamically, the process involves carrying heat energy 'uphill'. This requires work to be done on the system. Usually this is achieved with a compressor run by electricity. A working substance undergoes a cycle of changes of state. The cycle could operate in a closed circuit as well as in a circuit open to environment. Several types of heat pumps are available. Their classification is shown in Fig. 7.6. A schematic of a mechanical vapour compression heat pump is given in Fig. 7.7.

Mechanical vapour compression and absorption cycle heat pumps have received relatively more attention in the context of solar operation. Several methods have been suggested for the solar operation of heat pumps. These can be divided into three categories (Charters 1982b; Freeman et al. 1979):

• Parallel Systems
• Series Systems
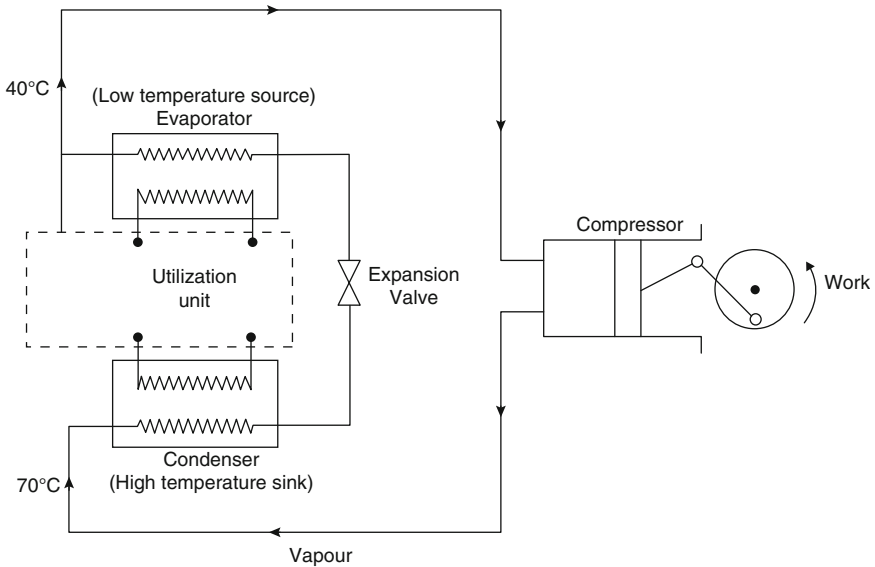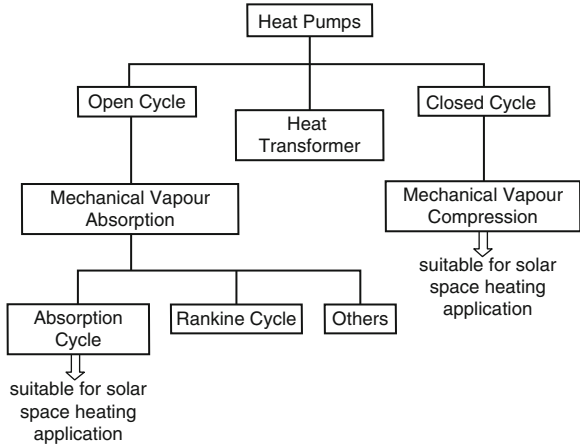• Dual Source Systems

Fig. 7.6 Classification of heat pumps

Fig. 7.7 Schematic of a mechanical vapour compression heat pump system

7.5   Solar Thermal Electric

7.5.1   The Concept

In the current power generation scenario, fossil fuels are major sources for electricity production. Solar thermal power plants are similar to that of fossil fuel thermal power plants except heat addition in the boiler. In solar thermal power
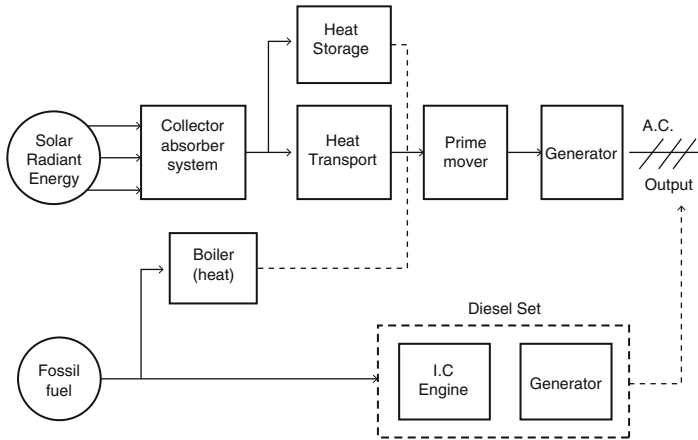
Fig. 7.8 Solar thermal power systems and its similarity with fossil fuel power systems

plants, the collector field acts as a boiler. The solar power generation in regions of high solar radiation (>5kWh/day) is an attractive option for sustainable electricity supply strategy. The solar radiation is converted to high temperature and high pressure steam to produce electricity in Rankine cycle based solar power plants. Figure 7.8 represents the block diagram of a solar thermal power plant and its similarities and differences with fossil fuel-based systems. The nature, quality and availability of input energy for solar power plant differ significantly from the fossil fuel-based power plant. However, its hybridization with fossil fuel-based system is possible at intermediate stages by fossil-fuelled heat boiler as well as by diesel generator set. The reliability of electricity generation in solar power plants can be improved significantly by introducing energy storage and/or hybridization with fossil fuels. The solar aided fossil fuel thermal power plants are another option for energy efficient and sustainable electricity generation. Both hybridization and energy storage of thermal power plant can provide continuous and reliable energy even during off-sunshine hours. This option not only saves fossil fuels significantly but also enhances the economic value of electricity generation.

7.5.2 Solar Thermal Power Technologies

There are many options open to the designer of a solar thermal power system. These options are listed in Table 7.2.

Solar collector field is the major cost component of the solar power system and is the major performance-governing component. Comparative studies of various collector characteristics are given in Table 7.3.

Based on solar thermal collector technologies wide range of systems have been proposed and tested. The solar thermal systems may be grouped into

Table 7.2 Various solar thermal power technologies

	Component/characteristics	Options
1.	Collector	Flat plate (metallic, solar pond) and evacuated
		Concentrator (low concentration)
		Concentrator (high concentration)
2.	Working temperature and pressure	Low temperature (<100 °C) and subcritical
		Medium temperature (100–400 °C) and subcritical
		High Temperature (>400 °C) and subcritical and supercritical
3.	Working fluid	Water
		Air
		Organic liquid
		Mixture
4.	Thermodynamic cycle	Rankine cycle – water or organic fluid
		Brayton cycle – helium or air
		Hybrid cycles
		Stirling cycle – helium or air
5.	Prime movers and generators	Turbine (low speed)
		Turbine (high speed)
		Stirling engine
		Uniflow steam engine
6.	Storage	Thermal
		Electric
7.	Electrical output	AC
		DC

Table 7.3 Comparison of solar thermal collector technologies

S. No.	Technology	Operating temp. °C	CR	Tracking	Thermal efficiency %
1.	Flat plate collector (FPC)	30–100	1	No	21
2.	Evacuated tube collector (ETC)	90–200	1	No	38
3.	Solar pond (SP)	70–90	1	No	19
4.	Solar chimney (SC – down draft)	30–80	1	No	17
5.	Parabolic trough collector (PTC)	260–400	8–80	Single axis	56
6.	Linear fresnel reflector (LFR)	260–400	8–80	Single axis	60
7.	Power/Central tower (PT)	500–800	600–1000	Dual axis	73
8.	Paraboloidal dish (PD)	500–1200	800–8000	Dual axis	80

(Tchanche et al. 2011)

Solar Thermal Power
Technologies

Non - Mirror Systems   Mirror Systems   Air Moving Systems

1.Solar Pond   1.Parabolic Trough   1.Solar Chimney (Up-draft)
($C_R = 1$,T < 95°C,P < 5MW) (C_R = 40-80,T < 400°C, (C_R = 1,T < 150°C,
                              P < 100MW)   P < 100MW)

2.Flat Plate Collector   2.Central Tower
($C_R = 1$,T < 200°C,P < 1MW) (C_R = 200-700,T < 1500°C,
                              P < 200MW)

3.Vacuum Tube Collector   3.Parabolic Dish
($C_R = 3$,T < 250°C,P < 1MW) (C_R = 100-250,T < 1500°C,
                              P < 150KW)
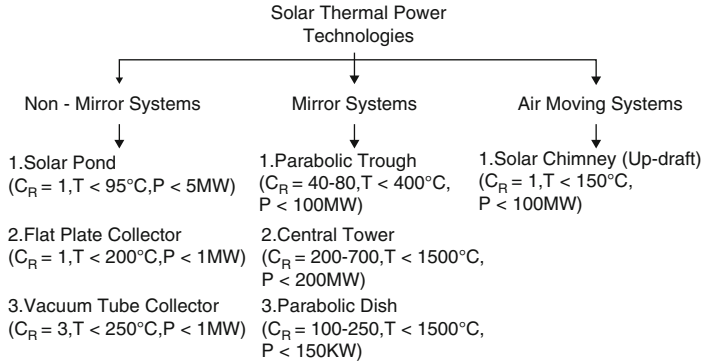
Fig. 7.9 Classification of solar thermal power technologies

(a) non-concentrating or non-mirror systems, (b) concentrating or mirror systems and (c) air moving systems. Figure 7.9 illustrates various solar thermal power generation systems with various ranges of operating parameters. In what follows, seven different solar thermal technologies are highlighted, among which three corresponds to non-mirror/stationary systems, three mirror/tracking systems and one air moving system. The non-mirror systems are simple in construction and passive in operation, which does not require tracking. These systems can produce low temperature heat due to their design and operation. The mirror systems such as parabolic trough, power tower and paraboloid dish are relatively complex and require single or dual axis tracking to concentrate solar radiation on the receiver/absorber for high temperature heat production. Solar chimney is the up-draft air moving system in which the temperature of air is increased by solar energy which in turn moves up due to density difference. The energy content of high velocity upward hot air can be harnessed by guiding this air movement through a chimney and wind turbine.

7.5.2.1   Solar Parabolic Trough Collector Power System

The solar parabolic trough collector made of linear parabolic concentrators of highly reflective surfaces. The PTC requires single axis tracking to concentrate solar beam radiation on the linear receiver located in the focus. A typical large scale solar parabolic trough collector based power plant is shown in Fig. 7.10. The power plant broadly consists of solar field and power block. The power block is essentially same as that of fossil fuel power plant. Whereas solar collector field represent the boiler and it consists of arrays of parabolic trough modules connected in series and parallel. The solar parabolic trough collector module is of 5.77 m concentrator aperture and 12 m long. The receiver/absorber is made of 70 mm metallic tube enclosed with evacuated glass tube to reduce heat losses. The typical length of one solar field row is about 600 m consisting of four solar collector assemblies. A single
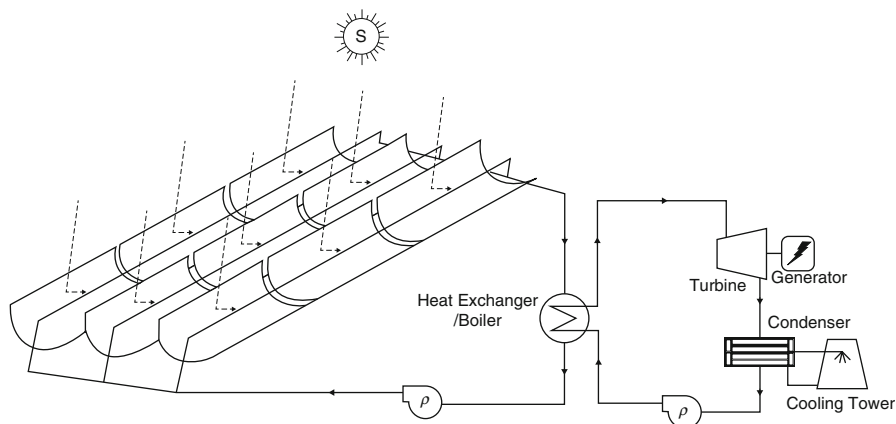
Fig. 7.10 Solar parabolic trough power plant

axis tracking mechanism keeps the parabolic collector normal to the incoming solar radiation. A heat transfer fluid (HTF), usually high boiling point synthetic oil is circulated through the receiver to absorb concentrated solar radiation. The hot HTF is used to vaporize the water in the boiler of Rankine cycle power block. In order to increase the reliability of power generation or to achieve a quick response on power changes, a fossil fuel based back-up system or a thermal energy storage can be integrated. The energy storage system allows the PTC plant to work on stored thermal energy even during off-sunshine hours.

7.5.2.2 Parabolic Dish-Stirling Systems

A solar dish system utilizes mirror elements to concentrate the incident solar energy onto the focal point of the dish by two-axis tracking. Concentration ratio of solar dish is much higher than the other solar energy technologies (over 2000). Heat transfer fluid in the receiver may be heated to high temperatures, around 1000 °C. Paraboloid mirror is the ideal optical configuration for dish concentrators which is infact very expensive to fabricate, its cost escalating rapidly with aperture area. A dish concentrator however, in practice is easier to fabricate from small elementary mirrors of approximate forms such as toroidal, spherical etc. The elementary components are known as reflecting petals or facets. A schematic of solar paraboloidal dish collector is shown in Fig. 7.11. Until recently a faceted glass metal dish represented the state-of-art of paraboloid dish concentrator. Several innovations have been reported during the last decade in the design and materials of dish technology. The diversity of construction approaches and technologies of dish concentrators include (Jaffe 1988; Mancini 1991; Schiel et al. 1994; Goldberg 1980; Kaneff 1983; Washom and Vanguard 1984; Rogan 1985; Kinoshita 1985; Strchan 1987; Barber 1985; Zewen 1986; Kaushika and Kaneff 1987; Schnidt

Fig. 7.11 Solar paraboloidal dish collector
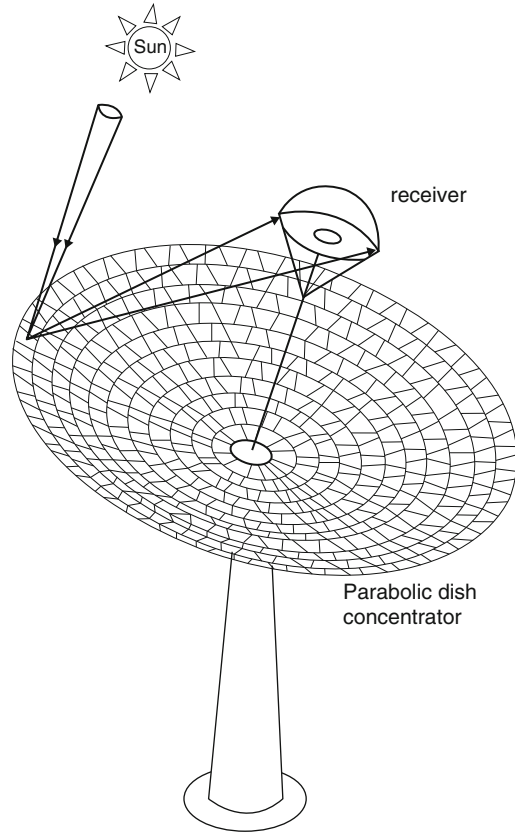
et al. 1983; Kaushika 1993); glass metal technology, aluminised film technology, silver polymer/steel technology and stretched membrane technology. Most notable development is that by reducing weight of the structure, the reduction in the system cost becomes possible. A rationale with respect to economic design of a dish concentrator is to use the inherent strength of a paraboloidal shell involving a deep dish wherein no frame would be required which in turn would reduce the weight and cost. A deep dish will have a shorter focal length in comparison to a shallower dish (Kaneff 1983; Kaushika and Kaneff 1987). The surface receiver can be used as a focal absorber when the rim angle is greater than 90° (Schmidt et al. 1983). A trade off between focal length, rim angle, nature of absorber and its life properties has been carried out by Kaushik (1993) to evolve a viable design involving deep dish of imperfect optics.

The dish Stirling system is a heat to electricity conversion system in which the prime mover (Stirling Engine) is mounted on one single rack. The two-axis tracked device can use only direct beam radiation for electricity generation. The heat absorber of the Stirling engine, usually a tube- or a heat-pipe absorber, is placed in the focal point of the dish reflector. It is cooled by gaseous hydrogen or helium,

the usual working fluids for Stirling systems. The Stirling engine is an externally heated hot gas engine with reciprocating piston that operates in a closed four step regenerative thermodynamic cycle. Stirling engines have multi-fuel capacity, high efficiency, low emissions, long life and operate very quietly. Dish-Stirling systems are highly modular, stand-alone units of 10–50 kW of power that can be connected to form larger grid connected electricity plants of more than 1 MW. Hybridization is possible but has not yet been realized (Stine and Diver 1994).

Six units of smaller streched membrane dish-Stirling systems with 9 kW power using the Solo V-160 engine were built by Schlaich, Bergermann and Partner (SBP) of Stuttgart, Germany in 1991 and erected in Almeria, Spain and in several sites in Germany (Mancini et al. 2003). The V-160 Stirling engine has a working temperature of 620 °C. The overall solar to electric conversion efficiency is maximum 0.203. Cummins Power Generation, Inc. (CPG) of Columbus, Indiana, USA is the first company in the world using a free-piston Stirling engine for solar electric power generation. Cummins is currently testing three 5 kWe prototypes. The design solar to electricity efficiency is over 0.19. Sun power, Inc. is developing the 9 kWe free-piston Stirling engine with a linear alternator for use in this system. The working gas is helium at 629 °C. Aisin Seiki Co., Ltd., of Kariya City, Japan, built the NS30A engine with 30 kWe under the Japanese government's New Energy and Industrial Development Organization (NEIDO) project. The four-piston double-acting engine operates on helium at 683 °C. One of these units has been tested with a McDonnel solar concentrator at Kariya City. Three further engines derated to 8.5 kW with Cummins CPG-460 stretched membrane concentrators are used for generating electric power on Miyako Island, 290 km southwest of Okinawa. To provide power after sunset, a electrochemical zinc bromine battery with a capacity of 30 kWh is incorporated to each system. Stirling Thermal Motors Inc. of Ann Arbor, Michigan and Detroit Diesel Corp. of Detroit, Michigan, have designed a solar power generating system incorporating the STM4-120 Stirling engine with 25 kWe power. The completely self-contained package is suitable for integration with a variety of solar concentrators.

7.5.2.3 Central Receiver Power Plants

The power tower or central tower solar power plants uses heliostats (plane mirrors) to concentrate the solar radiation on to the receiver centrally located at the top of the tower. A schematic of solar central tower power plant with thermal energy storage (TES) is shown in Fig. 7.12. The reflected solar radiation is absorbed by the surface/cavity receiver, which is subsequently transmitted to a circulating heat transfer fluid (HTF) at very high temperatures in the range of 1000–1500 °C. The heat transfer fluids used in power tower plant are molten salt, liquid metal and air. The working fluid is heated in the receiver to produce high temperature and high-pressure steam, which in turn is used for power generation. The heliostat dimensions are chosen based on the receiver surface area, and tower height. Various types of central receivers have tested for different working fluids steam (tubular receiver), air
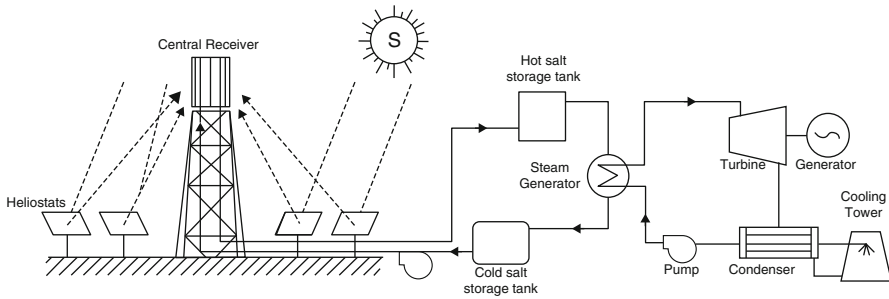
Fig. 7.12 Solar central receiver power plant

(open volumetric receiver), and molten salt (tubular or film receiver). Generally, Rankine power cycle with water or gas turbine cycle with air is employed for converting the extracted heat energy to electricity. The air system allows operating temperatures of up to 800 °C that clearly shows the enhancement of steam cycle efficiency. Thermal energy storage (TES) system, especially molten salt concept, can be integrated to the power plant to attenuate solar input fluctuations and to enhance the solar energy harvest. Hybridization of the power plants can be done using natural gas or fuel oil as backup. Ivanpah Solar Power Facility is the largest central receiver type power plant built by Bright Source Energy and Bechtel at California, U.S. in 2013 (Ivanpah 2013).

7.5.2.4 Solar Chimney Power Plant

Solar chimney is referred as up-draft air moving system in which the temperature of air is increased by solar energy which in turn moves up due to density difference. The kinetic energy content of upward hot air can be harnessed by allowing the air movement through a chimney. The solar chimney power plant consists of three important components (a) solar collector, (b) chimney, and (c) wind turbine. A schematic of solar chimney power plant is shown in Fig. 7.13. A tall central chimney is surrounded by a circular solar collector/greenhouse at its base. The solar collector made of a transparent cover supported by a few metres above the ground by a support structure. Solar radiation transmits through the transparent cover, allowing the air underneath it to heat up in the greenhouse. Convection of air sets up due to absorption of solar energy in which the air is drawn up through the central chimney due to natural draft. The transformation of kinetic energy of air results in turning of turbines located circumferentially near the base of the chimney. The hot air is continuously replenished by fresh air drawn in at the periphery of the transparent solar collector. The temperature difference of about 35 °C is created in the air underneath the cover from entry to the center due to greenhouse effect. The air absorbs both beam and diffuse solar radiations. The transparent cover is placed at a slight inclination towards the center. A tall chimney installed at the center
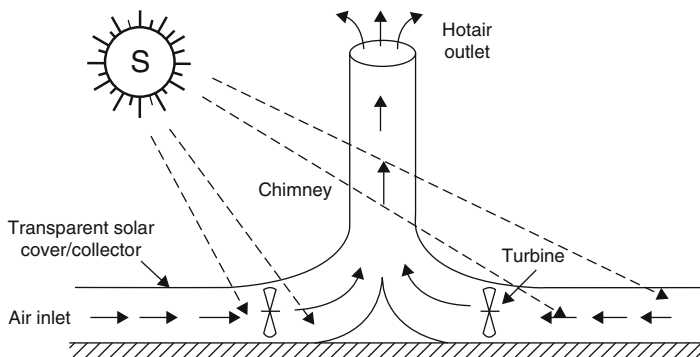
Fig. 7.13 Solar chimney power plant

creates draft due to pressure difference. The greenhouse effect created by the solar collector and draft created by chimney are responsible for the hot air to rise up which in turn develops an air stream of about 15 m/s speed at the entry of wind turbine. This stream can be used to drive horizontal axis wind generator for electricity generation. The solar chimney systems are generally recommended to install in desserts where the sand is a energy storage medium. The energy stored in the sand/soil can be retrieved to operate the plant during the night time or off-sunshine hours. A solar chimney power plant can be designed for a power of 30–100 MW (Schlaich 1994). The first experimental 200 m tall solar chimney plant with 45,000 m^2 solar cover area and 50 kWe capacity was built during 1981–1982 in Manzanares, Spain. The prototype plant was removed after 7 years of experimental period.

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Chapter 8
Solar Photovoltaic Power

8.1 Pollution Free Power Generation

In recent years global warming and associated climate changes have received steadily increasing attention and Greenhouse gas (GHG) pollution control has become an important issue in both industrialised and developing countries. In this regard environmentally benign power generation has been seriously counted upon to bridge the gap between demand and supply of power. Extensive efforts over the past 30 years aimed at research, development, testing and demonstration of several technologies have indicated that principal technologies are solar photovoltaics, solar thermal electric and wind power (Kaushika and Kaushik 2005; Winter et al. 1991). Solar photovoltaics has several positive attributes and scores over other technologies since it does not involve moving parts and there is now a growing optimism that incoming decades solar photovoltaic power supplies will be the solution for the crippling power shortage facing the world. It is now a global sunrise industry growing well over 30 % every year. It is fast becoming a major power resource, increasingly affordable and proving to be more reliable than utilities. Total global production of SPV modules in 1989 was 45 MW. It had increased to 62.5 MW in 1993 and to 1,36,697 MW (according to European Photovoltaic Industry Association (EPIA) data) in 2013. This awareness of PV technology is rising and there is an increasing number of systems beginning to appear as the concern for the need of 'clean' electricity is gaining importance. Some typical current applications of photovoltaic and their estimated share in the PV market are as illustrated in Table 8.1.

Table 8.1 Applications of photovoltaic and their estimated share in the PV market

S. No	Application	Percentage %
1.	Lighting, security and other consumer products	28
2.	Rural electrification	10
3.	Remote refrigeration	1
4.	Electricity for individual buildings	22
5.	Water pumping and irrigation	2.6
6.	Grid connected	1
7.	Communications	20
8.	Remote monitoring equipment	1
9.	Aids to navigation	1
10.	Cathodic protection	4
11.	PV/diesel hybrid generators	8
12.	Military application	0.5
13.	Miscellaneous	2

8.2   Solar Cells

Solar photovoltaic involves the conversion of the sun's radiant energy into electricity using a semiconductor device known as solar cell. The most common material used for solar cells is silicon. Based on the state and quality of the silicon material there are three types of solar cells that have been produced and marketed.

8.2.1   Mono-crystalline Cells

These are made from pure mono-crystalline silicon with almost no defects or impurities. These cells have a solar conversion efficiency of about 15–17 %. They are expensive to produce. The most efficient and expensive single-junction silicon cells have been reported to have about 22 % efficiency.

8.2.2   Polycrystalline Cells

These cells are produced from slightly poorer grades of mono-crystalline silicon or semiconductor grade silicon. The cells have white speckles on the surface due to impurities. They are comparatively less expensive since simpler processes are involved in their production. They have a solar conversion efficiency of about 10–12 %.

8.2.3   Amorphous Silicon Cells/Thin Film Cells

These are often referred to as second generation solar cells and are made from amorphous silicon rather than silicon of crystal structure. They absorb light more effectively than crystalline cells and can, therefore, be thinner. Thin film technology has been successfully used on rigid, flexible, curved and foldable substrates. Thin film cells of other materials such as cadmium telluride (CdTe) and Copper Indium Gallium Diselenide (CIGS) have also been fabricated and tested. They have a lower cost than crystalline cells but have a lower conversion efficiency of 5–7 %. However, the reduced cost often overweighs the reduced efficiency, leading to a net increase in ratio of performance to cost.

More recent developments in solar cells physics include third generation solar cells which combine in themselves the advantages of the first generation and second generation devices. The proposed and tested cells include nano crystal solar cells, photoelectrochemical cells, polymer solar cells, dye sensitised solar cells and fourth generation solar cells such as hybrid inorganic cells with polymer matrix.

8.3   Solar Pv Modules and Arrays

Solar cell is the smallest unit of a solar PV system (Fig. 8.1). A typical crystalline silicon solar cell manufactured in India produces about 1Wp at 0.5 Volts and 2.3 Amp. Under full sun at Standard Test Conditions (STC) of 1000 W/m^2 and 25 °C cell temperature.
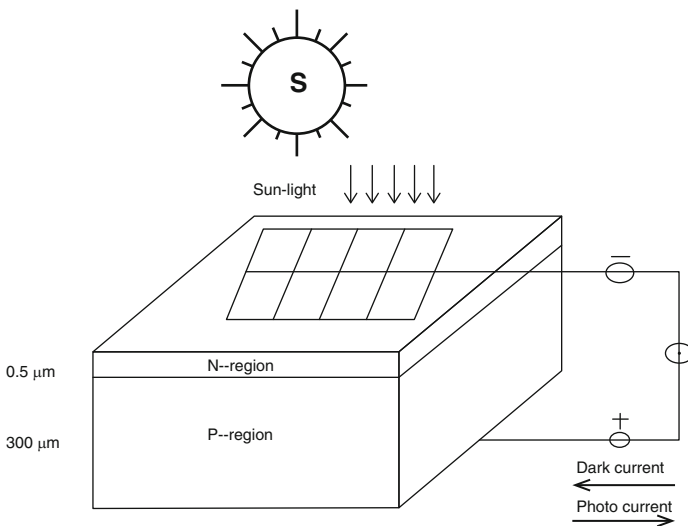
Fig. 8.1 Solar PV system

In a solar PV power unit, solar cells are connected in series to obtain the desired voltage and in parallel to obtain the desired current. A string of solar cells connected in a series arrangement is referred to as a series string or a sub-string. A group of series string or sub-strings connected in parallel forms an array. The array is constructed in the field and transported from the factory in the form of small units called modules. The modules can be used to construct mW to MW size PV arrays. The number of cells determines a module's size and power. Modules are typically available in ratings from 30 Wp to 300 Wp. Two basic types of PV modules are commercially available today:

(i) Those made from poly/single crystalline silicon and crystalline silicon, are presently the dominant (90 %) commercial product and deliver approximately 100–130 W/m^2 at STC.

(ii) Those made from amorphous silicon (A-Si). These are thin-film modules, and are beginning to enter the market. They require less material to produce than the thick crystalline products and so can be made inexpensively. Today's commercial A-Si modules deliver 40–50 W/m^2 under full sun at STC. The modules are connected electrically in series and parallel and mounted on structural support for exposure to sun to build arrays. Owing to cost considerations the fixed tilt arrays are often used.

Several options are possible for the mounting of module/array as follows:

(a) It may be placed at a fixed tilt angle to maximize the generation of yearly average energy.

(b) The tilt may be seasonally adjusted in accordance with the energy requirement in summer, equinoxes and winter respectively.

(c) The module/array may be mounted on a tracking unit that follows the sun. Single axis trackers follow the sun daily from east to west and two axis trackers further include elevation control to correct for seasonal north–south sun movement.

8.4 Balance of System

The array is the energy generating subsystem. It's output is variable direct current (DC) which is not available during off sunshine hours. It is stored in batteries if the power is to be supplied on continuous basis. The battery bank serves the load either directly or after conversion into alternating current (AC). The battery power produced tends to be at a low voltage (12 V) and, since general applications require 240 V, an inverter is needed to convert DC into AC. The charge controller is yet another component of PV systems. It protects batteries from excessive charge when the array produces more electricity than the batteries can store. Also, it prevents deep discharge of batteries. Sometimes, during over-charging, gassing from the acid of a battery may take place which in turn may become a fire hazard. Maximum power point tracker (MPPT) is also an important component to ensure maximum
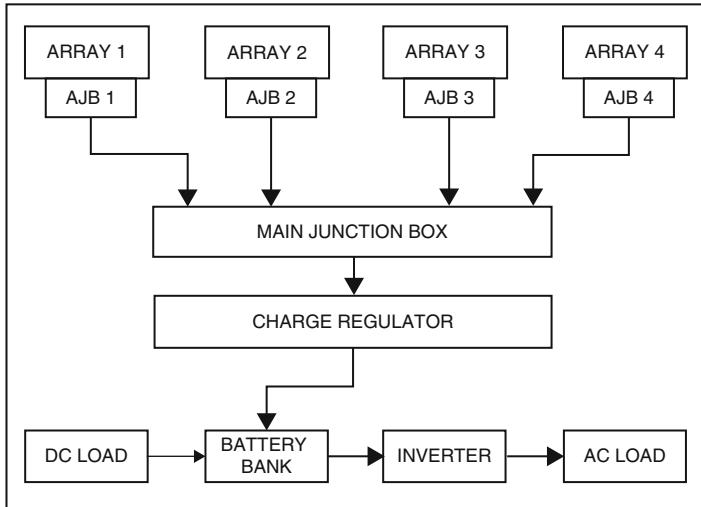
Fig. 8.2 Schematic diagram of a photovoltaic power supply system

power transfer from array to the battery bank. The photovoltaic system, in practice, therefore requires several other components in addition to the PV modules. Often called the balance of system, it includes system wiring, support structures, inverters, batteries, charge regulators, string combiners, lightning protection, over current protection, disconnect switches, and ground-fault protection. The components of the balance of systems may be classified in three categories.

(a) **Mechanical:** Panel structures, battery racks, poles, cables etc. designed to withstand wind-loading and adverse weather conditions.
(b) **Electrical:** Master control panel, circuit breakers, switchgear, connectors, cables, lightning arrestor, earthing for safety.
(c) **Electronics:** DC-AC inverter, DC-DC converter, power conditioner, charge controller, timer, load switching, monitoring, data-logging etc. control and management etc.

Schematic diagram of a photovoltaic power supply is shown in Fig. 8.2.

8.5 Systems and Applications

Solar PV plants are basically decentralised power units. They have several major differences with fossil fuel based power plants as shown in Table 8.2. Extensive efforts over the past 25 years aimed at testing and demonstration of solar photovoltaic technologies have been made throughout the world. SPV power system have been operated in various modes which can be classified into following three categories (Fig. 8.3).

Table 8.2 Major differences between SPV power plant and fossil fuel-based power plant

S. no	Item	Power plant configuration	
		Solar PV	Fossil fuel based
1.	Operation	Decentralised	Centralised
2.	Dependency on external fuel source	Very low	Completely
3.	Design	Load specific	Capacity-specific
4.	Suitability	Lower capacity	higher capacity
5.	Gestation period	Short	Long
6.	Transmission losses	Low	High
7.	O&M costs	Low	High
8.	Capital costs	High	Low
9.	Running costs	Low	High
10.	Environmental pollution	None	Adds gaseous and particulate toxins which causes pollution and ecological imbalance

(i) *Stand alone system:* The entire power is generated by an SPV array and stored in a battery to be provided in response to demand.
(ii) *Hybrid system:* In addition to an SPV array, other means such as AC mains, wind and diesel generators are also used to supply power.
(iii) *Grid-connected system:* In such systems the output of SPV plants is connected to the grid and there is no storage battery; Metering is used to keep account of imported and exported power by the user.

8.5.1   SPV System Design Considerations

Solar PV power system is designed in accordance with the load in distinction to the conventional power system which is designed in accordance with its capacity. The design involves the sizing of the array and battery bank to serve a given load. The array needs the use of an optimum load offered by the battery into which it can deliver maximum power. This requirement varies with insolation and solar cell temperature in a module as well as with the state of charge of the battery. This requirement is difficult to be realized in all field conditions and the resultant mismatch offers problem in optimum sizing of system components. A rationale for optimum utilization of variable solar radiation in terms of diurnal and seasonal variations is that the stand alone solar photovoltaic system should be sized in such a way that it can deliver power to the load without failure during diurnal and seasonal variations of solar irradiance. An undersized array will cause total discharge of the battery
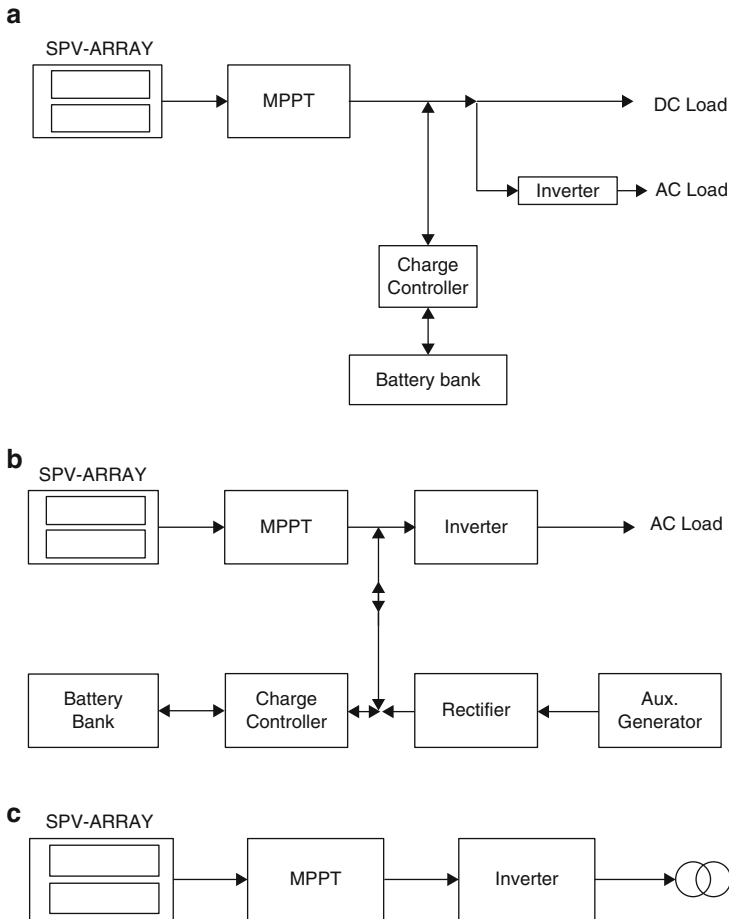
Fig. 8.3 Classification of solar PV power systems (**a**) Stand alone PV System (**b**) Hybrid PV System (**c**) Grid-connected PV System

and an oversized array involves waste of capital. The idea of solar PV system is therefore to have a reasonable size of the array and battery bank to meet the demand of particular load round the cycle allowing the battery to be discharged upto a minimum acceptable level during low/off sunshine period (Bandyopadhyay et al. 1995).

The array size in terms of peak array of current of (A) at 1 kW/m^2 is calculated from the following relationship

$$A_p = \frac{L_d}{R_d K} \tag{8.1}$$

where L_d is average daily load in Ah. R_d is the average daily radiation in kWh/m^2 in low/off sunshine period during which the soc of the battery is ensured to remain greater than 50 %; where K is battery efficiency.

8.5.2 SPV Plant Operating Experiences

Several demonstrations units of large size (upto 500 MW) SPV power plants have been operated around the world. These units are located mainly in USA, Europe, India and China. In USA both the utility industry and the government have participated in detailed performance evaluation of grid connected SPV power plants. Utility interest in SPV has grown steadily since the early 1980s; SPV has now received their greatest attention among all the renewable energy and power technologies. Extensive reviews of these experiences have been reported. The largest Solar Park built in India is on a 2000-ha plot of land near Charanka village in Patan district, Gujarat with a total installed capacity of 214 MW. As of 31 August 2015, the installed grid connected solar power capacity in India is 4230 MW (Ministry of New and Renewable Energy Annual Report 2014-15). Monitoring of these power plants is in progress for further development. The total number of SPV power systems in India are tabulated as below (Table 8.3).

Experience has proved that SPV technology and associated power conditioning equipments are technically viable. Specific global experiences may be outlined as follows (Winter et al. 1991).

Array Ratings Manufacturer-supplied DC power ratings were universally higher than those observed in field conditions even when the operating conditions were close to standard test conditions.

Array Efficiency In earlier power plants at Lugo or Phoenix the temperature induced decrease in efficiency was observed at higher insolation levels. However, the array operating efficiencies in subsequent plants were observed to be higher at insolation levels above 600 W/m^2. In crystalline cell modules the efficiency degraded with time at a rate less than 1 % per year.

Array Reliability An important fault which often results in the failure of SPV modules is known as 'hot-spot effect'; it is an excessive heating of the cell and may be caused by following factors:

 (i) Initial Mismatch of photovoltaic cell characteristics
(ii) Stress induced by environment or otherwise

Table 8.3 SPV power systems in India

Item	Number of installations
Solar lanterns	9,10,504
Water pumps	7771
Domestic lights	8,61,654

(*Source:* Press Information Bureau, MNRE 2012)

8.6   Building Integrated Photovoltaics (Bipv)

The cost of solar photovoltaic electricity has gradually decreased during the past decade from Rs. 25 per kWh to Rs. 15 per kWh in 2013. This decline in cost significantly owes to distributed PV systems on buildings which is an attractive application to compete commercially with the utility grid. In particular SPV could be a preferred power source for buildings in remote areas not served by the utility grid. The PV systems on buildings do not involve the cost of land required for ground-mounted systems, as well as the cost of site development, foundations, structural support systems, underground electrical distribution and the utility connection. In practice, PV modules often become an integral part of the building, serving as the exterior weathering skin of improved aesthetics. The building should provide sufficient solar exposure area to array and support structures and the building's utility service should become the consumer of PV electricity. The resultant systems are known as building-integrated PV systems (BIPV). The effectiveness in electricity generation of BIPV systems depends on several variables as follows:

(a) Location of building.
(b) Orientation of BIPV with respect to sun. For example in northern hemisphere a south-facing façade will collect the maximum solar energy throughout the year and produce the maximum electricity.
(c) Tilting solar panels towards the sun can increase the levels of solar irradiance on the array surface and therefore cause an increase in electricity output. The appropriate angle of inclination will depend upon the latitude of the proposed site.

These parameters can be easily optimized in the design of a building as shown in Fig. 8.4. The inclination of the roof of a building or a wall may be chosen to maximize electricity production.

Photovoltaic systems for building can be either stand-alone hybrid or grid-connected. In a stand-alone system, the building has no connection to the utility
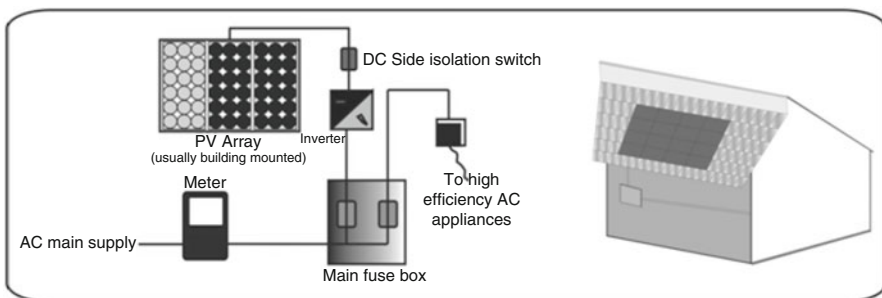
Fig. 8.4 Schematic of a building integrated photovoltaic system. (*Courtesy:* www.solarcentury.co.uk)

grid and often relies on a bank of batteries to store power for supply at night and during limited sun shine periods. In India, hybrid systems have been considered to avoid excessive cost of solar panels and the battery bank. In a grid connected or utility-interactive (UI) system, the building receives electricity from both the PV array and the utility grid. Some PV systems based on both stand-alone and utility-interactive modes of operation have also been reported.

Owing to various above mentioned advantages, and continued cost reductions, the potential for PV-powered buildings have escalated. In a best-case scenario, Arthur D.Little, Inc., has projected that the annual U.S. market for PV on buildings could exceed $2.5 billion in the next 10 years.

8.6.1 BIPV as Glazing Material

BIPV means that the solar features become part of the building. Initially, building cladding with solar photovoltaic panels was carried out as a retrofit. The PV modules were manufactured with aluminium frames. These modules were designed for grouping on racks placed on or around buildings or on the ground, to provide a reduction of building electrical load. The installation was often carried out in the post-construction phase of the building. This type of installation posed problems in building maintenance. In some cases PV installation had to be removed. In recent years the demand for solar PV modules as building elements has been recognized; the modules that become part of the weather proof skin of a building and can mimic windows or skylights or become part of the actual roofing material. In this approach, an array takes over the normal function of the roof and is not just placed on top of an existing structure. It serves both as a room covering and as an electricity-producing device. Based on this concept several BIPV demonstration units have been set up at a number of global locations. It has been experienced that the PV cell patterns can create interesting effects for instance in corridors, where you can experience the patterns in motion, as you pass by. Similarly, window-integrated photovoltaics' patterns can sometimes be architectural attachments. Hundreds of projects in Europe, USA and Asia are the glaring examples.

8.6.2 BIPV Projects in India

Several BIPV projects have been commissioned in India, the most notable of which are as follows:

(a) A 10 kWp PV Gasifier Hybrid Power Plant for the residential training facility at the Energy and Resources Institute (TERI), Delhi, and ten (type PL-11) stand-alone dusk to-dawn street lights.

(b) A building -integrated solar PV system plant at Mamata Machinery, Hyderabad.

(c) A 36.3 kWp hybrid PV power plant at Matrimandir, Auroville, Pondicherry.

In India, BIPV systems have used three types of modules:

(i) Solar PV modules,

(ii) Solar PV metal roofing modules and

(iii) Dummy modules.

The salient feature of dummy modules is that they have no solar cells. Instead of cells, the backing Tedlar is screen printed with solar cell images so that they look similar to actual solar cells.

The research and development activities in the field of building-integrated photovoltaic systems are concentrated on the development of constituent products in three principal areas: (i) integral roof modules, (ii) roofing tiles and shingles, and (iii) integral modules for vertical facades and sloped glazing.

8.6.3 Environmental Aspects

Solar photovoltaic systems in general, and building integrated photovoltaic systems in particular, offer a number of environmental benefits and hazards as listed below:

(i) Cutting edge design and technology that offsets the cost of traditional building materials.

(ii) Operation is noiseless.

(iii) No transportable fuels required.

(iv) No moving parts involved. The system requires minimum maintenance during its life span of 20 years.

(v) Clean Development Mechanism (CDM) benefits. For example 1kWp of solar cells displaces 1000 kg of carbon dioxide.

(vi) Decentralized generation at the point of use. Thus avoiding transmission and distribution cost.

8.7 Concentrating Solar Photovoltaic

Third generation SPV systems are characterized mainly by the fact that they offer substantial improvement in the efficiency of solar conversion or a large reduction in their cost of production as compared to previous generation of system. For cost reduction, concentrating module is an important approach to overcome the problem
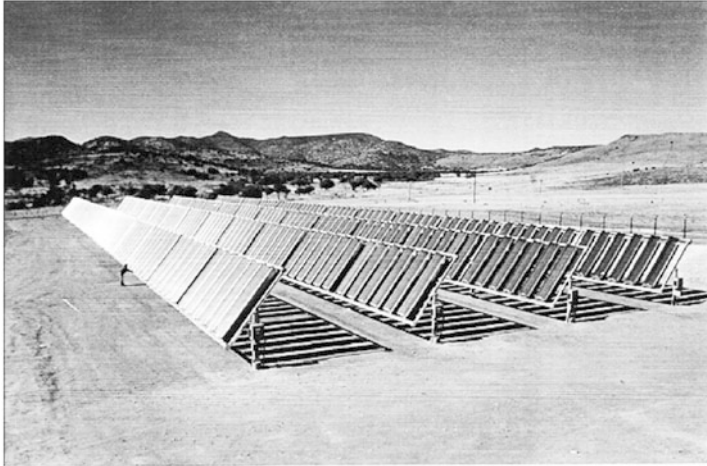
Fig. 8.5 Solar concentrating PV array (*Courtesy:* ENTECH-USA)

of high cost of solar cell. The low-cost optical concentrator focuses solar radiation onto the cell array of area much smaller than the concentrator aperture (Fig. 8.5).

The concentration of radiation also leads to an increase in photon generation current and hence cell efficiencies. The operation of solar cells under high illumination requires the removal of heat from the cells to combat the drop (0.45 % of power per degree Kelvin) in efficiencies of cells. The outstanding problems of this technology are the development of:

 (i) Efficient low cost concentrators
 (ii) Cost-effective tracking systems
(iii) Concentrator cells
(iv) Efficient low cost heat sink

Furthermore, research on photovoltaic devices based on organic materials has received serious attention. Organic solar cells based on heterojunction and nanocrystalline dye sensitized interface have been considered (Mikroyannidis et al. 2009). The solar conversion efficiency achieved to this date in 12 % and it may be improved to 22 % through optimisation of parameter. It is inexpensive to produce these cells. In the category of ultra high efficiency solar cells, nanostructured solar cells have been reported which include several advanced concepts of quantum dot solar cells (Nozik 2001). Quantum dot is a special type of nanocrystal. It enables several advanced concepts of Solar Cell design to be implemented which includes intermediate band and multiple exiton devices, hot carrier and up/down conversion devices etc. In these devices the ultimate conversion efficiency at one sun intensity can increase to about 66 %.

8.8   System Reliability

Solar PV system reliability means the ability of the system to serve the variable load and to continue functioning without failure. In this regard the study of factors related to array operational faults and electrical mismatches resulting from environmental stresses and shadow problems are of most concern. For example, in the field solar cell arrays are subject to shadows from both predictable sources as well as from such unpredictable sources as bird droppings or fallen leaves. The percentage power loss is much greater than the percentage of array area which is shadowed; for smaller arrays with few or no parallel connections, one leaf could cause the system output to drop to a fraction of rated power, eventually resulting in system failure. There could also occur a partial; or full opening of a string due to cell cracking provoked by hail impact or other environmental stresses. The shadowed/cracked cells in series with illuminated cells block the current flow in entire series connection and tend to become reverse biased. This not only gives rise to a mismatch loss but also could result in excessive heating of the regions of power dissipation which in turn can lead to solder melting and damage the encapsulant. The region of excessive heating are referred to as hot spots. The hot spots may also be developed in concentrating solar PV systems wherein reflecting or refracting optical concentrator nonuniformly illuminates the costly solar cell arrays. It may sometimes offset the gain due to concentrating configurations (Winter et al. 1991).

In practical situations, the above faults exhibit themselves with varying degree of complexities and influence the system reliability. The strategies to increase the fault tolerance and improve the reliability of the array have been investigated amongst others by Kaushika and Kaushik (2005). Fault tolerance by redundancy at subsystem level is found to be cost-intensive and is not considered as an attractive option. Fault tolerance at component level by proper arrangement of cell interconnections will function as an active redundancy and hold promise of cost effectiveness. In this regard several configurations such as series-parallel configuration, series-parallel with bypass diode, bridge-linked configuration and total cross-ties configuration have been considered. Kaushika and Rai (2007) have carried out experimental and theoretical investigations on performance and trade-off characteristics of these configurations and have shown that total cross-ties and bride-linked configuration excel over others in the minimization of mismatch loses in the cell network. However the total cross-ties configuration which is the highest cell interconnection redundancy performs slightly better than the BL array under mismatch and shadowing conditions, but under short circuit conditions it is inferior to BL array.

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Chapter 9
Biomass Energy and Power Systems

9.1 Importance

Biomass is one of the renewable energy resources and it is referred as a carbon neutral energy source. The biomass is obtained from living biological materials such as organic matter of plant and plant derived material and animal origin. The biomass essentially consists of hemi cellulose, cellulose and lignin. The organic components of municipal and industrial wastes are also referred as renewable energy resources for energy conversion. It is one of the few energy resources, whose supply is continuous and it does not significantly depend on weather conditions. The biomass can be stored for use on demand for higher reliability. Role of biomass in developing countries as energy supplier is particularly important and it is estimated that in India it accounts for major fraction of country's primary energy supply. The large size of biomass resource is comparable in magnitude to other fossil fuel resources and its renewable nature ensures a continuing place of prominence in future energy supplies. Biomass is manifestation of solar energy and it results from the solar bioconversion process. At the base of solar bioconversion is the process of photosynthesis wherein the carbohydrate $(CH_2O)_n$, a principal constituent of plant is produced with the help of chlorophyll. A typical photosynthetic conversion is given as:

$$CO_2 \ + \ 2H_2O \ + \ sunlight \rightarrow (CH_2O)_n \ + \ H_2O \ + \ O_2 \qquad (9.1)$$
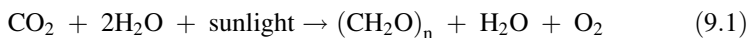
A few sources of biomass include crop and forestry residues, energy crops, sewage sludge, Municipal Solid Waste (MSW), animal dung, and industrial wastes. Various waste to energy technologies have reached to the maturity and are now available for converting biomass into fuels (refused derived fuels, biodiesel and biogas etc.) with subsequent electrical or thermal energy conversion. If biomass energy source is appropriately managed and harnessed, it can become a sustainable energy source and can contribute to displace the consumption of fossil and nuclear

fuels. Apart from its economic viability, biomass as a source of energy also has environmental benefits because of its simultaneous growth and rise in combustion leads to lower (or zero) emissions of greenhouse gases. It also emits lesser amounts of noxious pollutants, e.g. sulphur compounds and particulate on combustion. In this chapter, an attempt has been made to explore biomass energy conversion technologies.

9.2   Biomass Spectrum

The fuel wood accounts for about 6–8 % of total world energy consumption. This energy is used in developing countries where most of the population lives in rural areas and consume energy essentially in domestic sector. In Africa, 60 % of total energy in use is fuel wood and in rural India it accounts for about 70 % of total energy consumption.

Biomass spectrum includes wood, garbage, crops, landfill, alcohol fuels and is shown in Fig. 9.1. The biomass is available in various forms such as (a) crop residues (hay, rice husk, straw), (b) forest residues (barks, branches, twigs, leaves and wood), (c) plantation residues (coconut and cardamom, coffee and tea), (d) animal waste (animal dung, poultry droppings), (e) industrial waste (bagasse, wood chips and sawdust), (f) municipal solid waste and (g) aquatic biomass and sanitary waste (Brown 2003). The biomass can be converted into energy in its natural form (mass burn) or processed/compacted form (RDF, briquettes or pellets).
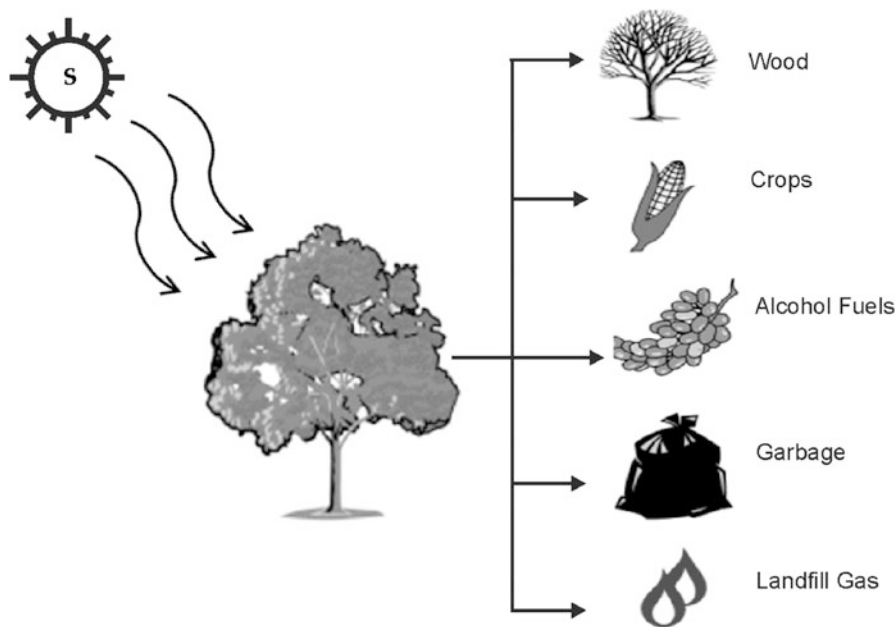
Fig. 9.1 Biomass energy sources

Biomass can be broadly classified into woody biomass and powdery biomass. Woody biomass is the one whose average density is larger than about 200 kg/m^3 and ash content is maximum upto 2 %. Firewood, cotton stalk, corn cobs etc. fall under woody biomass. In practical terminology, firewoods also include several agricultural wastes. Powdery biomass is in loose form and its density is identified as powdery. The density is as low as 50–150 kg/m^3 but the ash content is relatively higher about 20 %. Agricultural residues like sawdust, rice husk, straw, bagasse, sugarcane trash, groundnut shell etc. fall in powder biomass category. The advantage of the powdery biomass is that easy densification for obtaining higher calorific value fuels is possible.

9.3   Fuels from Biomass

Biomass often requires its conversion into suitable energy forms in terms of solid, liquid and gaseous fuels with the help of physical, chemical or biological processes. Biomass energy can be produced by burning it directly (mass burn) or be converted to intermediate solid, liquid or gaseous fuels. The biomass energy conversion processes may be classified as (a) Thermo-chemical conversion of biomass, (b) -Physico-chemical conversion of biomass, (c) Biological conversion of biomass. Table 9.1 summarizes these conversion processes corresponding to the usable fuel, end-use product and technology status.

9.3.1   Thermo-Chemical Conversion

Thermochemical conversion processes essentially consist of three processes, viz. (i) Combustion, (ii) Gasification, and (iii) Pyrolysis.

Table 9.1   Biomass power generation

Process		Usable Product	End-use
Thermo-chemical	Combustion	Heat	Process heat and electricity
	Gasification	Producer gas	Process heat, Power generation and liquid/gaseous bio fuels
	Pyrolysis	Fuels (oil, gas, char)	Process heat and power generation
Physio-chemical	Esterification	Liquid fuels (biodiesel)	Process heat, power generation and transport fuel
Biological	Hydrolysis and fermentation	Liquid fuels (ethanol)	Transport fuel
	Anaerobic digestion	Biogas and fertilizer	Process heat, power generation, transport fuel, and fertilizer

9.3.1.1 Combustion

Biomass is burnt in boilers to generate heat which in turn is used to produce electricity or combined heat and power. The biomass based boilers can be used for combustion of various biomass fuels. The grate fired or stoker fired boilers, pile burners, suspension fired boilers and fluidized bed boilers are most popularly used for biomass combustion. The simplest biomass based combustion system is a household *chulha*. Common types of biomass used in these systems include wood, dried animal dung cakes, dried leaves, coconut shells and rice husk. The grate fired biomass boilers are used for small and medium scale process heat and power generation whereas the fluidised bed boilers are used for large-scale country heating and power generation. The most traditional stoves and boilers show poor efficiency and high emissions. The efficiency of these can be improved by decreasing heat losses using enclosed stoves and introducing secondary combustion of unburned flue gases. The state-of-the-art biomass boilers and stoves are extremely efficient and attain clean burning.

9.3.1.2 Gasification

Gasification is the conversion of solid biomass into gaseous fuel/producer gas $(CO + H_2 + N_2)$ using partial oxidation at high temperature. The gasification is a quite complex thermo chemical process, it involves the conversion of solid biomass mainly into CO. The process can be accomplished in an air tight closed chamber under suction or low pressure relative to ambient pressure. Producer gas is the mixture of combustible and non-combustible gases with calorific value ranging from 4.5 to 6 MJ/m^3. The quantity of gaseous constituents of producer gas depends upon the type of biomass and operating condition.

Depending upon the efficiency of gasification process, the calorific value of the gas varies from 10 to 50 % of calorific value of natural gases. The producer gas can be used to generate steam by direct firing in boilers with appropriate cleaning mechanism, which subsequently used for producing electricity in a thermal power plant. Alternatively, the product gas can be processed further through reformation process to produce methanol and hydrogen. The gasification of biomass is more efficient than combustion process. The gasification can also be used to produce large-scale process heat and power.

The biomass gasification process involves essentially four processes viz. drying, pyrolysis, oxidation and reduction. In general, the biomass fuels consists of 5–35 % moisture. The moisture in the biomass is removed at above 100 °C by converting it into steam in drying process. Pyrolysis is the anerobic thermal decomposition of biomass fuel and it involves three kinds of products: gas, liquid, and solid. The products then undergoes oxidation process at about 700–2000 °C by introducing air in the oxidation zone. Besides oxygen and water vapour, inert gases such as nitrogen and argon are produced. In the oxidation zone, a heterogeneous reaction

takes place between oxygen/air and solid carbonized biomass fuel to produce CO. In this reaction 12.01 kg of carbon is completely oxidized with 22.39 m^3 of oxygen supplied by air blast to yield 22.26 m^3 of CO and about 0.04 GJ of heat. Hydrogen in fuel reacts with oxygen in the air blast, producing steam.

A number of high temperature chemical reactions take place in the absence of oxygen in reduction zone. The reduction zone, principal reactions involved are Boudouard, water-gas, water-shift and methane production reactions and they require heat therefore the temperature of the gas goes down during this stage. Under complete gasification condition, all the carbon is combusted or reduced to CO and vaporization of combustible gas and mineral matter leaving out ash and some char.

Several gasification designs are now available for conversion of biomass. The configurations of biomass gasifiers are dependent on wide range of parameters such as (a) design of gasifier (fixed bed, fluidized bed, entrained bed and twin bed), (b) operating pressure (atmospheric, pressurized), (c) heat for gasification (autothermal or direct, allothermal or indirect) and (d) gasification agents (air-blown, oxygen, and steam). The broad classification of biomass gasifiers based on operation is given as (i) updraft gasifier, (ii) downdraft gasifier, (iii) twin-fire gasifier, and (iv) cross draft gasifier.

(i) *Updraft gasifier:* An updraft gasifier also called as counter-current gasifier has clearly defined four zones of partial combustion, reduction, pyrolysis and drying. The schematic of updraft biomasss gasifier is shown in Fig. 9.2. The

Fig. 9.2 Updraft biomass gasifier
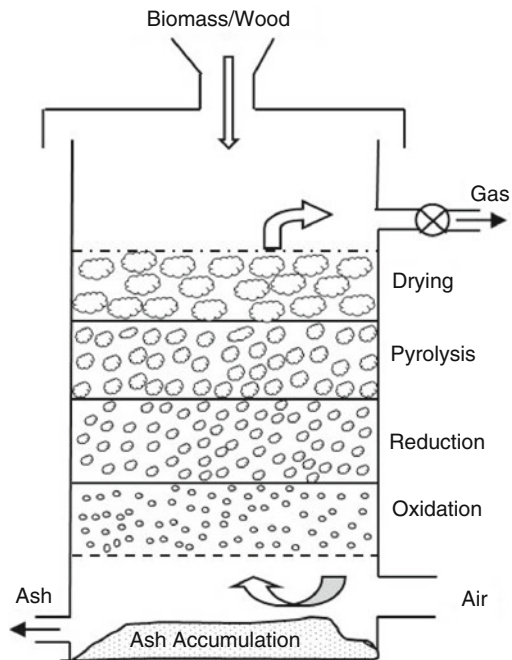
woody biomass pieces are fed from the top of the gasifier. Air is introduced at the bottom and flows upwards against the fuel movement. The producer gas is drawn at the top of the gasifier. The updraft gasifier achieves the highest efficiency as the hot gas passes through fuel bed and leaves the gasifier at low temperature. The sensible heat of gas is used to preheat and dry the biomass. The limitations of updraft gasifier are excessive amount of tar in raw gas and poor loading capability. In the updraft gasifier, producer gas leaves the gasifier with high tar content, which may seriously affect the operation of internal combustion engines. Therefore, the gas is not suitable for running IC engines directly. Cleaning of the gas is required for energy conversion.

(ii) *Downdraft gasifier:* In this type of gasifier, the producer gas is drawn out at the bottom whereas both biomass pieces and air are introduced at a higher level, which flows downwards through the biomass bed. The downdraft gasifier is also called as co-current gasifier and the working principle is illustrated in Fig. 9.3. The gasifier attains relatively lower efficiency and difficulties in handling higher moisture content biomass. Ash content biomass is another common problem in small downdraft gasifiers. The time needed to ignite and bring the gasifier to working temperature with good quality gas is less as compared to updraft gasifier. The tar problem in the gasifier is less in downdraft gasifier. This gasifier is preferred for running internal combustion engines than updraft gasifier.

Fig. 9.3 Downdraft biomass gasifier
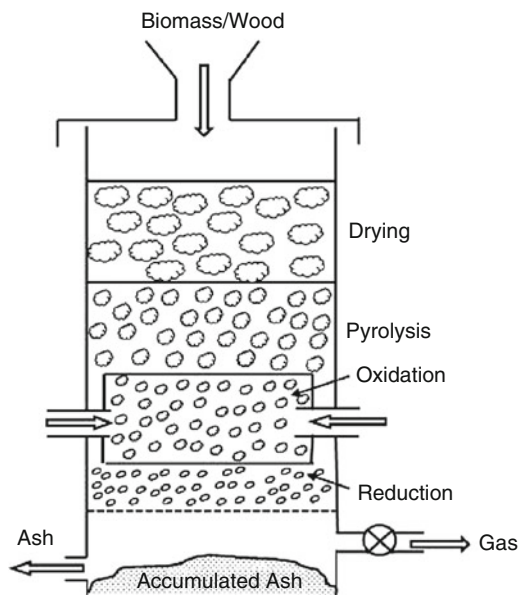
Fig. 9.4 Twin fire gasifier
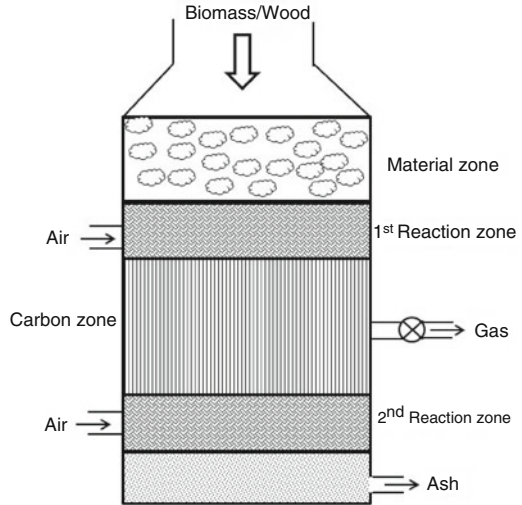
(iii) *Twin-fire gasifier:* The twin-fire gasifier consists of a well-defined carbon zone between two reaction zones (Fig. 9.4). The advantages of co-current and counter-current gasifiers are combined in twin-fire gasifier. Drying, low temperature carbonization and cracking of gases occur in the upper zone, while permanent gasification of charcoal takes place in the lower zone. The gas temperature ranges between 460 °C and 520 °C. Twin-fire gasifier produces fairly clean gas. The disadvantages such as high exit gas temperature, poor CO_2 reduction and high gas velocity are the consequences of the design. It is very difficult to use high ash fuels in this type of gasifier. The twin-fire gasifier design characteristics limit operation to low ash fuels such as woody biomass, coke, and charcoal.

(iv) *Cross draft gasifier:* The schematic of cross draft gasifier is shown in Fig. 9.5. The ashbin, fire and reduction zones in cross draft gasifier are distinguished in separate regions. Cross draft gasifier operates well on dry air blast and dry fuel. The load following ability of cross draft gasifier is quite good due to concentrated partial zones which operates at temperatures up to 2000 °C. The start up time is about 5–10 min and it is much faster than the other gasifiers. Cross-draft gasifier operates well on dry air blast and dry fuel. Although cross draft gasifiers have certain advantages over updraft and downdraft gasifiers, they are not very popular. The relatively higher temperature in cross draft gasifier has significant effect on the composition of the gas (high CO, low H_2 and CH_4) when dry biomass is used. The limitations of cross-draft gasifier include: high exit gas temperature, poor CO_2 reduction and high gas velocity.

Fig. 9.5 Cross draft gasifier
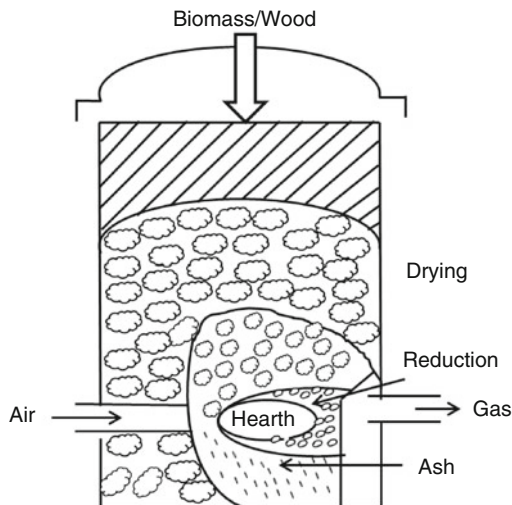
9.3.1.3 Pyrolysis

Pyrolysis is a process in which biomass is heated or partially combusted in the absence of oxygen. Typical pyrolysis of biomass is shown in Fig. 9.6. Volatile components of biomass feedstock are vapourized at high temperature, and produces gases whose vapours are condensed into liquids by liquefaction leaving solid residue char and ash. The liquid fuel can be stored and later used for various process heat applications and electricity generation. In pyrolysis process, in addition to liquid fuels, other fuels such as charcoal, producer gas and many value added chemicals are also produced. Simple pyrolysis systems are operated below 600 °C, but at higher temperatures of 600–1000 °C these systems need more sophistication, which also produce more hydrogen in the gas. In pyrolysis process, four distillation processes are involved below 600 °C. The sequence of these processes at different temperatures is listed as: (a) the input biomass dries at a temperature of 100–120 °C with moisture passing up through the bed, (b) the output gases are mainly N_2, CO, and CO_2, acetic acid and methanol distilled off at 275 °C, (c) exothermic reactions occur at temperatures ranging 280 °C to 350 °C, which drive off complex mixtures of chemicals (Ketons, aldelydes, phenols, esters) CO_2, CO, CH_4, C_2H_6, and H_2 and (d) all volatiles are driven off at 350 °C, with higher proportions of H_2 formed along with CO and Carbon remains in the form of Charcoal as residues. The condensed liquids, called tars and pyroligneous acid, may be separated. The approximate yield of various products from pyrolysis of 100 kg dry wood consists of: 30 kg of charcoal, 14 m^3 of gas (CV of 10.4 MJ/m^3), 7.6 l of wood oil and light tar, 1.4 l of methyl alcohol, 3 kg of pitch, 5.3 l of acetic acid, 0.8 l of esters etc.
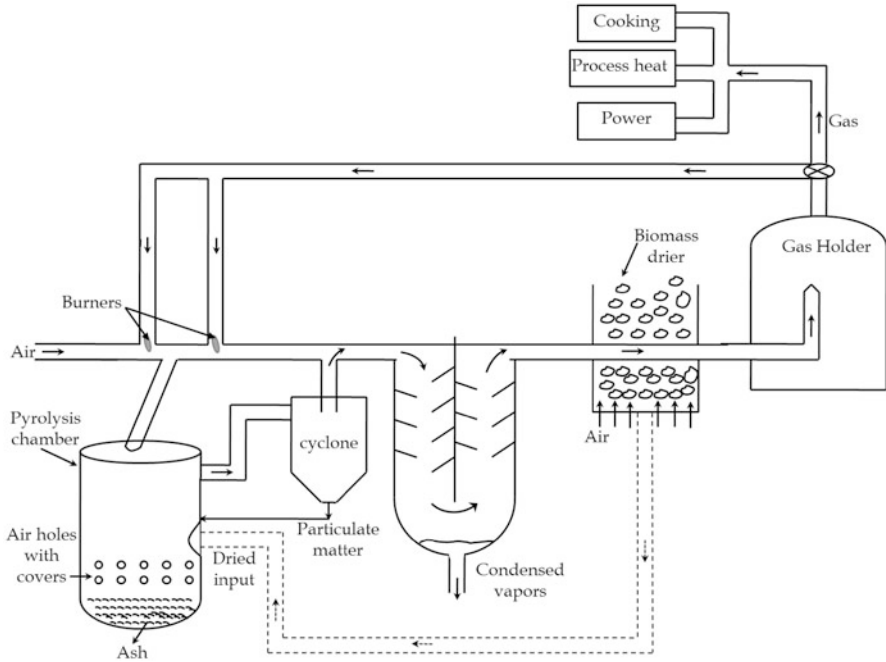
Fig. 9.6 Pyrolysis (destructive distillation) of biomass

9.3.2   *Physico-Chemical Conversion*

Biomass fuels are considered as low density fuels and are cost intensive to transport to the place of their use. They may be converted into high density fuels by the process of pressing and extraction. The oil is extracted directly by pressing biomass (e.g. seeds). The fats and oils required for esterification can be obtained by extraction or passing of seeds. The extracted vegetable oils are composed of triglycerides. Vegetable oil is not particularly a good fuel. Transesterification is the process of converting triglycerides to clean-burning methyl or ethyl esters. The triglycerides are esters formed by the reactions of three free fatty acids, glycerol, and the trihydric alcohol. In a transestrefication process, ethyl or methyl alcohol in presence of a catalyst (NaOH/KOH) converts fatty acids (Biomass) into methyl or ethyl esters (Biodiesel): Biomass $+$ ethanol $\rightarrow$ Biodiesel $+$ Glycerol,   Glycerol $+$ Steam $\rightarrow$ Hydrogen. Hydrogen on combustion gives water and hence is considered as a very clean fuel with high calorific value. The process of pressing and extraction of seeds to produce fuel grade esters is shown in Fig. 9.7. The seeds (edible/nonedible) from various plants are crushed in oil press to extract oil and cake as a byproduct. The extracted raw oil is then transestrified in a reactor. Glycerin is separated in a phase separator to get ethyl ester. Ethyl esters are then passed through water percolators to form fuel grade ester.
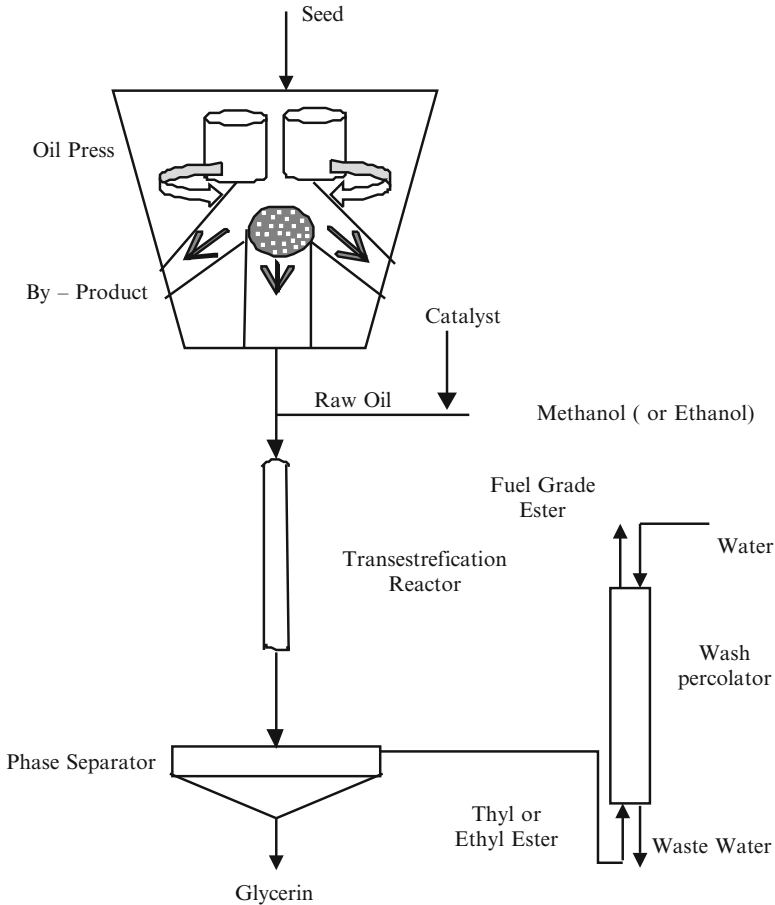
Fig. 9.7 Physio-chemical conversion of biomass

9.3.3 Biological Conversion

The biological conversion processes of biomass may be classified as:
(a) Fermentation, and (b) Anaerobic digestion.

9.3.3.1 Fermentation of Biomass

Liquid biofuels mostly alcohols can be produced from the starch content of
biomass to sugar through hydrolysis and fermentation of sugar processes. The
complex carbohydrate polymers of biomass such as cellulose, hemicellulose and
lignin are converted into sugars in hydrolysis process. Hydrolysis is of three types
such as concentrated acid hydrolysis, diluted acid hydrolysis and enzymatic
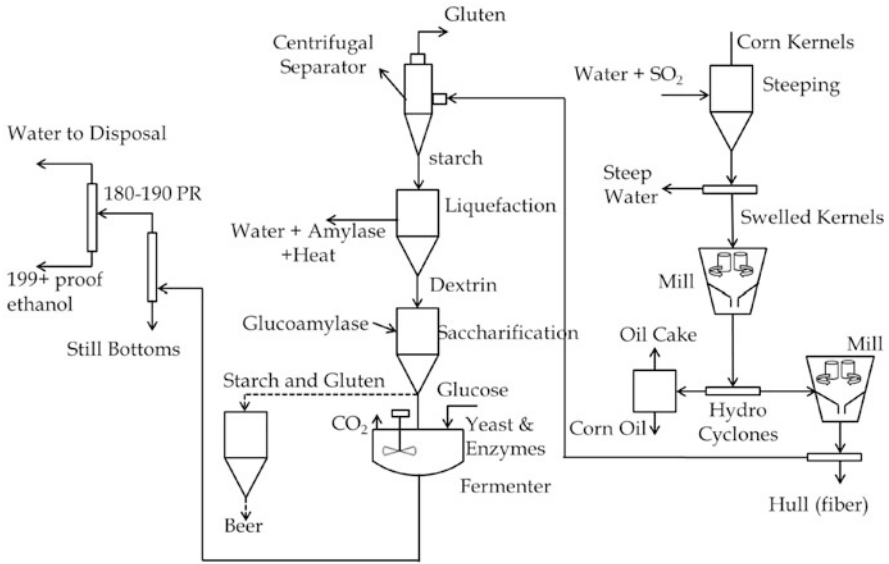
Fig. 9.8 Alcoholic fermentation by wet milling of corn

hydrolysis. The carbohydrate polymers are broken down/hydrolyzed into sucrose sugar by enzymes/dilute acids. Alcoholic Fermentation of corn/maize can be done by wet milling and dry milling processes. The wet milling of corn/maize is to produce ethanol as shown in Fig. 9.8. In wet milling process, the maize is made soft by soaking in steeping vat in the presence of water and SO_2. The softened/swollen maize is passed through mill to separate various parts of the maize/corn (starch, germ, gluten, and husk). The starch is passed through liquefaction unit to produce dextrin. Dextrin is then passed through saccharification unit to produce glucose.

Ethanol(C_2H_5OH) is produced naturally by certain micro-organisms from sugars under acidic conditions (pH 4–5). The glucose is then fermented by adding yeast and enzymes in the fermenter. The most common micro-organism, the yeast *Saccharomyces cerevisiae*, is poisoned by ethanol concentration $>10\%$, and so higher concentration up to 95% are produced by distilling and fractionating. The remaining mixture of 95% ethanol and 5% water is obtained at constant boiling point. The product is then distilled to produce high purity ethanol. Anhydrous ethanol is produced commercially with azeotropic removal of water by co-distillation with solvents such as benzene. In case of dry milling the corn is made to pass directly without soaking. The dry milling process for producing ethanol is shown in Fig. 9.9. The crushed corn is passed through liquefaction unit/starch cooker to produce dextrin. Dextrin is then passed through saccharification unit to produce glucose. During fermentation, glucose is then transformed into an alcohol (usually ethanol) and dried grain and solubles by fermenting with
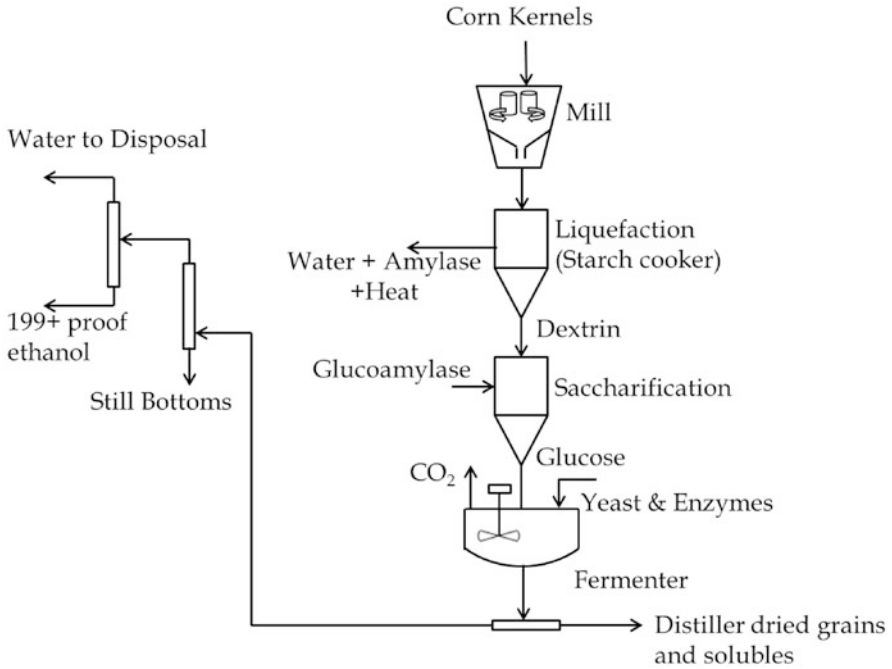
Fig. 9.9 Dry milling of corn

microorganisms. The product is then distilled to produce high purity ethanol and waste water for final disposal.

9.3.3.2 Anaerobic Digestion

Anaerobic digestion is a biological process in which the wet biomass (mainly animal waste) is converted into gas (mainly CH_4) in the absence of oxygen. Decay of biomass is broken down into elementary nutrients and soil humus by decomposer organisms, fungi and bacteria. In closed anaerobic conditions, bacteria are able to exist by breaking down general carbohydrate material. The carbon may be ultimately divided between fully oxidized CO_2 and fully reduced CH_4. The product gas is referred as biogas/gobar gas. The main byproduct of the process is nitrogen rich sludge which is a good fertilizer. The reaction takes place in two steps. First non-methane forming bacteria convert cellulose, starch, proteins, fat etc. into soluble compounds by hydrolysis and subsequently the methanogenic bacteria act on these acids and alcohol to produce methane as below:

$$(CH_2O)_6 \xrightarrow{\text{bacteria}} 3CH_3COOH \tag{9.2}$$
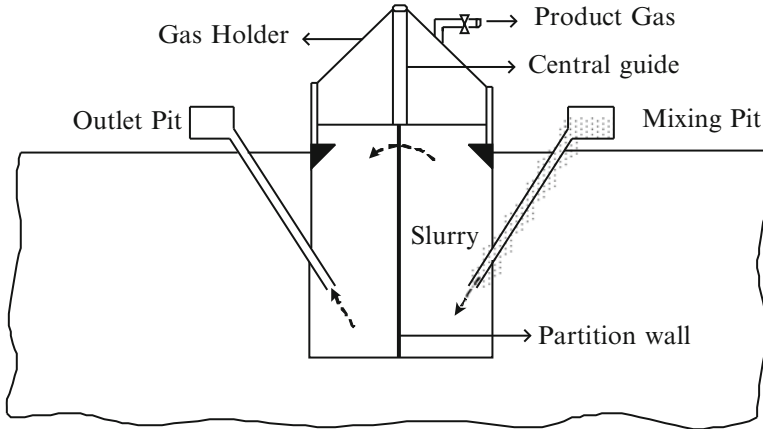
Fig. 9.10   Anaerobic digester – floating cover

$$CH_3COOH + 2H_2O \xrightarrow{\text{bacteria}} 2CO_2 + 4H_2 \tag{9.3}$$

$$CO_2 + 4H_2 \xrightarrow{\text{bacteria}} CH_4 + 2H_2O \tag{9.4}$$
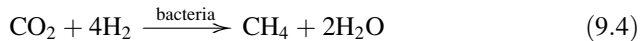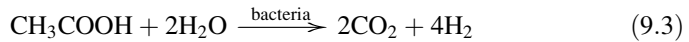
In general 95 % of the mass of the material is water and the reactions are slightly exothermic. The biogas mainly consists of methane and carbon dioxide and it also contains various trace elements. A typical floating cover anaerobic digester(AD) is shown in Fig. 9.10. The AD system consists of a floating metallic gas holder and two partition deep digester with inlet and outlet pits. The wet biomass such as animal/human wastes, sewage sludge, crop residues are mixed with water and resulted slurry is fed through the mixing pit. The heavy complex organic biomass is broken down to elementary nutrients and soil humus by decomposer organisms, fungi and bacteria. Then lighter slurry with nutrients moves into the next compartment and exits through the outlet pit. The generated product gas moves up into gas holder. As volume of gas increases, pressure in the holder builds up and the holder moves up with the help of central guide. The biogas from the holder can be used for energy conversion. The small-scale biogas digesters are more popular in rural India for domestic cooking application. Improved designs of anaerobic digesters have developed in recent times.

9.4   Barriers in Biomass Power Generation

Based on limited field experiences gain to this date few barriers have been reported in the large scale adaptation of biomass as a means of power generation. These may be classified into three categories: economic barriers, logistic barriers and technical barriers as follows.

9.4.1   Economic Barriers

The competition with fossil fuel for the power production cost becomes an economic barrier.In order to promote bio-energy many countries have stimulated the development and use of biomass for electricity, heat and transportation by introducing different measures such as governmental R & D programmes, tax cuts and exemptions, investment, subsidy, feed in tariffs for renewable electricity and mandatory blending of bio-fuels. Due to often small size of bio-energy markets and the fact that biomass byproducts are relatively new commodities, markets can be immature and unstable (Andre 2005). The other economic barriers related to commercialization include the seasonal dependence of the availability of biomass, problems related to storage as well as transport and very low tariffs and incentives offered by most of the state electricity boards.

9.4.2   Logistic Barriers

Biomass (e.g. producer gas) is a low density as well as low calorific value fuel in comparison to fuel wood as well as coal. The lack of technically mature pretreatment technologies in converting biomass to a high density fuel becomes a barrier. In recent years, the densification technology for making pellets has been improved significantly, but it is suitable for certain biomass types only. Pyrolysis may be a possible pretreatment option but techniques have to be proved as technically feasible and economically viable for their adoption on commercial scale.

9.4.3   Technical Barriers

Biomass such as forest, agricultural and organic processing residues can be converted to commercial products via either biological or thermo-chemical processes (Lin and Tanaka 2006; Caputo et al. 2005; Yoshioka et al. 2005). Biological conversion of low-value lingocellulosic biomass still faces challenges in poor economy and efficiency (Lin and Tanaka 2006). Combustion, pyrolysis and gasification are the three main thermo-chemical conversion methods. The barriers identified from these processes are: (a) the gasification process converts biomass through partial oxidation into a gaseous mixture of syngas consisting of H_2, CO, CH_4 and CO_2 (Knoef 2005; Higman and van der Burgt 2003) and (b) Air, while a cheap and widely used gasifying agent contains a large amount of nitrogen, which lowers the heating value of the syngas produced. If pure O_2 is used as the gasifying agent, the heating value of syngas as well as the operating cost increases. Gasification provides a competitive way to convert diverse, highly distributed and low-value lignocellulosic biomass to syngas for combined heat and power

generation, but more research is needed to improve syngas quality for its commercial uses in a high energy-efficient heat and power generator such as gas turbines.

Thus, it can be concluded that the most common problem with specific biomass is its physical and chemical properties such as low density, high ash and moisture content, nitrogen, sulphur and chlorine content that have already been discussed in previous sections. This makes the use of biomass directly for co-firing with coal or natural gas difficult. Power producers are generally reluctant to experiment with new biomass streams as costs will also increase due to the O_2 production.

The low efficiency of the process of gasification is due to the following reasons (Wang et al. 2007).

(a) Design of the gasifier; (Fixed bed, moving bed or fluidized bed). Both fixed bed and moving bed gasifiers produce syngas with large quantities of char and tar while the fluidized bed which consists of large percentage of hot inert bed material such as sand produces low percentage of char and tar.

(b) Ash-related problems including sintering, agglomeration, deposition, erosion and corrosion. (Fluidized bed has better performance than fixed bed in this case). These are the main obstacles to economical viable application of biomass gasification technology (Wang et al. 2007; Baxter 1993).

(c) The conversion of biomass to char and tar during the gasification process along with syngas is a hindrance to the process.

Gasification temperature (Low temperature) results in the high percentage of char and tar formation whereas high temperature decreases the energy efficiency and increases the risk of ash sintering and agglomeration installation modifications of boilers etc. have to be made. The use of biomass may damage the installations (designed for fossil fuels) specially the boilers. The modifications in the boilers may take several years to be implemented on a commercial scale (Bridgwater et al. 2002).

9.5 Strategies for Removal of Barriers

In what follows we present an outline of some strategies related to removal of barriers in biomass power generation.

1. *Biomass Hybrid Cogeneration Plants*: Cogeneration of process heat and power is an important energy saving approach. It is particularly suitable for paper, chemicals, textile, food and petroleum refining industries. To counter balance the problem related to the seasonal variation and scattered availability of biomass Kaushika et al. (2005) suggested a solar biomass hybrid cogeneration plant and indicated that the subsystem in such plants can indeed be performance matched. The schematic of such a plant is given in Fig. 9.11.
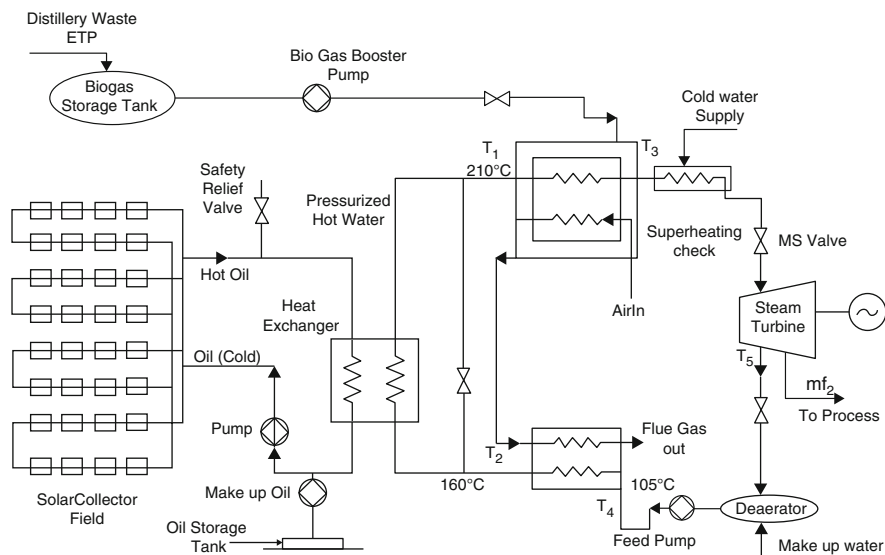
Fig. 9.11 Solar biogas hybrid co-generation plant (Kaushika et al. 2005)

2. *CDM Benefits:* Under the carbon credit programme the biomass power plants have been categorized to be eligible for CDM benefits in the international market and it has been experienced that many projects which are otherwise cost intensive become viable due to the cash flow emerging from CDM benefits.
3. *Revision of Tariffs and Incentives:* It has been reported that the power produced from biomass is often much more than consumption level of sugar mills. The excess power is sold to electricity boards. The tariffs fixed by these state electricity boards have now become out dated and need revision.
4. *Energy Efficiency in Power Plants:* The energy audits of various power plants have established that there is tremendous scope of energy efficiency in various stages of the systems.

The use of biomass, as an energy source for the third world can play an important role. Although, globally it is estimated that biomass contributes to 15 % of the world's energy needs, the total contribution of biomass towards the primary energy needs in the developing countries is only 4 %. Many different technologies are available for the use of biomass into heat and power. Some of these technologies are not yet mature and need more research to make the process commercially adaptable. Economic problems also exist because of higher investment and operational cost in comparison to fossil-fired plants. Hence, the Government subsidy is also necessary to improve the economic viability. Thus, it may be concluded that there are many possibilities as well as restrictions in the use of biomass for power production.

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Chapter 10
Wind Energy Conversion

10.1 Wind Energy Conversion Systems (WECS)

Wind is the air-in-motion. On Earth, it has two major components: (i) Planetary winds resulting from daily rotation of the earth and differential solar heating of earth and its atmosphere between polar and equatorial regions (ii) Local winds resulting from unequal heating and cooling of ground surface and ocean/lake surface during day and night. Wind Energy is a manifestation of the solar Energy. The wind has been playing a significant role in human development and civilization. The first ever known utility of wind energy is sea transport in Egypt way back 5000 years where boats were used to sail from shore to shore. The first windmill was built as early as 2000 B.C. in ancient Babylon, which is a system with vanes attached to its axis to produce circular motion (Gipe 1995). The grain grinding and water pumping were main applications of windmill. Although a large number of concepts of wind electrical generator (aero generators) have been introduced from time to time, there are basically two designs which have been put to real applications. These wind energy conversion systems may be classified mainly based on the direction of their axis of rotation. Two broad categories are wind axis (or horizontal axis) and cross wind (or vertical axis) machines. Horizontal Axis Wind Machines (Propeller Type) are wind turbines whose axis of rotation is parallel to the air stream. Some types of horizontal wind turbine with variable degree of operational and efficiency characteristics are shown in Fig. 10.1. Large Horizontal Axis Wind Turbines have a yaw adjustment mechanism that automatically positions the wind turbine head to face against the direction of the wind. This enables these turbines to maximize energy conversion 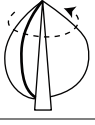efficiency. The configuration of a typical horizontal axis wind turbine with various components is shown in Fig. 10.2. Lift machines can have blade sections moving considerably faster than the wind speed, e.g. a keeled sail boat which can sail faster than wind. Vertical-Axis Wind Turbines accept wind from any direction without adjustment. Gearing and generators can be directly
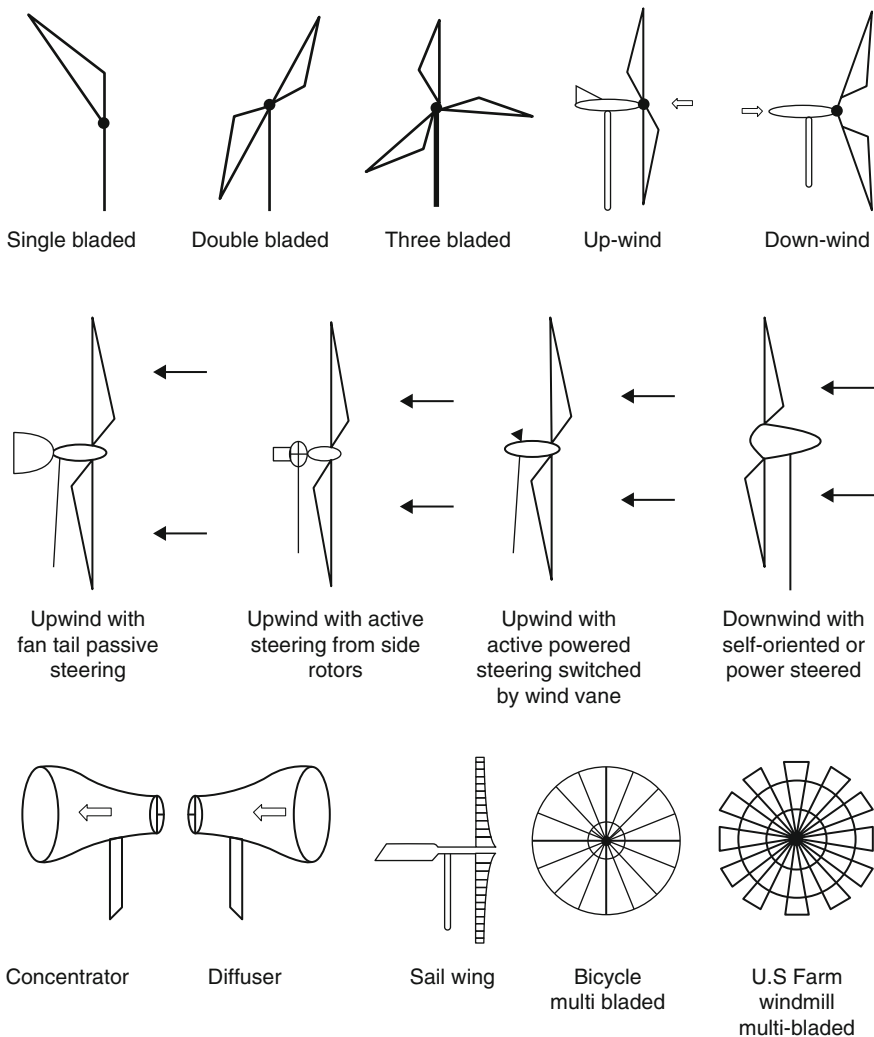
Fig. 10.1 Horizontal axis wind turbines

coupled to the axis at ground level. Various vertical wind energy conversion systems are shown in Fig. 10.3.

Yet another classification could be based on the capacity of the machines: Very small (0.5–1.0 kW), small (1–15 kW), medium (15–250 kW), large (250–1000 kW), very large (>1 MW). The pumping windmills have multi-bladed rotors that use a multi-vane design of fixed metal blades arranged in a single wheel form generally known as a fan mill. The minimum wind speed required for a wind mill is 2 m/s and with a wind speed of 7 m/s it could develop power up to 30 kW; the

Fig. 10.2 Configuration of typical horizontal axis wind turbine
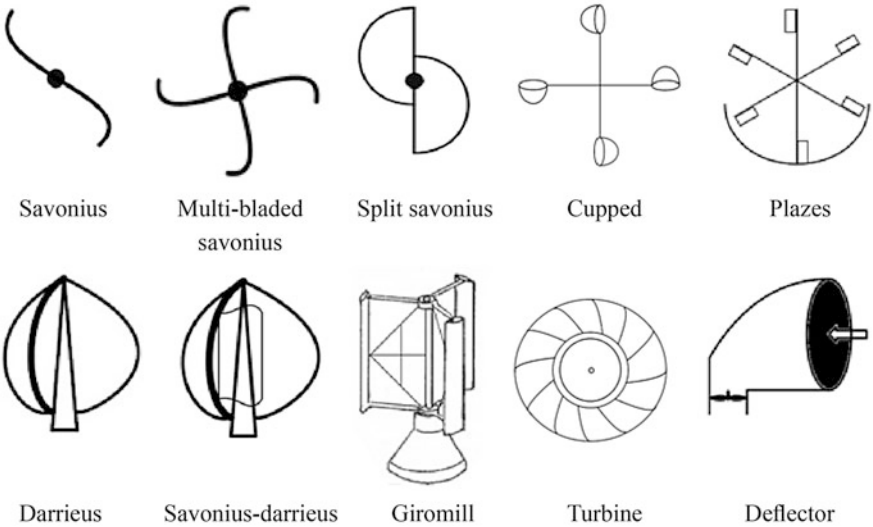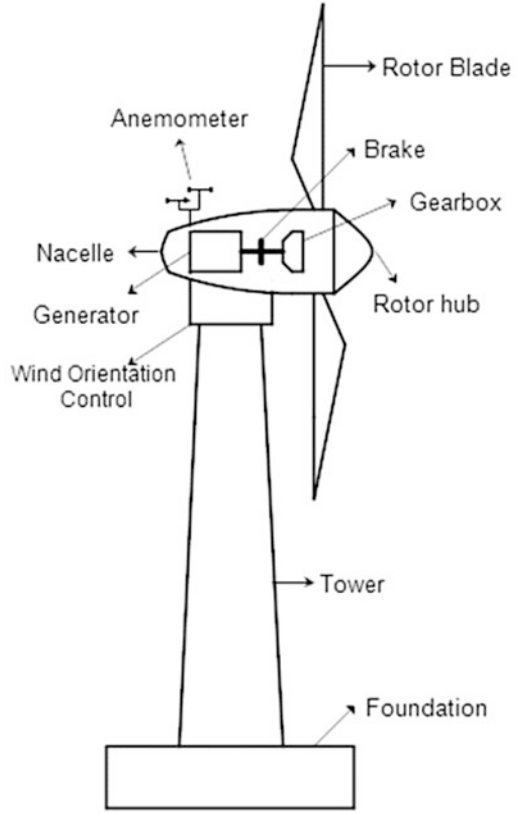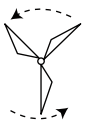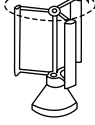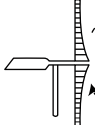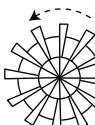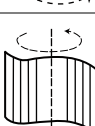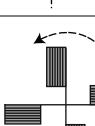
Fig. 10.3 Vertical axis wind turbines

cut out wind speed is 10 m/s. Wind electricity generators are propeller type with
small blades (2 or 3) so that starting torque is low and they are fast running. Reliable
wind generators ranging from 10 W to 8 MW rated output are now commercially
available. The installation and operation of a wind power system involves the
consideration of following factors: Machine structure, Tower, Nacelle, Blades,
Braking system, Control unit, Protection and safety, Data acquisition, Power
curve, Cable, Connection, Foundation, Access road, Service. The geometrical
configurations and operational characteristics of various wind turbine rotors are
illustrated in Table 10.1.

Table 10.1 Characteristics of wind turbine rotors

S.No	Wind turbine rotor	Configuration	Torque	Speed (rpm)	Power coefficient C_p
1	Three bladed		Low	1000–2000	0.42
2	Darrieus		Low	2000–3000	0.40
3	Cyclogiro		Moderate	600–900	0.45
4	Sailwing		Moderate	500–900	0.35
5	Fan-type		High	300–500	0.30
6	Savonius		High	200–500	0.15
7	Dutch-type		High	40–400	0.17

The blades are the heart of the system and the microprocessor controller is often used. Some of the incorporations of 1980's in wind machines are pitch regulation, fibre glass reinforced polyester blades and microprocessor controller. Pitch regulation is a high-tech feature, which allows the blades to pivot along their own longitudinal axis. At low wind velocity the pitch regulated blade offers large surface against the wind and as the wind velocity increases this surface decreases gradually. The result is optimum energy capture and prolonged lifespan of the system. The resultant systems are now cost effective for particular applications in suitable wind regimes. In what follows we present an aerodynamic aspect of design and operation of wind power systems.

10.2   Theory of Wind Energy Conversion

The wind exerts pressure and is capable to do work; the rate of this work is called wind power. Wind power can be extracted by the placement of an obstacle in the wind path. The wind power can be estimated using the following design formulations.

In the unperturbed state a column of wind upstream of the turbine, with cross sectional area A_1 (Fig 10.3) of the turbine disk, has

$$\text{Kinetic Energy} = \text{Work} = \tfrac{1}{2}mu_0{}^2$$

where $m =$ mass of moving wind column

$$
\begin{aligned}
&= \text{Density } (\rho) \times \text{Volume (Area} \times \text{Distance)} \\
&= \rho \times A_1 \times d \\
u_0 &= \text{velocity of moving object}
\end{aligned}
$$

$$
\begin{aligned}
\text{Power } P_0 = \text{Work}/t &= \text{Kinetic Energy}/t \\
&= \tfrac{1}{2}mu_0{}^2/t = \tfrac{1}{2}(\rho A_1 d)u_0{}^2/t \\
&= \tfrac{1}{2}\rho A_1 u_0{}^2(d/t)
\end{aligned}
$$

The total power in unperturbed wind stream is given by,

$$P_0 = \tfrac{1}{2}\rho A_1 u_{\text{o}}{}^3 \tag{10.1}$$

For typical values of $\rho = 1.2$ kg/m^3, $u_0 = 10$ m/s, $\rightarrow P_0 = 600$ W/m^2
In gale force condition, $u_0 \sim 25$ m/s $\rightarrow P_0 = 10{,}000$ W/m^2

10.2.1 Power in the Wind – Betz Model for Expanding Airstream

The rotor is treated as an "actuator disc", across which there is a change of pressure as energy is extracted and a consequent decrease in the linear momentum of the wind (Fig. 10.4). Power in the wind can be formulated using the Betz model of expanding air stream (Twidell and Weir 2006). Considering,

A_1 – is the rotor swept area
A_0 – is located in the oncoming unperturbed wind front unaffected by the turbine.
A_2 – is located at the minimum wind speed before the wind front reforms downwind
    and u_0, u_1 and u_2 are the velocities of wind at the areas A_0, A_1 and A_2 respectively.

The force or thrust on the wind turbine rotor is the reduction in momentum per unit time from the air mass flow rate m:

Fig. 10.4 Wind energy conversion considering it as an actuator disk. (**a**) Air stream over wind turbine. (**b**) Movement of unperturbed wind
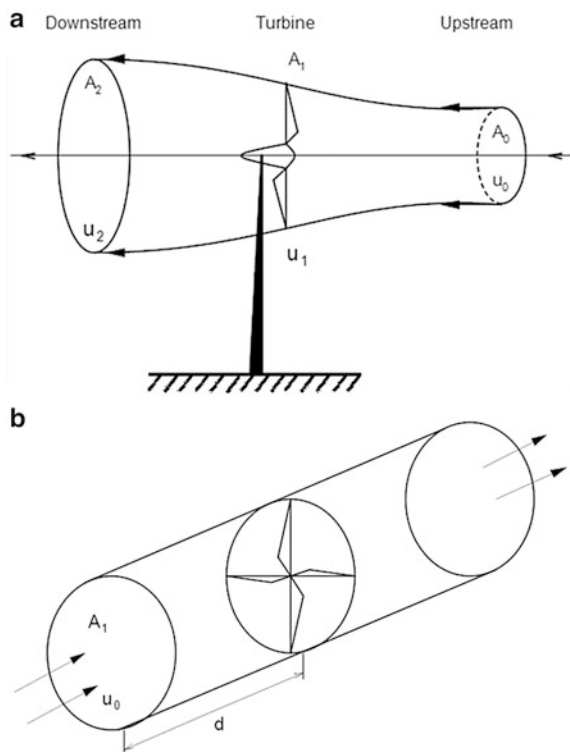
$$F = mu_0 - mu_2 \tag{10.2}$$

This force is applied by an assumed uniform air flow of speed u_1.

The power extracted by the turbine P_E is,

$$P_E = Fu_1 = m(u_0 - u_2)u_1 \tag{10.3}$$

The loss in energy per unit time by that airstream is the power extracted from the wind (P_w),

$$P_w = \tfrac{1}{2}m\left(u_0{}^2 - u_2{}^2\right) \tag{10.4}$$

By equating (10.3) and (10.4),

$$P_E = P_w \rightarrow (u_0 - u_2)u_1 = \tfrac{1}{2}\left(u_0{}^2 - u_2{}^2\right) = \tfrac{1}{2}(u_0 - u_2)(u_0 + u_2) \tag{10.5}$$

$$\text{Hence } u_1 = \tfrac{1}{2}(u_0 + u_2) \tag{10.6}$$

Thus, the air speed through the actuator disk of wind rotor is always higher than half the unperturbed wind speed.

The mass of air flow in through the disk per unit time is given by m:

$$m = \rho A_1 u_1 \tag{10.7}$$

From Eq. (10.3),

The power extracted by the turbine is,

$$P_E = \rho A_1 u_1{}^2(u_0 - u_2) \tag{10.8}$$

Now substitute for u_2 from $u_1 = \tfrac{1}{2}(u_0 + u_2)$

$$P_E = \rho A_1 u_1{}^2[u_0 - (2u_1 - u_0)] = 2\rho A_1 u_1{}^2(u_0 - u_1) \tag{10.9}$$

The interference factor I_F (induction or the perturbation factor) is the fractional wind speed decrease at the turbine. Thus

$$I_F = (u_0 - u_1)/u_0 \tag{10.10}$$

$$\text{and } u_1 = (1 - I_F)u_0 \tag{10.11}$$

Also From Eq. (10.6)

$$u_1 = \tfrac{1}{2}(u_0 + u_2), \quad I_F = (u_0 - u_2)/2u_0$$

From (10.11) substituting for u_1 in (10.9)

$$P_E = 2\rho A_1 (1 - I_F)^2 u_0^2 [u_0 - (1 - I_F) u_o]$$

$$= \tfrac{1}{2}\, \rho A_1 u_0^3 \left[4\, I_F\, (1 - I_F)^2 \right] \tag{10.12}$$

$$P_E = P_0 K \tag{10.13}$$

where P_0 is the power in the unperturbed wind and K is the fraction of power extracted, the power coefficient:

$$K = 4\, I_F\, (1 - I_F)^2 \tag{10.14}$$

The maximum value of K occurs when $F_I = 1/3$ and by substituting in Eq. (10.14), we get

$$K_{max} = 16/27 = 0.59$$

Betz' law states that *only less than 59 % of the wind power can be converted into mechanical power using a wind turbine.*

In practice, a good commercial Wind Energy Conversion System (WECS) may have a $K_{max} = 0.4$.

The efficiency of the machine is then given as $0.4/0.59 = 68\,\%$. The power coefficient K is the efficiency of extracting power from the mass of air in the supposed stream tube passing through the activator disk, area A_1. This incident air passes through area A_0 upstream of the turbine. The power extracted per unit area of A_0 upstream is greater than per unit area of A_1, since $A_0 < A_1$. The maximum power extraction per unit of A_0 is 8/9 of the power in the wind, so the turbine has a maximum efficiency of 89 %. Effects of this sort are important for arrays of wind turbines in a wind "Farm".

10.3   Aerodynamic Aspects of Wind Turbines

10.3.1   Thrust on Turbines

The motion of incompressible fluids in streamlined frictionless flow may be treated by Bernoulli's equation.

$$p_0/\rho_0 + g z_1 + u_0^2/2 = p_2/\rho_2 + g z_2 + u_2^2/2 \tag{10.15}$$

The changes in z and ρ are negligible compared with the other terms, so if ρ is the average air density then

$$\Delta p = p_0 - p_2 = (u_0^2 - u_2^2)\rho/2 \tag{10.16}$$

Δp is called the static pressure difference.

The terms in $u^2\rho/2$ are the dynamic pressures.

The maximum value of static pressure difference occurs as u_2 approaches zero.

$$\text{so,} \quad \Delta p_{\text{max}} = \rho u_0{}^2/2 \tag{10.17}$$

The maximum thrust on the turbine is

$$F_{\text{Amax.}} = \Delta p_{\text{max}} A_1 = A_1 \rho u_0{}^2/2 \tag{10.18}$$

On a horizontal axis machine this thrust is centred on the turbine axis and is called the axial thrust F_A.

The thrust equals the rate of loss of momentum of the airstream:

$$F_A = m(u_0 - u_2) \tag{10.19}$$

$$\text{Also,} \ F_A = (\rho A_1 u_1)(2u_0 I_F) \quad (\text{since,} \ u_0 - u_2 = 2u_0\alpha)$$

$$= \rho A_1 (1 - I_F) u_0 (2u_0 I_F) = \tfrac{1}{2} \rho A_1 u_0{}^2 [4I_F(1 - I_F)]$$

$$= C_F(\tfrac{1}{2}\rho A_1 u_0{}^2) = C_F F_{\text{Amax}} \tag{10.20}$$

Axial Force Coefficient $C_F = 4I_F(1 - I_F)$

$$C_F = 1 \text{ when } I_F = \tfrac{1}{2}, \text{ equivalent to } u_2 = 0.$$

$C_F = 8/9$, Max power extraction by the Betz criterion occurs when $I_F = 1/3$
$C_F = 1.2$, in practice owing to edge effects.

The term $\tfrac{1}{2}A_1 u_0{}^2$ in F_A increases rapidly with increase in wind speed. In practice, normal WECS become unable to accept the thrust forces for wind speeds above about 15–20 m/s.

10.3.2 Torque on Turbines

The torque causes rotational shaft power. For a propeller turbine of radius R (Fig. 10.5),

Fig. 10.5 Propeller turbine
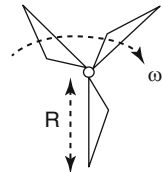
$$\text{The Torque is, } T_{\max} = F_{\max} R \tag{10.21}$$

Also,

$$T_{\max} = \frac{\rho A_1 u_0^2 R}{2} \tag{10.22}$$

The Torque coefficient,

$$K_T = \frac{\text{Torque of wind turbine}}{\text{Max. Torque of wind turbine}}$$

For a working machine,

$$T = K_T T_{\max} \tag{10.23}$$

The Tip Speed ratio (λ) is referred as a ratio of speed of outer blade tip (v_t) to unperturbed wind speed (u_0):

$$\lambda = \frac{\text{Outer blade tip speed } (v_t)}{\text{Unperturbed wind speed } (u_0)} = \frac{R\omega}{u_0} \tag{10.24}$$

Substituting for R in Torque,

$$T_{\max} = \frac{\rho A_1 u_0^2 (u_0 \lambda)}{2\omega} = \frac{P_0 \lambda}{\omega} \tag{10.25}$$

The shaft power is the power derived from the turbine (P_E)

$$P_E = T\omega \tag{10.26}$$

Also,

$$P_T = K P_0 \tag{10.27}$$

Therefore,

$$K P_0 = K_T T_{\max} \omega \rightarrow K P_0 = K_T P_0 \lambda \tag{10.28}$$

Fraction of power extracted (power coefficient) is given by:

$$K = \lambda K_T \tag{10.29}$$

In practice, K and K_T will both be functions of λ and are not constant

$$(K_T)_{max} = 0.59/\lambda \qquad (10.30)$$

- At high values of λ the torque coefficient (K_T) decreases, and hence the torque, drops to zero and the turbines 'freewheel'.
- Maximum torque and maximum power extraction are not expected to occur at the same values of λ.

10.3.3   Stalling of Wind Turbine Blades

Stalling is a condition in aerodynamics and aviation wherein the angle of attack increases beyond a certain point such that the lift begins to decrease. The angle at which this occurs is called the critical angle of attack. In practice following methods are used to stall the wind turbine:

(i) To change the turbine direction with respect to the wind.
(ii) To rotate the airfoil or extend the spoil flaps resulting in the reduction of power extraction and hence thrust.
(iii) To use self-stalling fixed blades which become extremely inefficient at high speeds.
(iv) To stop the rotation by braking.

Method (iii) is best, giving failsafe operation at low cost without severe stresses on the machinery. Self-stalling blades may have a low power coefficient and not give optimum power extraction in normal conditions.

10.3.4   Blade Planform – Solidity of Practical Turbines

Blade planform is the shape of the flat wise blade surface. Solidity is the ratio of total rotor plan form area to total swept area and it can be described by giving the number of blades. High solidity turbines operate at low values of tip speed ratio and have high starting torque, but soon reach maximum power at low rotational frequency (water pumping). Therefore, high solidity (>0.80) gives low speed and high torque. Low solidity machines have low starting torque and may indeed not be self-starting, but reach maximum power at high rotational frequency. Therefore, low solidity (0.10) results in high speed and low torque.

10.3.5   Drag Machines

The drag machine consists of flaps, which are moving parallel to the undisturbed wind of speed u_0. The pressure difference across a stationary flap held perpendicular to the wind velocity is given by (neglecting edge effects):

$$\Delta P_{\max} = \frac{\rho u_0^2}{2} \tag{10.31}$$

For a flap, the maximum drag force is

$$F_{\max} = \frac{\rho A (u_0 - v)^2}{2} \tag{10.32}$$

where A is cross sectional area of the flap, v is speed of the flap
The actual drag force departs from ideal drag force.
Therefore, the actual drag force is given as:

$$F_D = \frac{C_D \rho A (u_0 - v)^2}{2} \tag{10.33}$$

where C_D is drag coefficient.
The power transmitted to the flap is

$$P_D = F_D v = \frac{C_D \rho A (u_0 - v)^2}{2} \tag{10.34}$$

This is a maximum with respect to v when $v = u_o/3$,

$$\text{So,} \qquad P_{D\max} = \frac{4}{27} C_D \frac{\rho A u_0^3}{2} \tag{10.35}$$

The power coefficient for drag machines is defined as:

$$P_{D\max} = K \frac{\rho A u_0^3}{2} \tag{10.36}$$

$$\text{So,} \qquad K_{\max} = 0.148 \, C_D \tag{10.37}$$

The drag coefficient for a point object is minimum (zero) and for a concave shaped object as used in standard Anemometers is maximum (1.5).
The maximum power coefficient for a drag machine is

$$K_{\max} = 0.148 \, C_D = 0.148 \, (1.5) = 22\% \tag{10.38}$$

The efficiency of lift machine is about 40 %. The drag-only devices have power extraction efficiencies of only 33 % that of lift force turbines for the same area of cross-section. Power extraction may be improved by incorporating more flaps or by arranging concentrated airflow.

10.3.6   Characteristics of the Wind

Standard meteorological measurement of wind speed (u_s) measures the length or run of the wind passing a 10 m high cup anemometer in 10 min. The direction of the wind refers to the compass bearing from which the wind comes. In energy production terms, cut in wind speed means where the energy production begins and cut out wind speed means where the energy production ends. Furthermore the wind speed is always zero at ground level. An approximate expression for wind speed u_z at the height z above ground level is given as:

$$u_z = u_s \left(\frac{z}{10m} \right)^a \tag{10.39}$$

The coefficient, α is derived empirically and it varies with the terrain and the stability of atmosphere. The approximate value of α is 0.14 for open sites under neutral stability condition.

10.4   Wind Power Installations

Practical wind power installations involve three configurations: (i) grid connected systems, (ii) hybrid systems and (iii) autonomous systems. Early wind power projects involved large megawatt machines. These projects did not exhibit much of commercial success. However, the commercial activity of last decade has indicated various such advantages of smaller machines as lower cost per kW, design simplicity, reliability, and ease of installation and repair. Consequently there is a world-wide trend of setting up grid connected wind generators often referred to as wind farms; installed turbine ratings is in the range of few kilowatts to Megawatts, some as high as 8 MW.

Electric utilities have played a key role in the development of wind power technology; other contributors are the federal governments and wind power industry. Total estimated world-wide wind power generation in 2012 was 534.3 TWh. United States of America as the world leader in wind power installation had a production of 140.9 TWh. China was the world's second largest in wind power production. In India, wind power potential is very large. Wind speeds of the order of 2.5–5.5 m/s prevail over 20 % of land area. In the coastal area, average wind speed is 12 m/s. In 2012, India contributed 5.6 % to the global wind power generation with its 30 TWh (Global Wind Statistics 2012).

10.5   Offshore Wind Power Systems

Wind turbines can be sited offshore, where the wind blows harder and larger turbines can be installed. Many offshore wind farms are being proposed and developed today in densely populated countries, where there is limited space on

land and relatively large offshore areas with shallow water. Offshore wind energy conversion is a promising approach, particularly in areas with high population density and difficulties in finding suitable sites on land. The offshore wind systems are characterized with more wind speeds and hence higher energy production, less noise pollution, difficult installation, operation and maintenance and larger energy losses due to long distance transport. Various factors to be considered in regard to offshore wind farms include impact on sea transport, impact on marine life, visibility from shore, storm effects, seabed, disturbance and coastal erosion. Several offshore projects are currently operational worldwide. The offshore wind power contributed about 1567 MW of the total 11,159 MW of wind power capacity constructed in 2013.

10.6   Hybrid Wind Energy Systems

Wind electricity generators are propeller type with small number of blades (2 or 3) so that the starting torque is low and they are fast running. The generator shuts off automatically at wind speeds in excess of 35 km/h. In contrast the pumping wind mills have multi-bladed rotors. The minimum wind speed to operate a wind mill is 7 km/h. However, the wind exhibits variation with time and location. Consequently, commercially available generators provide competitive electricity generation option only at some windy parts of the world. At other locations the viability of wind electricity generation is mediocre. At these locations the hybridization of wind systems with other renewable and conventional options has exhibited promise. For example, the diesel generators are a major source of NO_x pollution which in turn is a major cause of urban smog. In such locations hybridizing diesel generation power with wind power makes sense. In rural areas plenty of biomass is available and biomass power can be blended with wind power. Furthermore, in some hilly areas mini-micro hydel power has been hybridized with wind and solar PV. Blending the wind power with solar PV is a common scenario in central (desert) areas of Australia.

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Chapter 11
Energy Efficient Architecture

11.1 General

A building enclosure in its own right is a modifier of the outdoor environment and its main objective is to provide conditions for comfortable living for its inhabitants. This objective is often met by air-conditioning. So, an important parameter that specifies a building is its energy demand. The fact that the sun's energy can be utilized for natural heating and cooling of indoor space in a building was recognized even by ancient people. The shape, location and orientation of buildings were considered to be effective in modifying climate to achieve thermal comfort inside a building. In 400 BC, Socrates pointed out the importance of the summer to winter variation of the penetration of the sun's rays in south-facing porticos. This can be considered as the starting point for the natural heating and cooling of buildings. From 900 AD, building cooling methods based on the 'wind tower' and 'air vents' were in vogue in Iranian architecture. The underlying principle of the wind tower is as follows. The arid region of Iran has a fairly stable wind pattern; it has hot, strong winds in the day and almost no wind in cold nights. During the day, the wind induces downward motion of air in the tower since the air becomes cooler as it advances downward either because the tower interior has been cooled on the previous night or is being cooled by a water fountain and plants. The cool air is circulated through the rooms in the building by suitable operation of doors, windows and ventilators. During the night when there is no wind, the walls of the tower which were heated during the day transfer heat to air in the top region of the tower and induce circulation that carries cool night air through living rooms and up through the tower. The cooling of air in the above process is essentially 'sensible cooling'. In later cooling configurations, the wind tower is placed some 30–50 m away from building and is connected by a tunnel. The air coming from the tower is moistened by water droplets in the tunnel which is damp owing to watering of trees and grass above it or due to inbuilt fountains or pools. The vapourization of these

droplets removes a large amount of heat from the air thereby cooling it. This is referred to as 'evaporative cooling'.

Air vents were used in areas where dust-bearing winds rendered wind towers unsuitable. These are essentially a set of holes cut through the protected apex of doomed roof. The wind movement across the holes reduces the pressure at the apex and induces the circulation of air through the building as with wind towers. The use of both wind towers and air vents has also been observed in some historical buildings of Jaiselmer situated in the harsh desert regions of India. Design concepts such as clustering, thick walls, vegetation, watering, plantation and living in basements were practiced in both ancient Iran and India. The importance of a courtyard has been observed in the buildings revealed by archeological excavations at Harappa and Mohenjodaro in Pakistan and Kurukshetra and Nalanda in India.

11.2   Energy Balance in Building System

A building system (commercial and/or institutional) involves several components such as the structure of the building enclosure, electrical equipment, lighting, furnishing (active as well as passive) and occupants. Some of these such as electrical equipment, lighting and occupants generate heat and are often referred to as primary heat sources. The heat from these sources is a useful contribution if the building needs heating but a liability for buildings which need cooling. This energy is commonly referred to as internal heat energy to distinguish it from the solar energy received by the building enclosure in the form of daylight as well as heat through the external facades.

Internal heat energy in a building may be estimated as follows (Hastings 1994; Bruck et al. 1991):

1. The electricity consumed by a typical office appliance and by lighting may be measured over a period of time. The total consumption may then be obtained by summing up these measurements for all the equipments.
2. Total electricity consumption (purchased energy) of the building over a period of time may be used as a measure of internal heat generation.

The estimated heat contribution of occupants is added to the above to obtain the total usable internal gains. The compatibility of the estimates based on the above methods is judged in terms of the coincidence factor, where the coincidence factor is defined as the peak measured power of equipment and occupants divided by the total rated power including the estimates of the heat contribution of occupants.

The design and measured data for internal gains in offices and other buildings in Sweden, Switzerland and Norway have shown that buildings with low installed power of between 5 and 10 W/m^2 have a coincidence factor in the range from about 0.60–0.85, whereas, the buildings with higher power ratings of 50–80 W/m^2 have a low coincidence factor of about 0.2–0.3 (Hastings 1994; Bruck et al. 1991).
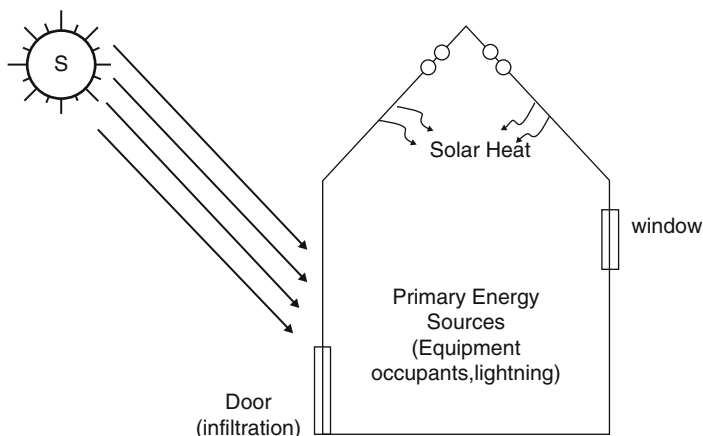
Fig. 11.1 Energy flow in a building system

Extensive statistical analysis of different building categories is required in order to obtain reliable values for internal gains which, in turn, would enable the evolution of national standards for internal gains.

The role of solar energy in a building may be controlled by appropriately sizing and orienting the building, siting windows and using shading devices. A wide range of strategies for the heating, cooling, day-lighting of buildings of different types are now available. These include integrated building strategies, such as the atrium, which can be a means to achieve all three objectives (heating, lighting and cooling) and which are widely practiced. The schematic of the typical energy flow in a building system is illustrated in Fig. 11.1. This includes solar energy, internal heat gain, day lighting, ventilation, infiltration and the use of an atrium (central sky lighting).

11.3 Passive Solar Building Technologies

The practical study of passive solar heating and cooling of buildings may be considered to have started in 1881, when Morse patented the south-facing glazed wall for keeping a house warm. This idea was later tested by Trombe (1972, 1974) who showed that it could be successful in practice. Various passive methods and devices have since been proposed and tested. Thousands of houses around the world have incorporated these passive concepts and have exhibited good performance (see for example (Trombe 1972; Szokolay 1975; Balcomb 1978; Sodha et al. 1986) and references therein for a review). In what follows a discussion is presented which first treats cooling and heating concepts separately and then describes concepts which could perform both of these functions.

11.4   Basic Cooling Concepts

11.4.1   Reduction of Heat Flux through the Roof

In the passive cooling of a building, the main aim is to reduce the solar heat flux entering the living space. The tropical and mid-latitude regions of the earth are characterized by an intensive solar irradiance on a horizontal roof. Concepts such as reducing the solar heat flux into the building by increasing the roof thickness; optimal placement of insulation and introduction of air gaps (single or double) in the masonry are well known in the literature (Sonnderegger 1977). Recently, concepts such as removable canvas, placement of inverted earthen pots on the roof top, shading the roof with a vegetable pergola and roof gardens, have also been investigated (Kaushika 1988; Kaushik 1988). Some of these are schematically illustrated in Fig. 11.2. In a hot and dry climate, a roof garden is most effective but involves structural problems. Flow of water through plastic pipes laid in the roof has also been considered as a means of reduction of heat flux.

11.4.2   Induced Ventilation

The wind towers and air vents of ancient buildings in the harsh desert regions of Iran and India are the basis of this concept. It makes use of solar gain to induce ventilation. Absorption of solar energy in one restricted area sets up a temperature gradient in the building, which drives the hot air out and admits cool air to the building. The source of cool air is either the cool night air or air from a well shaded planted area. Night air-cooling is shown schematically in Fig. 11.3a. Cool night air is circulated through the bed of rocks which, besides cooling the living space at night, keeps the indoor air cool during the day. Natural ventilation cooling is shown in Fig. 11.3b. Properly positioned openings at floor and ceiling set up natural air movement even in calm weather. Wind-driven ventilators are sometimes used to assist air circulation.

A highly effective approach in dry climates is cooling by water evaporation from the roof. Evaporative cooling relies on the principle of converting the sensible heat of hot air into latent heat of evaporation of water by humidifying the hot air. In dry climates it is often achieved by adding water droplets in air by placing sprays, fountains and open pools in and around the building. The vaporization of droplets lowers the air temperature and raises its humidity. Both of these effects combine to make the environment more comfortable. Combining mechanical fans with water filters (evaporative coolers) is also an example of evaporative cooling. It is an effective and common method of cooling in hot and dry climates.

One of the earliest works on this subject is due to Houghten (Houghten et al. 1940), who investigated the cooling produced by (i) an open pool of water and (ii) spray of water on the roof and reported both to be very effective. Sutton
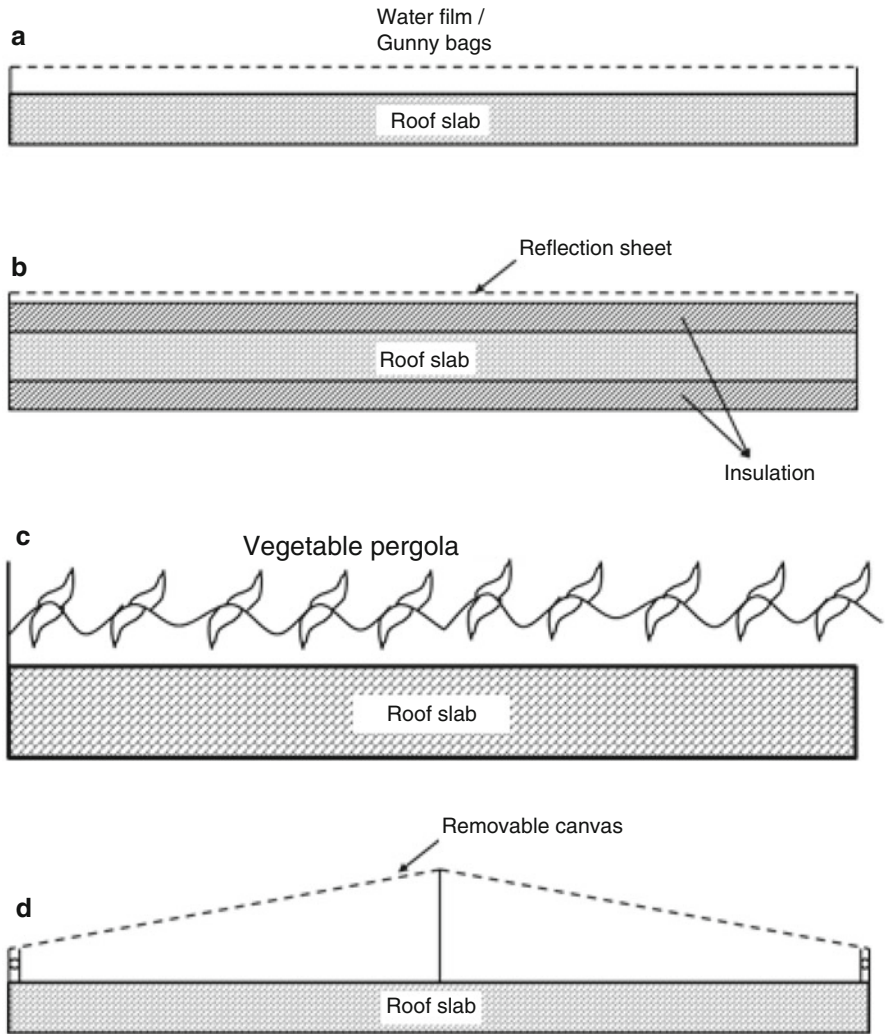
Fig. 11.2 Methods of reducing solar heat flux through roof: (**a**) Water film, (**b**) Reflection and Insulation slabs, (**c**) Vegetable pergola and (**d**) Removable canvas

(1950) reported his observations that the surface temperature of a roof dropped to 23.4 °C and 26.2 °C respectively when open roof ponds of depth 0.05 m and 0.15 m were maintained above it. Rao (1983) suggested an alternate method of water evaporation, using wet gunny bags on the rooftop. These authors have reported that an open roof pond reduces the roof surface temperature, indoor ceiling temperature and indoor air temperature by 23 °C, 13 °C and 3 °C respectively; the reductions corresponding to a spray roof and wetted gunny bags were (25°, 15°,
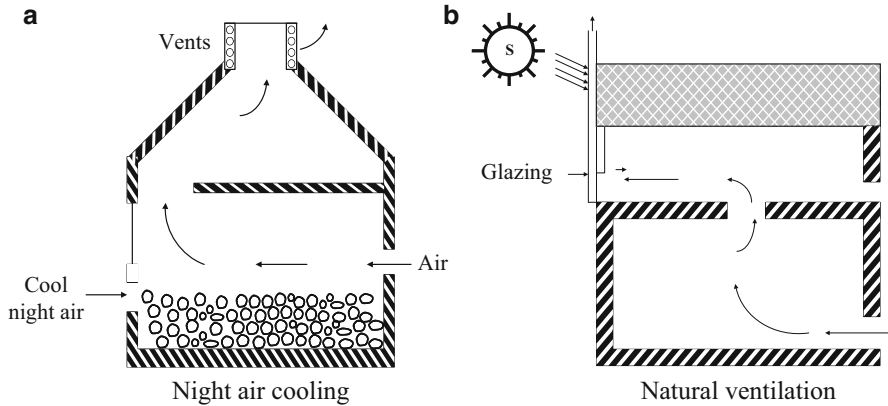
Fig. 11.3 Illustrative schematic for induced ventilation cooling. (**a**) Night air cooling. (**b**) Natural ventilation

3.5 °C) and (27°, 17°, 4 °C) respectively. More recently, the flow of water over the roof has been proposed as a means of cooling greenhouses (Van Bavel and Sadler 1978; Mannan and Cheema 1979) as well as other buildings.

11.5 Basic Heating Concepts

In the passive solar heating of a building, the main aim is to maximize solar energy collection. The solar heat must be stored for later use and the warmth distributed by natural means of heat transfer. These functions are performed by three basic elements: the sun, the storage mass and the living space. Based on different relationships between these elements, three basic concepts have been identified and tested in practice and are set out in the following sections.

11.5.1 Direct Gain

This is the most widely used form of passive solar design. Solar radiation enters the living space directly through a window, clerestory or wall of glass. Most of it is absorbed and converted into heat; a major portion of this heat is transferred to thermal storage mass for later use. Energy thus flows from the sun to the living space and then to the storage mass. Several variations in configurations and controls are often used. For example, location and material of storage mass varies with from one unit to another; concrete/brick walls, sand/slate floors, stone fire places and even a water reservoir all retain heat quite effectively. Typical location options include the walls, floors and free standing masses.
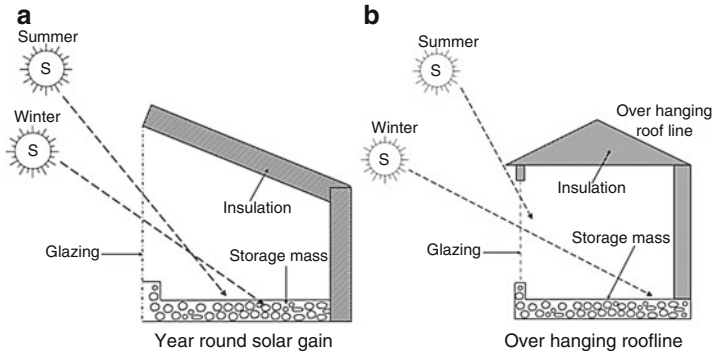
Fig. 11.4 Direct gain heating concepts. (**a**) Year round solar gain. (**b**) Over hanging roofline

South-facing glazing (north-facing in the southern hemisphere) must admit more heat than it loses. Two layers of glass are needed in cold climates. Movable insulation panels (such as curtains or shutters) can further reduce heat losses on sunless winter days and nights. Unwanted heat gains in summer may also be avoided by the use of movable insulation. Sun shading on the sun-facing glass can avoid them further. A schematic cross-section showing a direct gain building system along with some controls is shown in Fig. 11.4a, b. Configuration (a) corresponds to solar gain in winter as well as in summer and configuration (b) corresponds to solar gain in winter but its avoidance in summer by using an over-hanging roofline.

One disadvantage of a direct solar gain system is that it admits ultra-violet radiation into the living space where it may damage materials.

11.5.2 Indirect Gain

In the indirect gain method, energy flows from the sun to the storage mass and then to the living space. The storage mass collects solar energy and stores it as heat for gradual transmission to the living space. This scheme has two obvious advantages: (i) the material in the living space is not exposed to ultra-violet radiation damage and (ii) the storage wall provides thermal capacity between the solar collector (outside of wall) and the living space. Temperature fluctuations in the living space are consequently considerably reduced. Containers of water and heavy materials, such as concrete, stone, brick, adobe and earth, are commonly used for thermal storage. They possess appropriate thermal capacity and good emission properties. In recent years, Phase-Changing Materials (PCMs') such as paraffin-water and salt hydrates have also been suggested as storage materials for passive space heating applications. PCM stores energy as heat of fusion by changing from the solid to the liquid phase. On recovery of heat the material solidifies again at constant temperature. The thermo-physical properties of

several salt hydrates make them appropriate for the above application. Among those considered is sodium sulphate decahydrate ($Na_2SO_4 . 10H_2O$; melting point, 31–32 °C; heat of fusion, 251 kJ/kg; density, 1535 kg/m^3). Thus a PCM material offers two advantages: (i) its storage capacity per unit volume is relatively larger and (ii) its storage temperature is constant and equal to the melting temperature of storage material. PCMs often exhibit degradation under cyclic operational conditions. This problem is circumvented by adding gels or other agents. In most cases the storage material is encapsulated. An alternative approach is for the PCM to be interspersed in a cement or concrete-like structural material. It is then known as a phase-changing component material (PCCM). This has the thermo-physical properties of the bulk (cement/concrete) material and properties such as latent heat of fusion and melting temperature typical of a PCM.

The storage mass usually consists of a wall exposed to the sun. In practice, for the sake of structural stability, most thermal storage components are walls made of materials such as concrete, brick and adobe. A thermal storage water wall has been proposed by Meloney (1978). Telkes (1978) has favored a PCM wall because a 2.5 cm thick PCM wall would have thermal capacity equivalent to a 50 cm thick concrete wall.

The thermal storage wall (often known as a Trombe wall) absorbs sunlight at its outer surface which is blackened and glazed. Some of the heat is absorbed by the material of the wall and the rest is conducted through the wall. At night, the moderately warm wall transfers heat to the living space by convection and radiation. The addition of vents at the bottom and top of the wall allows the heat to enter the living space immediately by natural convection. Convective heat flow can be regulated by controlling the area of the vents. A south-facing storage wall in the northern hemisphere (or north-facing in southern hemisphere) is recommended for locations at fairly high latitudes (30° and above (Charters 1979)). For these locations the wall is suitable for heat collection in winter months. Protection from heat gain in the summer months can easily be accomplished by overhanging shading as illustrated in Fig. 11.5a. The roof pond/ skytherm was first proposed and tested by Hay and Yellot (1969). Two variations in system configuration are illustrated in Fig. 11.5b, c. Solar energy is collected and stored in a rooftop pond covering much or all of the roof area. Stored heat is then distributed by convection and radiation to the living space. During periods without solar gain, the warm water is covered with insulation to reduce heat loss. The insulation cover can also prevent over-heating. The pond used in such a system is usually of convective type and about 0.25 m deep. The system is quite appropriate for mild winter heating. Kaushika and Rao (1982) have suggested that if a non-convective pond is used instead of the convective type, it should be possible to use the above system to heat houses in colder climates. In recent years, cladding using transparent insulation material (Kaushika and Sumathy 2003) has been suggested as a means to improve the solar collection efficiency of thermal storage walls.
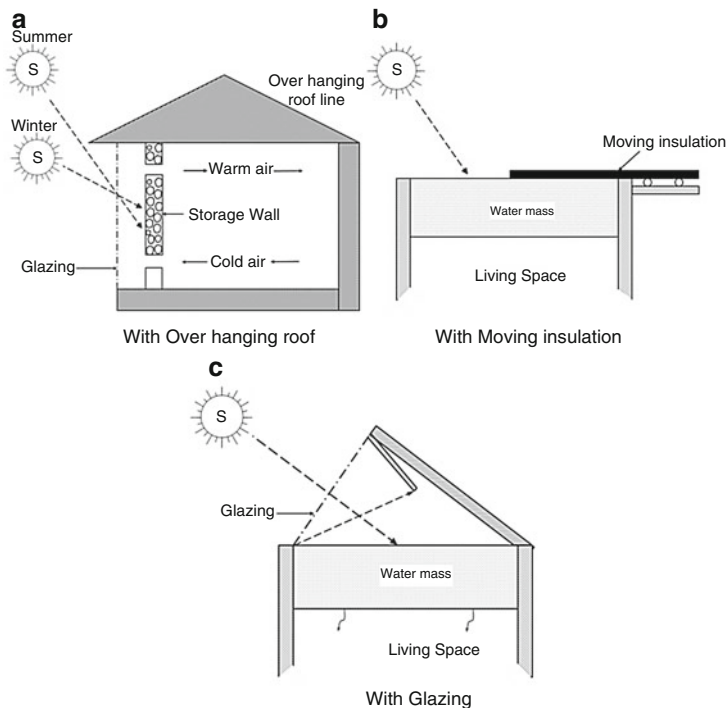
Fig. 11.5 Indirect gain heating concepts. (**a**) With over hanging roof. (**b**) With moving insulation. (**c**) With glazing

11.5.3   Isolated Gain

In this approach, energy flows from the sun to the collector space, thence to the storage mass and eventually to the living space. It is a mixed type of concept resulting from the mixture of direct gain and indirect gain (Balcomb 1978). Two configurations are used in practice: (i) sunspace and (ii) convective loop (Fig. 11.6a, b). The former has a collector space consisting of a greenhouse/solarium, a porch or an atrium which may be referred to as a sunspace. It receives the sun's energy by direct gain. The living space receives heat by indirect gain through a thermal storage wall. The sunspace reduces heat loss from the building and has many uses. It is a good space for growing food and house plants as well as for other similar activities. It can extend across the entire side of the building and the storage mass stores excess heat for later use. Multiple layers of glass and movable insulation, such as curtains or shutters, are desirable for the greater reduction of heat losses. The convective loop configuration consists of an array of collectors, which collect solar energy and supply it as heat to the living space. The collectors are attached to, or built into the walls of, the building. Solar radiation heats the air in the collector, which becomes buoyant, rises and enters the building. The cooler air from
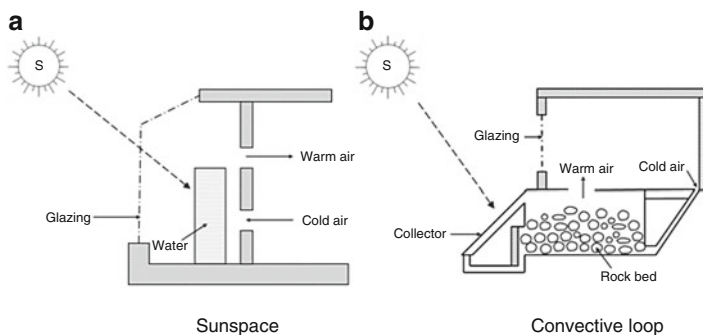
Fig. 11.6 Isolated gain heating concepts. (**a**) Sunspace. (**b**) Convective loop

the building, in turn, enters the collector to be heated. The intermediate area between collector and living space is occupied by a bed of rocks or other material for storing the excess solar gain.

11.6 Heating and Cooling Concepts

11.6.1 Ground Heating and Cooling

Locating a building partly or wholly under the surface of the earth has been found to be a viable means of reducing heating and cooling requirements. The underlying physics on which this idea is based is the decrease in amplitude of the diurnal and annual cycles of temperature with depth into the ground. At a depth of about 5 m, temperature remains almost constant throughout the year. Setting a building partly or wholly into the ground is, therefore, an easy way of obtaining the thermal comfort in the building. The use of underground pipes, ducts or air tunnels can make the approach more effective. The thermal performance of earth-sheltered buildings has been examined in detail by Moreland (1981). Generic types of such buildings include the single window wall dwelling and the atrium dwelling. An earth-sheltered building will have reduced air infiltration and can receive direct solar gain through apertures. The energy required for the construction of such buildings is often high (Moreland 1981). However, this is usually offset within a few years in terms of saved energy.

11.6.2 Skytherm

This is an extension of the roof pond system, discussed earlier, for passive space heating. The same arrangement can also be used for cooling by reversing its mode
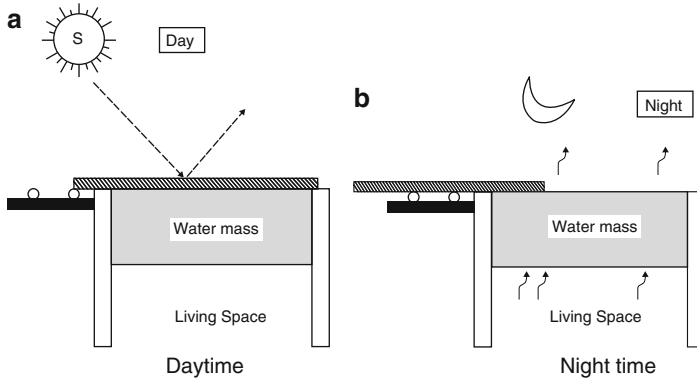
Fig. 11.7 Skytherm cooling concept (Hay and Yellot 1969). (**a**) Daytime. (**b**) Night time

of operation as illustrated in Fig. 11.7 (Hay and Yellot 1969). A solar reflecting insulation cover is placed over the roof pond during sunny periods to reduce the heat flux entering the building. The cover is removed at other times. In hot climates where night skies are usually clear, the water pool being thermally heavier absorbs heat from the living space below and radiates it to night sky. In mild climates this concept can provide total heating and cooling needs.

11.6.3   Variable Emittance Roof

This concept relies on the phenomenon of night sky radiation i.e. warm objects radiate heat to cooler objects and the night sky constitutes a cold object having a temperature lower by about 10 °C than atmospheric temperature and having infinite thermal capacity. The variable emittance roof cooling system consists of aluminium louvres covering the roof. In winter, the louvre system is opened during the day and closed during the night. The absorption of solar radiation during the day is maximized by the blackened surface of the roof made of concrete slab. Much of the heat is stored in the roof slab. During the night time loss of energy resulting from emission of radiation is reduced by a low emittance cover consisting of aluminium louvres. In summer, the louvers are closed during day to reflect insolation and cut the solar heat flux through the roof, while at night the louvres are opened to expose the high emittance, black surface to the sky. A project based on this concept has been carried out at the Architectural Science Unit of Queensland University. It was funded by the Australian National Energy Research Development and Demonstration Council (NERDDC) with Dr. S.-V. Szokolay as the chief investigator. Two test huts were built, one having the roof covered with louvre system and the other having a conventional roof and serving as control (see Fig. 11.8).

Fig. 11.8 Rectangular
building having the roof
covered with louvre system
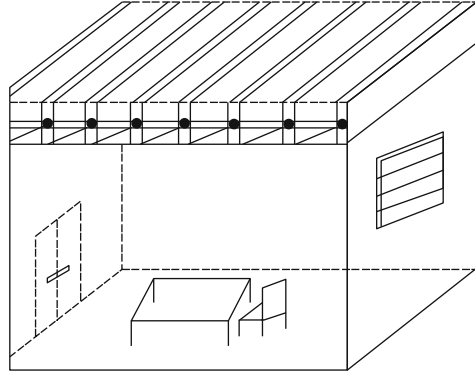
11.6.4   Ventilation

In a building, ventilation is used for providing fresh air and/or cooling. So it is an
essential requirement in both the heating and cooling of buildings. Throughout the
world many buildings are naturally ventilated. In this process, the natural driving
force of wind and stack effect (resulting from indoor and outdoor temperature
difference) are the motive forces responsible for air flow. Since these forces are
constantly fluctuating, the challenge of natural ventilation is therefore, to harness
these forces such that the air flow rate into living space is maintained at the
desired rate. The range of effectiveness of a natural ventilation system may be
improved by introducing mechanical assistance. Such ventilation systems are
referred to as mixed mode or hybrid ventilation. Hybrid ventilation may often
consist of an auxiliary low energy extract fan located in a natural ventilation
extract duct. In passive solar buildings, solar gain may also be used to augment
the natural ventilation. Based on these principles many types of ventilation
systems have been developed for a range of buildings include dwellings, schools,
offices and other commercial spaces. Common ventilation systems include the
following:

(a)   Natural Ventilation

–   Wind pressure induced ventilation
–   Thermal gradient induced ventilation
–   Combining wind with thermal gradients

(b)   Mixed Mode (Hybrid) Ventilation

–   Solar induced ventilation
–   Energy efficient ventilation
–   Integrated mixed mode system

11.7   Day Lighting

11.7.1   Principles and Processes

In buildings, lighting has a major effect on the appearance of space and objects and is a significant energy consumer. The energy consumed by the artificial lighting is converted into heat, raising room temperature and thereby increasing cooling loads in summer. It has often been observed that in centrally air-conditioned buildings the energy consumption for lighting and the resultant increase in air-conditioning load is comparable to the basic air-conditioning load. In India it has been estimated (TERI 1994; TERI-MNES Report 1996) that electricity consumption for lighting in household, commercial and industrial sectors for 1995 was 31×10^9 kWh which was 15 % of total electricity consumed (210×10^9 kWh) during the same year. The typical distribution of energy consumption in a building is shown in Fig. 11.9.

In educational buildings and commercial offices about 60 % of energy is consumed for lighting. The lighting load is, therefore, a major component of the services costs in industrial and other commercial buildings. In residential buildings the lighting load is also a significant component. The proper use of daylight would impose much smaller cooling loads. Appropriate design of day-lighting for buildings has therefore received steadily increasing attention as a means of reducing the energy loads.

Furthermore, the sun provides natural light for vision. The brain finds visual comfort and satisfaction in daylight. The human eye has evolved over billions of years in the light of the sun. Its efficiency in receiving sensory information and transmitting it to the brain is at its maximum in sunlight. The eye can easily adjust to variations in the intensity and frequency of the solar-flux which may range from a few lux inside an unlit room to as much 100,000 lux in bright sunshine.

The temperature of the surface of the sun is around 6000 K and it radiates energy which corresponds to wavelengths of 0.25–8 µm. 48 % of solar radiation is in the visible range of 0.38–0.78 µm. The peak spectral sensitivity of human eye for photopic (day) vision is at 0.56 µm which lies almost in the middle of the solar spectrum. Moreover, the efficiency of sunlight in terms of lumen/W is very high
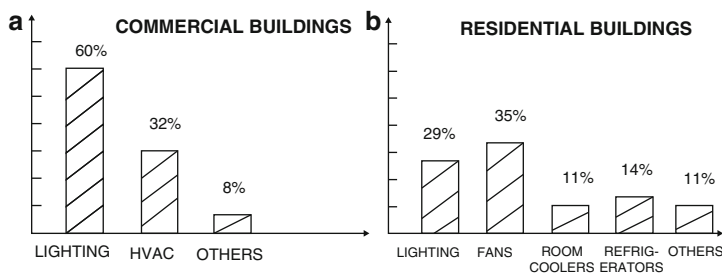
Fig. 11.9 Distribution of energy consumption in buildings in India. (**a**) Commercial buildings. (**b**) Residential buildings

(100–200 lm/W) as compared to the efficiencies of either incandescent lamps of 0–20 lm/W or fluorescent lamps of 30–80 lm/W. Thus for a given visual task, the solar radiation energy used in a room will be much smaller than the energy required by other light sources.

The full spectrum of sunlight is composed of many different wavelengths of electromagnetic energy, both visible and invisible to the human eye. These wavelengths of energy play an important role in human function and evolution. Scientists have found that exposure to sunlight regulates some of the basic biological functions of the body (Sharma et al. 2005). The basic reason for this is that many hormones and enzymes are very light sensitive. Exposure to sunlight consequently influences a host of physiological and psychological functions. Among these, fertility and mood are two of the most profoundly affected.

Sunlight is also an important source of vitamin D which is required for healthy bones, muscles and for the immune system. The principal function of this vitamin is to promote calcium absorption in the gut and calcium transfer across cell membranes. This contributes to strong bones and a contented nervous system. Scientists believe that sunlight possibly reduces the risk of several types of cancer including cancers of colon, ovary and bladder.

The syndrome known as SAD (seasonal affective disorder), which is defined as having a number of symptoms including depression, lack of motivation, change of appetite with particular food cravings, memory impairments, headaches, anxiety and irritability is caused by insufficient exposure to sunlight. It also appears evident that the pristine, full spectrum sunlight is a logical solution to the modern-day common dilemma posed by SBS (sick building syndrome).

The use of solar radiation has an advantage in that it changes direction and intensity with time. This variability of daylight is very pleasing to building occupants. It is in contrast to the monotonous environment produce by artificial lighting. It helps to create optimum working conditions by bringing out the natural contrast and colours of an object in the visible region of occupants. Windows and skylights which admit daylight in a building keep the occupants in contact with the outside world which is often very relaxing to the eyes.

11.7.2 Conventional Methods of Daylighting

Daylight (global radiation) is composed of direct (beam radiation) and diffused sunlight. Both of these components exhibit variability with time of the day, day of the year and atmospheric conditions. The global radiation suffers reflection from the ground and other objects. The daylight entering a building is therefore made up of three components:

1. Beam radiation from the sun.
2. Diffused sun light received from the sky.
3. The light reflected from the ground and other exterior objects.

All three of these components must be considered in relation to daylighting at an early stage of building design as do the orientation, space organization and geometry of the spaces to be lit. The lighting and thermal characteristics of glazing materials and internal partitions also play a part in deciding the location, form and dimensions of the openings through which light is to be admitted. Many methods of daylighting have been proposed and tested including light pipes, atria, external reflectors, light shelves, roof monitors, light wells, external/internal shades, claustras, tilted/reflective surfaces, prismatic components, reflective blinds and clerestories. Some of these components are illustrated schematically in Fig. 11.10. The daylighting of a room is characterized in terms of a parameter known as daylight factor which is defined as follows:

$$DF = (E_i/E_o) \times 100\% \qquad (11.1)$$

where E_i is the illuminance at a given point on a given plane due to light received from the sky of particular illuminance and E_o is the illuminance of same component of light on the horizontal plane due to the unobstructed hemisphere of the sky.

Daylight factor consists of three components:

1. The direct sunlight component.
2. The component resulting from light reflected from exterior objects.
3. The component resulting from light reflected within the room.
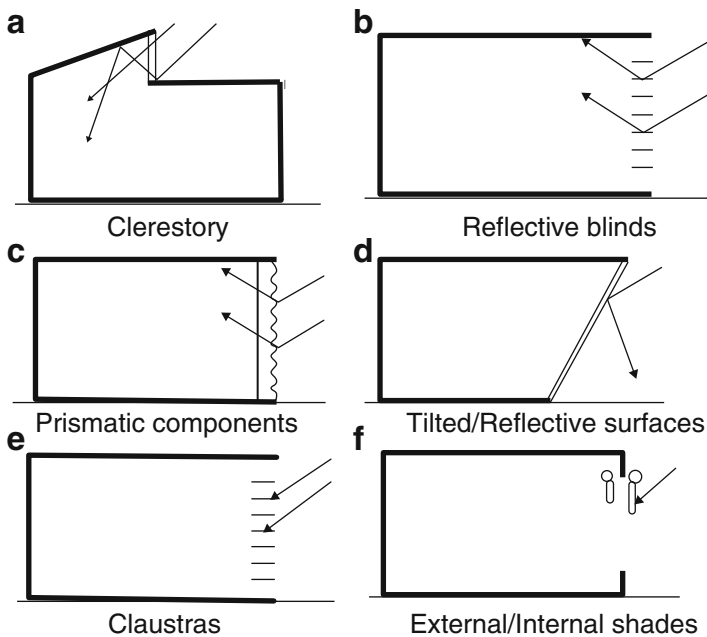
Fig. 11.10 Methods of daylight integrations in buildings. (**a**) Clerestory. (**b**) Reflective blinds. (**c**) Prismatic components. (**d**) Tilted/reflective surfaces. (**e**) Claustras. (**f**) External/internal shades

The recommended range of daylight factor for a workspace involving reading, drawing, typing or kitchen work is 2–4 % and for living and general purpose space, the day is 0.5–1.5 %.

11.8   Architectural Implementation and Experience

Passive technologies are simple to build and can go hand in hand with building design. They must preferably be incorporated as a part of the building since the latter is exposed to cyclic variations of climatic influences on a daily and seasonal basis. New and improved building styles are possible. As a result, a new design art in architecture has started to emerge which may be referred to as solar architecture. In solar architecture, building design seeks harmony with environment and balances human needs with environmental opportunities and liabilities. In what follows we present general guidelines of this approach.

Several passive components have been proposed and tested. In his book entitled 'Thermal Shutters and Shades', William Shurcliff (1980) gives about a hundred schemes for reducing heat loss through windows. Many other components for control of solar input, thermal storage and energy distribution have been reported in the literature.

Passive solar building design usually involves three criteria. These are ordered in a range from large-scale concerns to smaller ones. The first criterion takes care of the building environment in relation to sun, wind, temperature, humidity and trees. Building shape and orientation, protected entrance, prevailing wind direction and locations of trees etc. are some of the factors that are considered in this connection. This criterion is often referred to as bioclimatic consideration. The climate, temperature, sun, wind, and moisture are its basic constituents. Secondary considerations include rainfall, vegetation, topography, bodies of water (lakes, ocean, rivers etc.), geology/soil, seismic sensitivity, pests and wildlife. Other factors which also need to be considered in the finishing touch of a building are the archeological, historical and local arts and crafts resources as well as the impact of vernacular architecture. The second criterion is used for the selection of passive design concepts and components such as solar gain windows, clerestories and skylights, thermal storage walls, attached greenhouse systems and roof ponds are some of the factors often considered to this end. The third criterion is concerned with making the building more efficient as a passive solar system. Movable insulation, reflectors, shading devices etc. are considered for this purpose. In the terminology of practicing architects the above criteria are often referred to as patterns.

The solar contribution to the total building load can be significantly altered by careful application of the above design criteria (Szokolay 1975). It has been demonstrated that even in the cold Scandinavian climate it is possible to build a zero energy house (Tabor 1984). Passive solar design, therefore, seems to have high possibilities.

11.9   Thermal Evaluation of Passive Concepts: Sol–Air Temperature

In the thermal design of a building, the main aim is to calculate the solar heat flux entering the living space. The capacity, and hence the capital cost, of an air-conditioning plant is determined by the maximum thermal load, so the load-levelling of heat flux is also a consideration. A large number of factors related to climate and the structural configuration of the building control the indoor heat flux and hence the temperature. The effectiveness of these factors is too intricate to be assessed independently in a physical model. It is, therefore, necessary to have a mathematical model which can enable engineering analysis of the passive design concepts as well as predicting system performance. In this connection, the first step is the formulation of the thermal transfers in the building. The heat transfer through building envelope involves the solution of the Fourier heat conduction partial differential equation with a set of boundary conditions and initial conditions characterizing the building geometry. This is not always a simple task. There are many practical situations for which an exact solution cannot be obtained. This inability to obtain an exact solution may be attributed to the complex nature of the governing differential equations. The task becomes more difficult when the boundary conditions are nonlinear or thermal properties are temperature or space/time dependent.

Available methods for thermal calculations include numerical methods, harmonic or matrix methods and the response function methods. However, the climatic data (solar intensity and atmospheric air temperature) are usually periodic on a daily as well as yearly cycle basis. So the variations of solar intensity and atmospheric air temperature may be represented by Fourier series. Six harmonics are considered sufficient to provide a fairly good representation. Each term of the finite series is considered as a separate input. The responses are then synthesized to yield the desired output. This procedure obviously involves restriction on the applicability of analysis to situations where the thermo-physical parameters of the system are time and space invariant; the system must be linearized with regard to convective and radiative boundary conditions. However, for heat transfer in building walls and roofs, one-dimensional Fourier heat conduction is considered sufficient.

The harmonic method (often referred to as the periodic heat transfer method) has, therefore, been widely used for the evaluation of passive design concepts. One of the earliest analyses is due to Mackey and Wright (1946) who estimated heat gains through the walls and roof of a building having constant indoor temperature. For ease of analysis, Mackey and Wright combined air temperature and solar radiation into a single input variable known as sol-air temperature, as set out below.

The energy balance on the outer surface of the building element (wall/roof) is given by

$$-K' \frac{\partial T}{\partial x^{x=0}} = \alpha_1 S(t) - h_o(T(x=0) - T_A(t)) \qquad (11.2)$$

h'_o is a loss coefficient made up of convective, (h_c) and radiative (h_r') components

So we have

$$-K' \frac{\partial T}{\partial x^{x=0}} = \alpha_1 S(t) - h_c(T(x=0) - T_A(t)) - h_r(T(x=0) - T_A(t)) \quad (11.3)$$

The radiation loss (Q_r) in the above equation may, therefore, be expressed as

$$\begin{aligned} Q_r &= \varepsilon\sigma\left(t_{x=0}^4 - t_{SK}^4\right) \\ Q_r &= \varepsilon\sigma\left(t_{x=0}^4 - t_R^4\right) + \varepsilon\sigma\left(t_R^4 - t_{SK}^4\right) \end{aligned} \quad (11.4)$$

Or

$$Q_r = h_r(T_{x=0} - T_A) + \varepsilon\Delta R \quad (11.5)$$

Where,

$$h_r = \frac{\varepsilon\sigma\left(t_{x=0}^4 - t_{SK}^4\right)}{(T_{x=0} - T_A)}; \quad h_r = \frac{\varepsilon\sigma\left(t_{x=0}^4 - t_{SK}^4\right)}{(T_{x=0} - T_A)}$$

and ΔR is the difference between the long wavelength radiation incident on the surface from the sky and the surroundings and radiation emitted by a black surface at ambient temperature. Eq. (11.3) is more convenient an expression for finding exact solution for $T(x, t)$. Following Tiwari et al. (1985), $\varepsilon\Delta R = 61.1$ W/m^{2}K for a roof and $\varepsilon\Delta R = 0.0$ for a wall.

From Eqs. (11.2) and (11.3), we have

$$-K' \frac{\partial T}{\partial x^{x=0}} = h_o(T_{SA}(t) - T(x=0, t)) \quad (11.6)$$

$$h_o = h_c + h_r \quad (11.7)$$

$$T_{SA}(t) = \frac{\alpha_1 S(t) - \varepsilon\Delta R}{h_o} + T_A(t) \quad (11.8)$$

$T_{SA}(t)$ is known as the sol-air temperature.

In recent years several authors have used the periodic heat transfer approach to evaluate and optimize the performance of passive solar building components. Among other applications, the optimal location of insulation on walls/roof, cooling by water evaporation over roof and thermal storage and load-levelling by storage walls and roof ponds (Sodha et al. 1981; Kaushik et al. 1981) have been considered. The approach has also been applied to evaluate the thermal performance of energy efficient controls such as movable insulation (Kaushika and Rao 1983). In general, this involves the solving of the heat conduction equation for temperature distribution in the building element (wall/roof) when subjected to periodic solar radiation and atmospheric air temperature on one side and in contact with room air at

constant temperature (corresponding to air-conditioned rooms) on the other side. The day-to-night change due to movable insulation has been represented by a rectangular pulse functional variation of the heat transfer coefficient.

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Chapter 12
Energy Conservation

12.1 Terms and Definitions

In the preceding chapters it has been noted that energy is a key component of interactions between nature and society. It is key input for economic development and there is no source of energy that is absolutely benign in respect of the environment. These factors have led to global energy related environment concerns and call for effective short-term actions that are sustainable (which do not prejudice the future). An obvious and most overlooked approach in this regard is to reduce the consumption of coal, oil and wood fuels and conserve (save) them as the exhaustible gift of nature. The approach is referred to as Energy Conservation in resource conservation terminology. If the rate of growth of energy consumption is cut to 2 %, the life span of fossil fuel reserves is almost doubled. The may be affected by either reducing the energy demand or substituting the fossil fuel supply with less polluting energy sources for power production and other applications.

The schematic representation of various terms related to energy conservation is illustrated in Fig. 12.1. In practice, use of less energy to produce the same result by a rational use of energy involves energy management measures such as good housekeeping and operational practices as well as product mix. It can be taken up even without any technological improvement and significant amount of energy can be saved. Thus energy conservation is possible in an otherwise inefficient system. However, the term energy efficiency is explicitly used when as a follow up to energy management strategies the technological improvements such as design changes, new process technologies and modernization schemes are incorporated in the system and when the energy conservation is most effective.
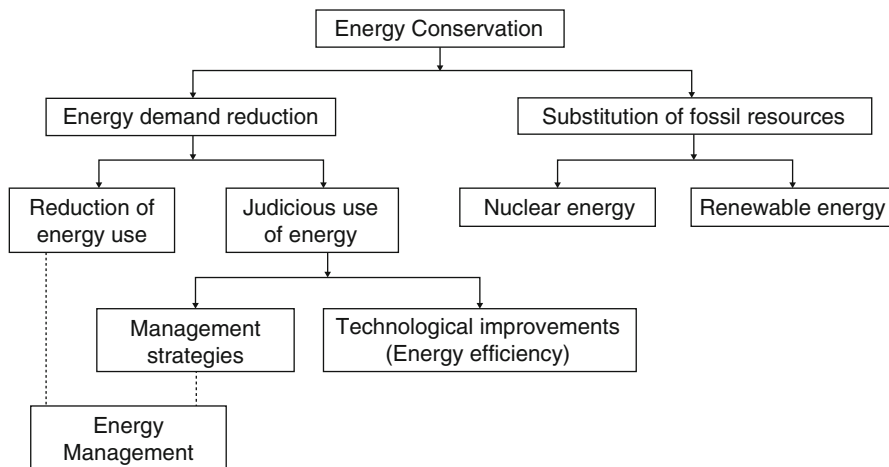
Fig. 12.1 Schematic representation of energy conservation implementation approach

12.2 Energy Management Strategies

Energy Management means the reduction in energy consumption through pragmatic policies and programmes without sacrifice of any sort. It is a strong management function and involves administrative fiscal and legal measures in housekeeping and operational practices as well as product mix.

General Principles of Energy Management
For suggesting an initial approach to the problem, the attractive conceptual way is to identify the fundamental principles of energy management. Some of the general principles that we experience in a wide variety of situations have been summarized in Tables 12.1, 12.2, and 12.3. A brief discussion will clarify how these principles will be applied to an energy user (Smith 1981).

12.3 Energy Management Programme (EMP)

The first step to begin a programme must come from either the company executive officer by responding to information from the company's energy suppliers that the firm faces possible curtailment or raising energy cost. The EMP involves three phases which include (a) Initiation phase, (b) Audit and Analysis phase and (c) Implementation phase.

Table 12.1 Energy management general principles: low cost

S. No.	Principle	Description	Remarks
1	Review historical energy use (review of historical data)	Sometimes seasonal variations or scheduling discontinuities are present but unrecognized; the review process brings them to light and may suggest ways of combining operations or otherwise effecting savings. However, historical data can provide the total picture but not sufficient details	Low relative cost; 5–10 % beneficial; Less complex and implementation time is about 1 year
2	Energy audits (review of current practice)	These are a means for investigating energy use by specific processes and machines, and provide insight into inefficient operations and less efficient methods	
3	Housekeeping and maintenance	Improving housekeeping and maintenance in the organization will generally save energy. Well maintained equipment has reduced frictional losses. Cleaned light fixtures transmit more light. Changing filters reduces pressure drop	Low relative cost; 5–15 % beneficial; Less complex and implementation time is about 1 year
4	Material quality selection (material purity and properties)	This is extremely important because the unnecessary extra quality will always lead to a higher cost and also greater energy use. For example, is distilled water needed, or is deionized sufficient? Purity of chemicals and process streams has an important impact on energy expense	
5	Economic evaluation	New equipments, processes or options must be studied to determine cost and returns which is very essential for energy management	
6	Material economy (acrap recovery, salvage, and recycle)	Recovery of scrap, reduction of waste and design for salvage; Product design which permits salvage or recovery of reusable parts, motors and components is a good example	Low relative cost; 10–50 % beneficial; Low to high complex and implementation can take a couple of years

Table 12.2 Energy management general principles: moderate cost

S. No.	Principle	Description	Remarks
1	Substitute material	**Substitute materials** can sometimes be used to advantage. For example, in low temperature applications, low melting point alloys can be substituted for high temperature materials	Moderate cost; 10–20 % beneficial; Less complex and implementation may take about 1 year
2	Analysis of energy use (engineering analysis, computer simulation, availability studies)	**Analysis** goes hand in hand with the energy audit to determine how efficient the equipment is, to establish what happens if a parameter changes (reduce flow by 50 %), how to simulate operations (computer models of building of process use)	Moderate cost; 10–20 % beneficial; Moderate complexity; implementation can take a couple of years
3	Energy containment (heat recovery and waste reduction)	**Energy containment** seeks to con- fine energy, reduce losses and recover heat. Examples include repair of steam leaks, better insula- tion on boilers	Moderate cost; 10–50 % beneficial; Moderate complexity; implementation can take many years

Table 12.3 Energy management general principles: high cost

S. No.	Principle	Description	Remarks
1	Alternative energy sources (energy form or fuel substitute)	These energy sources act as an alternative to fossil fuel. These alternatives are produced or recovered without the undesirable consequences inherent in fossil fuel use, particularly high carbon dioxide emissions, an important factor in global warming	Relatively moderate to high cost; 10–30 % beneficial; Moderate to high complex and implementation may take many years
2	Energy conversion	Energy in many of its forms may be used in natural processes, or to provide some service to society such as heating, refrigeration, light, or performing mechanical work to operate machines. For example, a solar cell converts the radiant energy of sunlight into electrical energy that can then be used to light a bulb or power a computer	

Table 12.3 (continued)

S. No.	Principle	Description	Remarks
3	Energy storage	Energy storage provides an important tool in efforts to increase overall process efficiency and helps reducing the peak demand for certain energy forms particularly electricity	
4	More efficient Equipment	This can often be substituted to fulfil the same function, e.g. LED, CFL lamps rather than incandescent lamps for area lighting. Many types of industrial and residential/commercial equipment are now rated or labelled in terms of their efficiency; there are wide variations among different manufacturers depending on the size, quality, capacity and initial cost	
5	More efficient processes	Efficient processes can often be substituted without detrimental effect on product quality. A classic example is that a small sawmill may simply throw away the sawdust and old wood scrap but this can be used as a sweeping compound for cleaning floors and hallways in large buildings	
6	Aggregation of energy uses	This permits energy efficiency to be achieved in certain situations. For example in a manufacturing plant it is possible to physically locate certain process steps in adjacent areas so that energy used for transportation of materials is minimised	Relatively moderate to high cost; 20–50 % beneficial; highly complex and implementation may take many years
7	Cascade of energy uses	Maximum utilization of energy can be done by cascading the systems like using condensate from a cooling tower to preheat materials or feedstocks	

12.3.1 Initiation Phase

After deciding to initiate the program, the energy manager should take certain steps to ensure its acceptance and success. Depending on the size and complexity of the firm, the first step may be the formation of an energy management committee with representatives from various departments or divisions using energy. Secondly, the energy manager should explain the department heads or line supervisors about the need for the program in economic and supply point of view. The committee should take steps on reducing wastes by informing the need to production personnel. The purpose of such a committee is to coordinate plans, bring in new ideas and perspectives, and to ensure that the actions taken in one part of the plant do not have an unfavourable effect on the other part.

12.3.2 Audit and Analysis Phase

After the completion of initiation phase, the next phase involves determining how and where the energy is being used. First look at the methods and objectives of the historical energy use analysis. In many cases it is useful to relate historical energy use to weather conditions and to some measure of productivity. The historical survey can be compiled from utility bills, plant records, and production statistics. The objective is to understand both near and long term trends and energy use.

Often it is useful to relate the past 5 years energy usage to some measure of productivity. This not only gives the information useful in assessing the operation of a particular plant or process, but it can also provide comparative data between two or more plants.

In the energy audit, the detailed information is obtained for each piece of equipment and process. This can be done on process basis or a facility basis. The results of the audit can be used to delineate major areas of energy use and to formulate an energy management programme. During the audit, typical loads and equipment usage are measured or estimated. By combining all loads the monthly total energy use can be calculated compared with historical records. The final step in the programme is to establish energy usage goals and reporting procedures for follow-on activities which permits a review of the success of projects.

12.3.3 Implementation Phase

This phase is the most critical aspect of the entire programme, since this is the central goal of any energy management effort. The main desire for the firm is to carry out the measures which have been identified by the energy management. Obviously, one requirement of this phase is to prepare the firm to make the necessary investments to begin saving energy. The next step is to get the management to agree to flagging the savings resulting from the first implementation steps.

When the possibilities for saving money and energy are fully understood, the necessary changes will be made.

Ultimately, the human beings who are entrusted with marvels of engineering are supposed to save all this energy and money. Finally, the programme must succeed and be reviewed periodically to determine its strengths and weaknesses.

The step by step process of each phase in Energy Management Programme has been illustrated in Table 12.4

Table 12.4 Planning steps of three phases in energy management programme (EMP)

	Initiation phase		Audit and analysis phase		Implementation phase
a.	Commitment by management to an energy management programme	a.	Review of historical patterns of fuel and energy use	a.	Establish energy effectiveness goals for the organization and individual plants
b.	Assignment of an Energy Management Coordinator	b.	Second step in the audit and analysis phase is facility walk-through survey	b.	Determine capital investment requirements and priorities
c.	Creation of an Energy Management Committee of major plant and department representatives	c.	Preliminary analyses, review of drawings, data sheets, equipment specifications	c.	Establish measurement and reporting procedures. Install monitoring and recording instruments as required
		d.	Development of energy audit plans	d.	Institute routine reporting procedures ("energy tracking" charts) for managers and publicize results
		e.	The next step includes conduct facility energy audit, covering both the processes, facilities and equipment	e.	Promote continuing awareness and involvement of personnel
		f.	Calculation of annual energy use based on audit results	f.	Provide for periodic review and evaluation of overall EM programme
		g.	Comparison with historical records		
		h.	Analysis and simulation step to evaluate EM options (Engineering calculations, Heat and mass balance, Theoretical efficiency calculations, computer analysis and simulation)		
		i.	Economic analysis of selected EM options (Lifecycle costs, Rate of return, Benefit-cost ratio)		

12.4   Energy Audit (EA)

Energy audit can be defined as follows: An energy audit serves the purpose of identifying where a building or plant facility uses energy and identifies energy conservation opportunities. It is the fundamental part of an energy management programme of any organisation which wishes to control its energy cause. The construction of a complete and detailed energy audit is an intricate, tedious but necessary procedure so that major energy use activities can be identified.

There is a direct relationship to the audit and the number of energy conservation opportunities to be found. Thus, a first distinction is made between cost of the audit which determines the type of audit to be performed. The second distinction is made between the type of facility. For example, a building audit may emphasize the building envelope, lighting, heating and ventilation requirements. On the other hand, an audit of an industrial plant emphasizes the process requirements.

The Energy Audit (EA) consists of:

(a)   A complete study of the consumption and costs of all purchased energy
(b)   How it is distributed throughout the plant
(c)   How it is used in individual systems and processes
(d)   The potential for energy saving and where it exists
(e)   The capital costs involved in recovering that potential

EA provides the basis for creating a very inexpensive energy information system (EIS), which can and should be incorporated into the present management information system (MIS) (Haimes 1980). EA also represents in effect the total body of knowledge needed by management to institute effective energy conservation (EC) programme.

The particular uses to which the audit can be applied are:

(a)   To inform management of the growing cost of energy and to provide motivation for carrying out an EC program as a cost-containment measure
(b)   To inform the engineering staff of the plant's energy utilization characteristics so that intelligent EC measures may be planed
(c)   To provide management with the information needed to make wise investment decisions concerning EC measures
(d)   To provide part of the basis for planning and installing alternate fuel
(e)   To provide base-line energy consumption data to which future energy consumption can be compared
(f)   To provide the basis for a perpetual EIS that can be integrated with existing MIS
(g)   To uncover poor housekeeping practices that can be quickly remedied to give almost immediate energy and cost savings

In other words, EA provides the rationale for an energy management program. All the information for design, implementation, evaluation of EC measures, and the base upon which to build the EIS which is needed to complete the MIS.

12.5   Energy Conservation

Energy conservation is a broad term that includes stoichiometry, thermodynamics and economics. The First Law of Thermodynamics states that energy can neither be created nor destroyed. This law alone is of little help in determining how effectively a given energy resource is used to perform a given task. In this era, thermal energy and electrical energy are the major forms of energy to be conserved.

Energy conservation is best achieved by aggregating sequential and interacting activities both in space and time so that energy systems may supply requirements in a continuous manner from the highest temperature level in small steps to the lowest temperature sink (Smith 1981).

The consumption of energy implies following basic processes:

(a) **Combustion**: In the most ideal and efficient combustion of fuels, the fuel is burned completely to CO_2 and H_2O with 0 % excess air so that there is no oxygen leftover. When extra air is used for combustion, energy loss increases. Excess air increases the fuel rate because of greater amount of hot combustion gas leaving the furnace and it also raises the temperature of the exhaust combustion gases.

(b) **Transformation and utilization**: Energy transformation and utilization is to be carried out to its different forms with the maximum efficiency. Different techniques like cogeneration in power plant, combustion air preheating in IC (Internal Combustion) engines, heat transfer through counter flow heat exchangers etc. should be adopted to minimise the losses.

(c) **Rejection to the environment**: The useful form of energy is to be stored in such a way that it does not affect the surroundings and the released energy during the processes should not harm the environment. So, rejection of heat to the environment is also one of the important concerns that is to be taken care of. Therefore, all these play an important part to study energy optimization.

12.6   Energy Conservation in Various Sectors

There is a significant potential to conserve energy in various sectors such as (a) Buildings, (b) Heating and cooling, (c) Electrical loads and (d) Lighting etc.

12.6.1   Building and Site Energy Surveys

The site and building energy systems include: electricity, natural gas, LPG, chilled water, hot water, potable water supply. The first step is to identify all the possible energy forms and then obtain historical data on their annual use and cost. The second step is to obtain or prepare simplified plans which shows the location of each building, substations, transmission lines, steam lines, water lines, etc.

Surveys of all building and site energy and utility systems should be performed to determine and document the following:

1. Energy entering the site or building
2. Energy generated, distributed and consumed on the site or in the building
3. Energy leaving the site or building
4. Site-wide waste energy collected, treated, discharged, re-circulated and reused on site

So energy audits, consisting of building and site surveys, are a useful tool for the energy manager. They assist in setting priorities and provide a mechanism for evaluating the effectiveness of an energy management programme.

Principles of EM in Site and Building Surveys

Following are the important activities to be performed during the survey:

1. Coordinate with operating management. (Solicit assistance of people working at
   facility)
2. Obtain and review historical data prior to survey
3. Conduct preliminary walk throughout the facility
4. Plan the energy audit survey
5. Conduct the energy audit survey, following the plan as a guide and using the proper facility energy audit forms
6. After the survey, review the forms to assure completeness, readability, and reasonableness of values
7. Recheck suspicious entries before leaving the site

Important Survey Items

Lighting: Check for unnecessary lighting in halls, stairwells, unused areas, storage areas and parking lots, excessive levels.

HVAC: Check thermostat settings, filter maintenance, and other systems maintenance performed at proper intervals, controls, system capacity, overall operation.

*Process Area***:** Check total capacity measured against needed capacity, heat losses and vapour losses, equipment use schedules.

Furnace and ovens: Check total capacity measured against needed capacity, idling temperatures, need for constant operation.

*Plant air systems***:** Check for leaks and maintenance procedures.

Boilers and steam lines: Check for efficiency of burner settings, steam leaks, and lack of insulation, opportunities for heat recovery.

*Numerical controlled machines***:** Check need for full operating pressure to maintain hydraulic fluid flows and temperatures.

*Electrical and other special building equipment***:** Check need for continuous operation, demand control, power factor, etc.

Water: Check pumping capacity requirements, pump efficiency, head losses.

*Material transport***:** Check for more direct routes, less energy intensive modes, and operating requirements.
General: Verify need for all energy-using equipment.

12.6.2   *Management of Heating and Cooling (HVAC)*
Systems

Heating, Ventilating and Air conditioning (HVAC) systems are the major users in buildings. Systems designers are now beginning to recognize the importance of more efficient designs. Given the new energy economics, energy managers will find it useful to probe into the operation of existing HVAC systems and to review carefully the design of new installations.

Major and minor energy savings can be achieved by coming out with certain strategies in the form of:

1. Operation and maintenance strategies applied to heat sources, chiller, fans, pumps, ducts, and dampers and controls.
2. Modification and retrofit strategies applied to components or complete systems.
3. New system design, utilizing variable air volume and other approaches.
4. Heat recovery and economizer systems.

Principles of EM for HVAC System

Optimize controls: Use controls to provide heating and cooling only when it is required.
Optimize capacity: Review the system capacity and get rid of excess capacity.
Reduce the load: Minimize heating and cooling loads by reducing infiltration, solar heat loads, etc.
Heat and cool people, not buildings: Do not condition unoccupied spaces; provide heating and cooling where people work, rather than in aisles, etc.
Use efficient processes: select the most efficient heating and cooling process for the building, its occupants, and for the climate. Customize systems for intended uses.
Use efficient equipment: select the most efficient equipment for the heating and cooling process.
Operate equipment efficiently: Make certain existing equipment to operate as efficiently as possible; correct deficiencies.
Use passive concepts: Make the building and the climate do as much of the heating/ cooling work as possible.
Employ heat recovery: Heat can be recovered from equipment, building exhausts, and other sources.
Provide energy storage capability: Energy stored can permit off-peak use of equipment, load levelling, and more efficient utilization of equipment.

12.6.3   Electrical Load Management

It provides a review of certain basic relations of electrical engineering theory and outlines steps the energy manager can undertake to evaluate electrical loads. Typical energy management opportunities for each type of loads are reviewed. In fundamental thermodynamic terms, the efficient use of electricity is several times more important than the efficient use of other fuels.

Rising costs, coupled with an increasing demand for electricity in the future, combine to give electrical energy management programmes a special importance.

Principles of EM for Electrical Loads

Optimize controls: Use silicon-controlled rectifier (SCR) motor drives; install selective switching for lighting circuits.
Optimize capacity: Provide required power on electric drives and heating systems.
Reduce the load: Provide only necessary illumination levels.
More efficient processes: Use microwave or dielectric heating rather than resistance heating.
Employ special techniques to reduce losses: Decrease I^2R losses, apply power factor corrections.
Energy containment: Reduce losses from heaters, recover heat from motors, transformers, or equipment.
Cascade of energy uses: Co-generate electricity used in the facility.
*Energy conservation***:** Convert pneumatic powered equipment to electric.
Energy storage: Use demand control technique to shift loads off-peak.

12.6.4   Lighting System Management

12.6.4.1   Illumination and Human Comfort

Illumination has been considered from two points of view by building designers. An architectural medium is the first view which sense that illumination may be combined with building shape, form, colour and other variables to produce an esthetic and functional structure. The second view is to emphasize the pragmatic aspects of illumination and to provide the illumination required to accomplish visual tasks. To ensure human comfort, illumination must provide more than just light. The factors which enter into acceptable illumination are:

(a)   Illuminance and luminance
(b)   Glare
(c)   Colour
(d)   Contrast
(e)   Shadows
 (f)   Task difficulty and duration
(g)   Occupant age

The luminous flux emitted by lights is measured in *lumens* (lu).
The luminous flux per unit area is called the *illuminance* (lu/m^2 or lux)

Visual acuity, which is measure of one's ability to perceive fine details, depends on Contrast. Contrast related to the luminances of an object and its immediate background.

$$Contrast\ (C) = (Lo - Lb)/Lb \tag{12.1}$$

where Lo = luminance of object Cd/m^2
Lb = luminance of background Cd/m^2

Reflectance = Luminance/Illuminance
Contrast Rendition Factor (*CRF*) is given by

$$CRF = \frac{actual\ visual\ task\ contrast\ in\ building}{visual\ task\ contrast\ with\ sphere\ illumination} \tag{12.2}$$

12.6.4.2   Illumination Systems and Equipment

A Lighting system mainly consists of the following components: Ballast, Reflector, Lamp, Lens and Controls. Systems are generally classified according to lamp category, although purpose or type is an alternative method of classification. The lamp types of interest to the energy management are incandescent, fluorescent, mercury vapour, metal halide, sodium vapour and tungsten. Properties of typical lamps and ballasts are tabulated in Table 12.5.

Energy Management Opportunities in Lighting Systems

Delamp: It is appropriate to reduce the lightning levels where excessive illumination occurs.

Disconnect ballasts: Ballasts dissipate energy in much the same manner as transformer. Savings can be obtained by disconnecting the ballasts which still dissipate energy even if the lamps have been removed.

Table 12.5 Properties of various lamps and ballasts (Smith 1978)

S. No.	Lamp type	Power (W)	Overall efficacy (lu/W)
1	Incandescent	100–200	13.8–15.2
2	Incandescent tungsten glass halogen	100-200-500	16.7-17.6-19.8
3	Compact Fluorescent	9–32	46–75
4	Light-emitting diode (LED)	7, 8.7	60, 69–93.1
5	Gas discharge sulphur lamp	1400	100
6	Low-pressure sodium	90, 180	55–80, 85–125
7	High pressure sodium	250, 400	60–86, 72–103
8	High pressure metal-halide	400, 1000, 2000	45–52, 51–60, 58–68

Relamp: If illumination levels are already too high, but it is desirable to maintain the present distribution of light fixtures, it may be possible to relamp with a lamp which uses less power.

Using the most efficient light source: It is appropriate to replace incandescent with CFL and fluorescent with metal halide of sodium to reduce the energy losses.

Use time clocks or photocell controls: Automatic switching either by photocontrol can ensure that lighting is being used only when it is required.

Use zone switching: A selective switching will enable an individual to turn off specific light fixtures when no one is using that particular area.

Use task lighting: Optimum efficiency can be achieved by keeping the light source as close as reasonably possible to the work area.

Effective use of day lighting: Day lighting can be incorporated by using effective building designs whereever possible.

Use of more efficient lenses: It is economical to replace the lenses which will increase light output as well as reduce the number of lamps.

Clean luminaries to increase illumination: By cleaning light fixtures more light can be delivered, better appearance can be obtained.

Improve colour and reflectivity: Illumination can be improved by cleaning walls, ceilings, and floors or repainting them with lighter colours to reduce lighting energy needs.

Energy awareness programme will help training personnel to turn lights off when not needed.

12.6.5 Electric Heat Management

Electric heat is not used extensively for process heat due to its higher relative cost. However, there are some types of applications where electricity offers advantages for heating. Electric heat can take several forms such as microwave heating, induction heating, electron beamheating, RF drying and heating, dielectric heating, electric arc heating and infrared heating.

Resistance Heating

The generation of heat by electric conductors carrying current; degree of heating is proportional to the electrical resistance of the conductor; used in electrical home appliances, home or space heating, and heating oven sand furnaces. Some of the drawbacks are: (a) source of heating is required along with a container to which the heat is supplied, (b) Irreversible losses associated with heat transfer and (c) Since the container must be heated, more energy is supplied than really required.

Microwave Heating

It is highly efficient technique for heating by heating frequency electromagnetic radiation. There is no loss associated with the warm-up and cool-down of ovens. The heat is applied directly when needed. Furnaces can be designed to be resonant or non-resonant. The microwave oven is an example of resonant cavity device. A microwave frequency is selected that permits the microwave energy to interact with

the material to be heated, and not with other material. Typically the frequency is greater than 2000 MHz. By interacting at the molecular level, heat is deposited directly in the material to be heated, without having to preheat an oven. It also avoids the heat leakages from the oven. By selectively applying heat only to the material to be heated, parasitic losses are avoided. This improves quality by not heating other materials.

The following are the energy management opportunities to reduce heat losses

(a) Insulate furnace walls, ducts, piping.
(b) Put covers over open tanks or vats.
(c) Reduce the time of doors being opened.
(d) Avoid cooling time for heated products.
(e) Shut down heating system when not in use, or at least lower temperature (reduce standby losses).

For more efficient equipment or process, we have to

(a) Use alternative processes such as microwave, dielectric etc.
(b) Employ recuperators, regenerators or preheaters.
(c) Use direct-fired rather than indirect-fired systems.
(d) Use less energy-intensive materials in processes.
(e) Use heat pumps for low temperature process heat.
(f) Reduce moisture content mechanically in materials used in drying processes.
(g) Use lower temperature processes (cold rinses, etc.)

12.6.6   Process Energy

Process energy especially in industry is a vital application of energy resources. Industrial processes are responsible for food preservation, clothing, pharmaceuticals, vehicles and many other products which have improved the standard of living. Certain processes require precise control of temperature or pressure or some other variable and deviations will almost certainly affect product quality or production.

Yet, there are also other areas where substantial improvements in process energy use efficiency are possible. So, energy manager should review the energy used by the processes and identify those areas where losses occur. With this knowledge it may be possible to improve energy use efficiency.

Some of the operational and maintenance strategies (OMS) for process energy management are to reduce infiltration in buildings, repair leaking valves or steam traps, reduce compressed air leaks, correct power factors, optimize excess air to combustion processes and clean lamps and filters. Secondly, retrofit or modification strategies (RMS) are to insulate buildings, steam pipes, furnaces, ovens etc. and to reduce radiation losses from high temperature processes. Orienting proper buildings on sites and using passive design techniques for new buildings are the new design strategies.

12.6.7 Recovery Heat Management

There are multiple sources stacks, processes, building exhaust streams, cooling towers compressors etc. Recovered heat can be used for space heating, water heating, process preheating, cogeneration etc. Heat recovery by commercial systems can be of many types such as heat wheels, run around systems, heat pipes, heat exchangers, heat pumps etc.

12.6.8 Electrolytic Process Management

Electrolysis involves the movement of positively or negatively-charged ion within an electrolyte between an anode and a cathode. Some of the familiar processes that involve electrolysis are storage batteries, welding, corrosion, refining of metals, plating and anodizing, electroforming and etching and fuel cells.

The energy management opportunities in electrolysis for corrosion protection are using protective films, paints, epoxy etc., provide cathodic protection with an applied voltage, electroplating and anodizing, using chemical water treatment (corrosion inhibitors) and avoiding contact of dissimilar metals (dielectric unions).

In storage batteries, it is efficient to provide adequate maintenance (replace electrolyte, clean terminals), by using efficient charging techniques, charge at proper rates, avoid overheating and prove adequate ventilation. During electrolytic processes, insulating the plating tanks, providing proper maintenance of electrodes and rectifiers, recovering waste heat, using more efficient rectifiers (silicon versus mercury arc), using more efficient controls and developing improved electrode design and materials to increase efficiency are some of the energy management opportunities.

12.6.9 Energy Management in Manufacturing Processes

In machining, eliminate unnecessary operations and reduce scrap, sizing the tool, the feed rate, the depth of cut, the motor to the job and substituting power metallurgy for machining operations (use induction furnace) will improve the efficiency of the processes.

Following are some more energy management opportunities which will help in improving the efficiency of manufacturing processes.

(a) Carefully review hardening requirements. Carburizing is energy-intensive.
(b) Substitute cold forging for hot if possible.
(c) Avoid overdesign which requires excessive use of energy intensive materials.
(d) Reuse or recycle scrap
(e) Design products to permit recovery of energy intensive materials or components.

 (f) Control air usage in paint spray booths. Exhaust air carries away heat.
 (g) Evaluate paints and coatings.
 (h) Solvent-based paints are less energy intensive than plating; water based paints
      still less.

   (i) Improve plating efficiency by reducing heat losses from tanks, improving
        rectifier performance, checking cables and conductors, modifying
        controls.

12.7   Energy Efficiency: Exergy Analysis

The potential of energy saving in an industry depends on the efficiency with which
it is used. The common practice to define the efficiency of energy use by the first
law of thermodynamics states that: Energy is conserved. It deals with the amount of
energy of various forms; it takes into account the changes in energy stored in the
system and the energy transferred between the system and its surroundings. It treats
work and heat interactions as equivalent forms of energy. The second law of
thermodynamics deals with the work potential of an energy source; which is the
amount of energy that we can extract as useful work; it is referred to as available
energy (exergy). The energy that is not available for converting to work will
eventually be discarded as waste energy. The second law allows us to define
quantities like 'available work', 'lost work' and the second law efficiency (ideal
maximum efficiency) as follows:

$$\text{First law efficiency: } \eta_{\text{I}} = \frac{\text{Work output}}{\text{Energy input}}$$

$$\text{Available work of a system: } B = E + P_0V - T_0S - \Sigma_i^n \mu_i n_i$$

Second law efficiency:

$$\eta_{\text{II}} = \frac{\text{Useful energy, heat or work transferred by a system}}{\text{Maximum useful heat or work transferrable (Available work)}}$$

where E – Internal energy, V – Volume, S – Entropy, P_0 – Atmospheric pressure,
T_0 – Ambient temperature, n_i – number of moles of ith component and μ_i – potential
per mole of ith component. The corresponding first and second law formulations for
various energy conservation systems are given in the Table 12.6.

   If the characteristic temperature of fossil fuel combustion is T_1 and the amount of
heat produced is Q. The exergy of heat input (Ex_i) in the boiler is given by:

$$E_{xi} = Q\left(1 - \frac{T_0}{T_1}\right) \tag{12.3}$$

Table 12.6 First law and Second law efficiency formulation for energy conversion systems

S. No.	System	First law efficiency η_I	Second law efficiency η_{II}	Remarks
1	Furnace	$\eta_I(COP) = \frac{Q_2}{Q_1}$	$\eta_{II} = \eta_I \left(\frac{1 - \frac{T_0}{T_2}}{1 - \frac{T_0}{T_1}} \right)$	W_{in} – Work input
2	Power plant	$\eta_I = \frac{W_0}{m.CV}$	$\eta_{II} = \frac{W_0}{B}$	W_0 – Work output
3	Engine driven heat pump	$\eta_I(COP) = \frac{Q_2}{m.CV}$	$\eta_{II} = \frac{Q_2}{B} \left(1 - \frac{T_0}{T_2} \right)$	CV – Calorific value
4	Electrical driven heat pump	$\eta_I(COP) = \frac{Q_2}{W_{in}}$	$\eta_{II} = \eta_I \left(\frac{T_0}{T_3} - 1 \right)$	Q_1 – Heat from hot reservoir at T_1
5	Electric refrigerator	$\eta_I(COP) = \frac{Q_3}{W_{in}}$	$\eta_{II} = \eta_I \left(1 - \frac{T_0}{T_2} \right)$	Q_2 – Heat added to warm reservoir at T_2
6	Vapour absorption system (VAS)	$\eta_I(COP) = \frac{Q_3}{Q_1}$	$\eta_{II} = \eta_I \left(\frac{\frac{T_0}{T_3} - 1}{1 - \frac{T_0}{T_1}} \right)$	Q_3 – Heat extracted from cold reservoir at T_3
7	Gas power cooling system	$\eta_I(COP) = \frac{Q_3}{m.CV}$	$\eta_{II} = \frac{Q_3}{B} \left(\frac{T_0}{T_3} - 1 \right)$	B – Available work
8	Electric motor	$\eta_I = \frac{W_0}{W_{in}}$	$\eta_{II} = \eta_I$	

Since the first law efficiency of steam production is 85 % for the exergy used in the production of steam (Ex_o) of temperature (T_2) is given by:

$$E_{xo} = 0.85 Q \left(1 - \frac{T_0}{T_2} \right) \tag{12.4}$$

Second law efficiency is, therefore given by:

$$\eta_{II} = \frac{0.85 Q \left(1 - \frac{T_0}{T_2} \right)}{Q \left(1 - \frac{T_0}{T_1} \right)} \tag{12.5}$$

Example 1 Consider the case of steam production in a fossil fuel based boiler. Plant engineers usually cite an efficiency of 85 % based on first law of thermodynamics. Let us examine the second law efficiency for the process of steam production at 550 K.

For typical parameters:

$$T_0 = 300 \text{ K (Ambient temperature)}$$
$$T_2 = 550 \text{ K}$$
$$T_1 = 10^4 \text{ K}$$

We have

$$\eta_{II} = \frac{(0.85)\left(1 - \dfrac{300}{550}\right)}{\left(1 - \dfrac{300}{10,000}\right)} = \frac{0.4545 \times 0.85}{0.97}$$

$$\eta_{II} = 0.398$$

Example 2 Let us consider a solar concentrating collector of first law efficiency of 65 % at a collector temperature (T_c) of 500 K. The second law efficiency may be estimated as follows:

The exergy input is in the form of solar radiant energy of concentration, Q.
If the solar radiation temperature is T_R.
The exergy input in the collector is given by:

$$E_{xi} = Q\left(1 - \frac{T_0}{T_R}\right) \tag{12.6}$$

Exergy of the collected heat

$$E_{xo} = 0.65Q\left(1 - \frac{T_0}{T_C}\right) \tag{12.7}$$

The second law efficiency of the collector is given by

$$\eta_{II} = \frac{0.65\,Q\left(1 - \frac{T_0}{T_C}\right)}{\left(1 - \frac{T_0}{T_R}\right)} \tag{12.8}$$

Typical parameters are:

$$T_0 = 300 \text{ K}$$
$$T_C = 500 \text{ K}$$
$$T_R = 5760 \text{ K}$$

So we have

$$\eta_{II} = \frac{0.65\left(1 - \dfrac{300}{500}\right)}{\left(1 - \dfrac{300}{5760}\right)}$$

$$\eta_{II} = 0.268$$

Table 12.7   Typical energy efficiencies of selected processes

S. No.	Application	1st law efficiency (%)	2nd law efficiency (%)
1.	Solar concentrating collector	65	27
2.	Boiler	85	40
3.	IC Engine (Diesel)	40	10
4.	Space heating or cooling	50	5
5.	Lighting (Incandescent)	5	5

The above numerical illustrations show that the energy services have low efficiencies when estimated using the second law of thermodynamics. Same has been reported (Raghuraman and Mahajan 1985) true for several industrial processes as shown in Table 12.7. The lower value of second law efficiency points out that there are gross mismatches between the energy and the tasks to be performed by that energy. Consequently, second law efficiency may be used as an indicator for estimating the potential for improving the efficiency of a process. In contrast the efficiency evaluated on the basis of first law indicates only the quantity of heat available in different states of the process. This can be obviated by understanding the heat levels quality-wise and each category of heat usage can be analysed through exergy analysis. The exergy analysis can, therefore, be used to optimize the design of energy systems to keep down the energy input into the system to the minimum possible level.

12.8   Energy Efficiency Technologies

The commercial energies such as electricity and heat are extremely used in industry, transport and building sectors. Energy efficiency in these sectors are very important and discussed in the following sections.

12.8.1   Thermal Energy Efficiency

In industrial sector several new developments have taken place in the domain of thermal energy efficient technologies. These developments may be classified into two categories: (i) those which are specific to a process within one industry and (ii) those which are applicable to more than one industry. The second category includes combustion efficiency, cogeneration, waste heat recovery and the use of industrial waste.

(a)   **Combustion Efficiency**: In industrial sector, heat is often generated from the combustion of fossil fuels. In traditional systems, combustion efficiencies are quite low; for example 50 % for low temperature and 10 % for low temperature

processes. Several improvements in combustion technologies have been proposed and tested around the world which include improved burner configurations, coal fired retrofit combustors, oxygen enriched combustion, fluidized bed combustion and microprocessor based combustion controls. Most of these technologies have been discussed in the chapter on air pollution control methods. Some of these technologies are still not cost effective. For example, oxygen enrichment increases the energy efficiency and significantly increases the production rate. However, the cost of equipment for producing oxygen enriched air and the incremental energy required in oxygen separation plant often offsets the advantage resulting from the decrease in fuel requirement.

Yet another method to utilize the coal efficiently is through the gasification route. The resultant gas can be utilized in a combined cycle power plant to generate electricity; the gas can also be used in process industries for several non-fuel applications such as reduction, feed stock for synthetic gas etc.

(b) **Co-Generation**: The use of single stream of energy for several processes in sequence is referred to as energy cascading. The concept of co-generation of process steam and power is the most discussed form of energy cascading. Experience over the years has indicated it to be an important energy saving approach. It is particularly suitable for chemicals, paper, textiles sugar, food and petroleum refining industries. The co-generation systems can be set up in two configurations referred to as: (i) bottoming and (ii) topping cycle. The terminology refers to the point at which the electrical or mechanical energy is produced. In topping cycle the fuel used to produce high temperature steam which is expanded through a turbine to produce mechanical or electrical power; the waste heat from power generation is used to produce process steam. The topping cycle co-generation systems have an overall efficiency of 70–75 % as compared to an efficiency of 50–55 % for the separate power plants. The cost effectiveness of a topping cycle co-generation system for a particular application is a sensitive function of the variability of steam demand, advanced multi fuel high power to thermal ratio prime mover are, therefore used in such co-generation system.

(c) **Combined Cycle**: The combined cycle of a topping cycle co-generation system can be quite advantageously retrofitted to existing plants. For example, the second law efficiency of paper production is of the order of 1 % and heat to power ratio 2:5 makes a strong case for co-generation system. Presently in India paper mills meet 25–100 % of their needs through such co-generation systems.

In the bottoming cycle, the fuel is burnt to produce process steam and the waste heat is converted to either electrical or mechanical power. The bottoming cycles operating in low temperature (200–300 °C) can provide a substantial saving of energy. Organic fluid turbines are used in such co-generation systems. Organic fluid turbines are similar to steam turbines and are based on Rankine power cycle. Their working fluid is not steam but an organic fluid with low boiling temperature (such as freons), chlorinated hydrocarbons, or hydrocarbons such as toluene. These are high-molecular weight fluids and so the turbine

is smaller in size than the corresponding steam turbine. In most industrial applications the demand for process steam is too low for waste heat to be effectively used in power generation. Many industries utilize the co-generation systems as a contingency measure to combat the shortage in grid power rather to generate captive power.

(d) **Waste Heat Recovery**: Waste heat of broad range of temperatures is generated in almost all industries. The flue gases from boilers and industrial furnaces constitute the single biggest source of high temperature waste heat. Present day engineering efforts for this high temperature heat recovery lay emphasis on combustion air preheaters. This approach as compared to conventional waste heat recovery methods has several such advantages as better combustion and improved flame pattern. The air preheating equipment is a special type of heat exchanger which involves relatively large heat transfer area for the same heat transfer conditions. Based on these special constructional features two types of air preheaters have been developed: (i) regenerative and (ii) recuperative. In the regenerative type preheater the heat transfer surface is alternatively exposed to hot flue gas and cold combustion air respectively. The recuperative type air preheaters are available in three basic configurations: tubular, plate and cast fin. The cast fin air preheaters are perhaps most versatile. It has horizontal fins on inside and vertical fins on the outside.

For low temperature (90–140 °C) waste heat recovery, the trend is to use the heat pumps. Heat pump is a device meant for heat upgrading. It raises the temperature of heat in excess of source temperature. Process may be regarded as reverse of refrigeration. In thermodynamic sense process involves carrying heat energy 'uphill' so work will have to be done on the system. Usually it is done with a compressor run by electricity. In the above process a working substance undergoes a cycle of changes in states; the cycle could operate in a closed circuit as well as in a circuit open to environment. Mechanical vapour compression and absorption cycle heat pumps have received relatively more attention in context with solar operation.

12.8.2 Industrial Sector: Electrical Energy

In industries electricity is mainly used for various applications of production and illumination. The improvement of power factor has been accepted as one of the important energy efficiency measures. The importance of power factor may be understood from the concept of average power associated with the voltage and current in an AC circuit as follows:

Let $v(t) = V_m \sin\omega t$ represent the applied voltage across the branch terminals of a given inductive circuit and

let $i(t) = I_m \sin(\omega t - \theta)$ be the corresponding current flowing through the branch circuit. The instantaneous power may then be expressed as

$P(t) = v(t)\ i(t) = V_m I_m \sin\omega t\ \sin(\omega t - \theta)$ which on simplification (see for example Vincent Del Tero 1978) yields

$$P(t) = \frac{V_m I_m}{2} \cos\theta - \frac{V_m I_m}{2} \cos(2\omega t - \theta) \qquad (12.9)$$

From instantaneous power versus corresponding current and voltage characteristics, it may be noted that there are time intervals when the power is negative. It means that during these intervals the circuit is returning power to the source and it is possible only when the branch circuit has at least one energy storing element.

The average value of power represents the capability of the circuit to do work and is given by

$$P_{av} = \frac{1}{T}\int_0^T P(t)dt \qquad (12.10)$$

Substituting the value of $P(t)$ from Eq. (12.7) yields

$$
\begin{aligned}
P_{av} &= \frac{V_m I_m}{2}\cos\theta\,\text{Watts} \\
P_{av} &= \frac{V_m\,I_m}{\sqrt{2}\sqrt{2}}\cos\theta \\
P_{av} &= VI\cos\theta
\end{aligned}
\qquad (12.11)
$$

V and I represents the RMS values of applied voltage and the resultant current; the product VI represents the real power which can be entirely converted to work and is referred to as apparent power; this power is not always realizable in the circuit for doing work. The useful part depends on the value of $\cos\theta$ which is referred to as the power factor. So we have

$$P_f = \cos\theta = \frac{\text{Average Power}}{\text{Apparent Power}}$$

Lighting is a substantial consumer of electrical energy. For example, in India in 1992 the electricity consumption for lighting accounted for approximately 15 % of total electricity consumption (210 billion kWh) (Teddy 2000–2001); in commercial buildings 60 % of total electricity consumption (21.6 billion kWh) is used for lighting (Misra and Kumar 1996). The energy efficient lighting techniques involve the consideration of following components of lighting system:

1. Efficiency of various components of lighting system; it includes lamps, ballasts and luminaries.
2. Operation and maintenance of lighting installation; it includes the control system

3. Day lighting; it includes methods of day light integration in the building.

In industries power factor always tends to be lagging due to the inductive loads with varying magnetization excitation requirements during different plant operations. The resultant varying loads need to be corrected for, to improve the power factor by installing the shunt capacitor in the branch circuit. According to Petroleum Conservation Research Association (PCRA) tips for electrical energy conservation in industries, the improvement of power factor from 0.85 to 0.96 will give 11.5 % reduction of peak kVA and 21.6 % reduction in peak losses. This corresponds to 14.5 % reduction in average losses for a load factor of 0.8.

Furthermore, in the industries the electrical energy consumption of several variable speed applications involving fans, motors and pumps can be minimized by the use of variable frequency drives, slip power recovery systems and fluid couplings. On maintenance and operation account an important precaution is to use the rewound motors only for low duty cycle applications. The rewinding of motors increases the no load losses which in practice may result in the efficiency loss of up to 5 %.

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Chapter 13
Solid Waste Management

13.1 Solid Waste

From the days of civilization, humans and animals have used the natural resources to support life and to dispose off wastes. In early times, the disposal of wastes did not pose a significant problem due to less population and meagre amount of waste generation and availability of abundant land for the assimilation of wastes. Problems with the disposal of wastes can be identified from the days when humans first began to congregate in communities and generation of wastes became a consequence of life. Solid waste material arises from various human and industrial activities. The solid waste is normally highly heterogeneous mass discarded as useless or unwanted. It is generated from the urban community as well as the more homogeneous accumulation of agricultural, industrial and mining wastes. The wastes are of two forms viz. Solid waste and Liquid waste. Among the wastes, solid waste is predominant in present day world. Solid waste may contain the following (a) Human pathogens – municipal and hospital solid waste, (b) Animal pathogens – waste from pets and other animals and (c) Soil pathogens – garden and agricultural waste. The solid waste comes mainly from industry, agriculture and mining and the rest is municipal solid waste. Some part of the solid waste is recycled or reused and the rest is dumped. After air and water pollution, the solid waste, is often referred as 3rd pollution. The solid waste generation has several adverse effects on environment. Some problems associated with waste include: (a) Inadequacies of existing systems for handling and safe disposal, (b) Environmental pollution – pollution of land, water and air, (c) Breeding flies and rats, (d) Emission of green house gases mainly CH_4 and CO_2 and (e) Non-availability of land for landfills close to source.

13.2   Solid Waste Generation

The Industrial Revolution in the world increased the usage of natural resources and raw materials through various technological advancements; which resulted in solid waste disposal problems. Thus, along with the benefits of technology, there also came problems associated with the disposal of resultant wastes. To understand the nature of these problems, it will be helpful to examine the flow of materials and the associated generation of wastes in a technological society and to consider the direct impact of technological advances on the design of solid waste facilities. In what follows we present a detailed description of related processes.

13.3   Classification and Sources of Solid Waste

Solid wastes generated as a consequence of using earth materials. They occur in and travel through the geological environment. Waste management schemes use geological reservoirs for containment and use geological processes for dilution and dispersal. The main sources of solid waste are illustrated in Fig. 13.1.
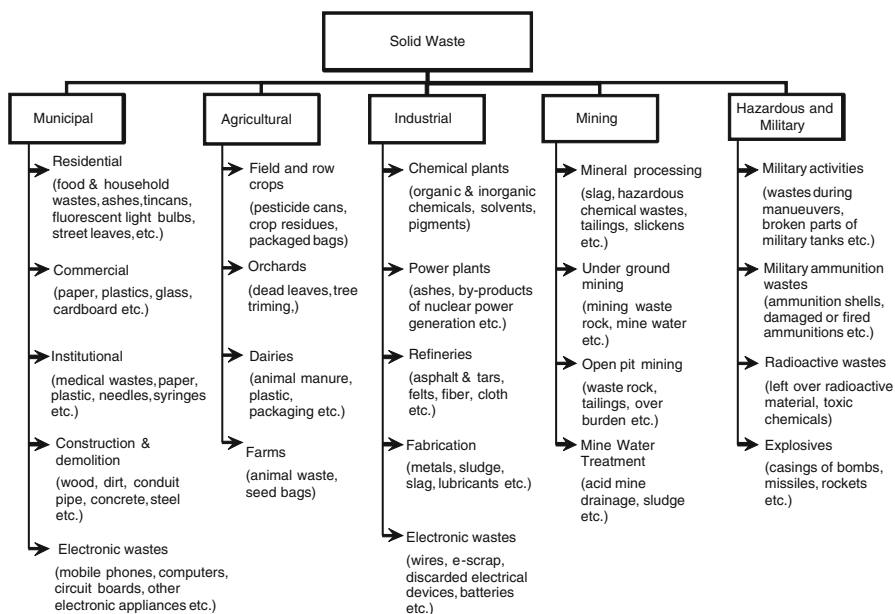
Fig. 13.1 Classification of solid waste with their sources

13.3.1   Municipal Solid Waste

Municipal Solid Waste (MSW) comprises of items that we consume and discard in our day-to-day life. The composition of MSW varies significantly from location to location with time. Migration of people from rural areas to cities and towns due to urbanization leading to an uncontrolled growth of population in urban areas. MSW is one of the major wastes used for converting waste-to-energy. It can directly be combusted as fuel mass burn, refuse-derived fuel, pyrolysis/thermal gasification and composting. MSW especially includes market waste, food waste, street waste, yard waste, abandoned vehicles, empty containers and product packing and other miscellaneous wastes from domestic/residential, industrial, commercial and institutional sources. And also inorganic wastes include newspapers, office and classroom equipments, clothing, furniture, wooden boxes, rubber tires etc. MSW is otherwise known as trash or garbage. Garbage contains putrescible constituents, has water content of about 70 % and a heating value of around 6×10^6 J/kg. Rubbish which is non-putrescible has moisture content of about 25 % and a heating value of around 15×10^6 J/kg. The waste contains dead animals, human waste with moisture content of about 85 % and a heating value of around 2.5×10^6 J/kg (Agarwal and Sangal 2010). Commercial sources generate both biodegradable and non-biodegradable wastes such as food waste, glass containers, metal cans, plastics, paper and cardboard. In contrast, the urban construction and demolition activities gives rise to the waste such as building materials, packaging and rubble.

13.3.2   Electronic Waste

Electronic waste or e-scrap describes the discarded electrical or electronic devices. The e-waste consists of end of life products and comprises of a range of electrical items such as home appliances, mobile phones etc. Major devices we use daily include Cathode ray tubes (CRT), Printed circuit boards (PCB) and plastic materials from monitors, keyboards, printers etc. (Wath et al. 2011). As there is rapid growth in industries producing these items across the globe, e-waste is growing exponentially. Recent digital equipment has a life-cycle of only a few years or even less and new technology is coming rapidly which is replacing existing one quickly. In comparison with other waste materials, e-waste comprises a lot of precious and valuable materials but also toxic substances. It is known that about 60 elements from the periodic table can be found in these discarded electronics. Cadmium (Cd) is one of the major toxic substance present in CRT monitors as well as rechargeable batteries. Cadmium adversely affects human kidneys and bones by accumulating in the environment. It is one of the toxic substances that has been banned in Europe by Hazardous Substances Directive. Apart from CRT monitors and plastics, Polyvinyl chloride (PVC)

cabling used for printed circuit boards, plastic covers, connectors and cables is also very hazardous by nature.

13.3.3   Agriculture Waste

Agricultural waste contains crop residue, which is lignocelluloses in nature, fertilizers, pesticides and animal products or manure. It comprises wastes such as pesticides containers, waste oils, silage wrap, scrap machinery, rubber tires, packaging materials, pump sets, scrap metals, veterinary medicines etc. Wastes containing hazardous characteristics like waste pesticides, infectious waste arising from animal health care, asbestos materials and chemicals are subjected to additional controls to protect human health and environment. Large amounts of biomass wastes are produced in forest industries (like sawdust, degradable waste paper, charcoal dust), sugar industries (bagasse – waste generated during extraction of sugar), rice industries (rice husks), palm oil industries (empty fruit bunches). These biomass wastes can be incinerated in boilers for heat and power production.

13.3.4   Industrial Solid Waste

This type of waste is produced from manufacturing and processing plants consisting of wastewaters, sludge, solids and various inorganic and organic chemicals. Since the beginning of industrial revolution, the quantity of these wastes has been increasing rapidly. Industrial sectors producing food, basic metals, wood products, paper products, beverages and tobacco products generate most of the these solid waste. The major quantity of industrial wastes include the ash produced in thermal power plants, iron and steel mills, red mud and tailings produced at non-ferrous metal industries such as zinc, aluminium, copper etc., press mud generated in sugar industries, lime and fertilizers produced in paper and pulp industries and gypsum produced at allied industries. Lack of infrastructural facilities at many industries lead to improper disposal of the industrial solid waste. Large scale and medium scale industries located at Government authorized industrial areas are provided with dump sites to dispose solid wastes.

13.3.5   Waste from Mining Activities

These waste include the waste generated during the process of mineral or ore extraction, beneficiation i.e. ore separation and purification of metals. The waste products during the mining operations generally include soil and rocks removed to

gain access to ore deposits at pit mines, tailings (finely ground rock and mineral waste products of mineral processing operations), slag (non-metallic by products from metal smelting), mine water, waste treatment sludge and gaseous wastes. These types of wastes lead to ground and surface water contamination, air pollution due to dust emission and erosion.

13.3.6 Hazardous and Military Waste

Hazardous wastes are those which pose harmful threats instantly or over a period of time to human and plant life. Hazardous wastes can be classified based on their physical, chemical or biological properties such as toxic, radioactive, corrosive, reactive, ignitable or infectious. When exposed to toxic substances like chlorofluorocarbons (CFCs) used in cooling units, polyvinyl chloride (PVC) used for cable insulation, chromium used in data tapes, heavy metals like cadmium, lithium, lead, nickel used in batteries etc., they lead to various skin diseases, damages heart and liver and causes cancer. Corrosive wastes include strong alkaline and acidic substances. Infectious wastes include wastes from hospitals or biological research facilities like used bandages and needles. Radioactive wastes particularly wastes from nuclear reactors emit ionizing energy causing harm to any living organism. Certain house hold waste like cleaning fluids are also hazardous by nature. Military wastes like bomb shells, damaged or deteriorated explosives or munitions, unexploded ordnance, or any other potentially harmful chemical munitions are disposed very carefully in particular dump sites.

13.4 Solid Waste Management (SWM)

Solid waste management primarily deals with controlling waste generation, accumulation, storage, waste transportation, disposal and recycling of solid wastes in a manner considering the principles of public health, engineering, economics, conservation and other environmental studies. A typical SWM system is illustrated in Fig. 13.2 (Eriksson and Carlsson 2005) SWM also includes all financial, legal, administrative, engineering and planning functions involved with any sort of issues arising regarding solid wastes. The solutions for disposing solid wastes are drawn from complex relationships between the fields such as public health, conservation, economics, political science, geography, sociology, regional planning, communications as well as material and engineering science. Final disposal of the solid waste can be done by well recognized methods like reduction, dumping on land and into water, incineration, feeding to hogs and plowing into soil. Harmful or hazardous wastes are treated chemically or biologically and buried deep into soil. Some wastes can be reduced, reused and recycled for further processing in industries. An integrated solid waste management (ISWM) prioritize the handling of materials/
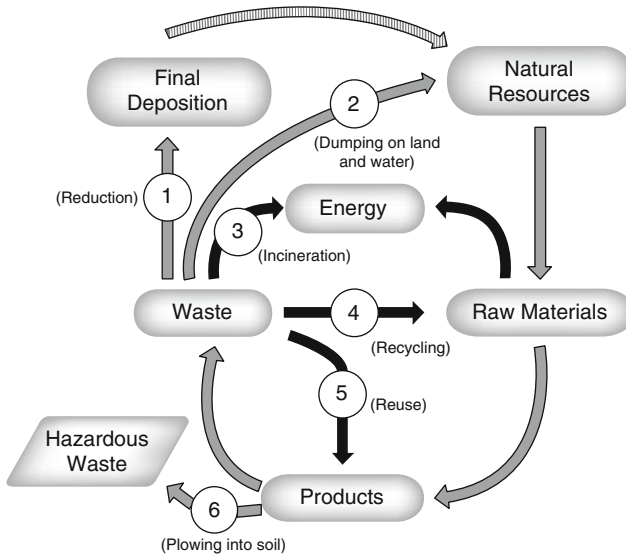
Fig. 13.2 Typical solid waste management system

products in a comprehensive way (George et al. 1993). Various priorities of ISWM are shown in Fig. 13.3.

Priorities of SWM involve selecting and applying suitable methods, technologies and management programmes to accomplish specific objectives and goals evolving in response to the regulations developed to implement various laws. A hierarchy of waste management activities has also been established for management of hazardous waste. The material and energy flow processes in a typical solid waste management system are shown in Fig. 13.4. Materials turnover is characterized by (i) the supply of waste materials and process chemicals, (ii) the output of products and by-products and (iii) emissions to air, water and crops (Eriksson and Carlsson 2005).

13.5 Solid Waste Disposal Practices

13.5.1 Open Dumps

Open dumping is relatively cheaper and doesn't require any planning. These are commonly found in backyards, outskirts of cities and towns, abandoned buildings and low lying areas. Open dumps usually breeds dangerous vectors such as rats, mosquitoes, flies and other pests causing severe diseases to the people staying near by the dumps. They are the source of objectionable odours causing air pollution as well when the wastes are burned in order to reduce or conserve dumping space.
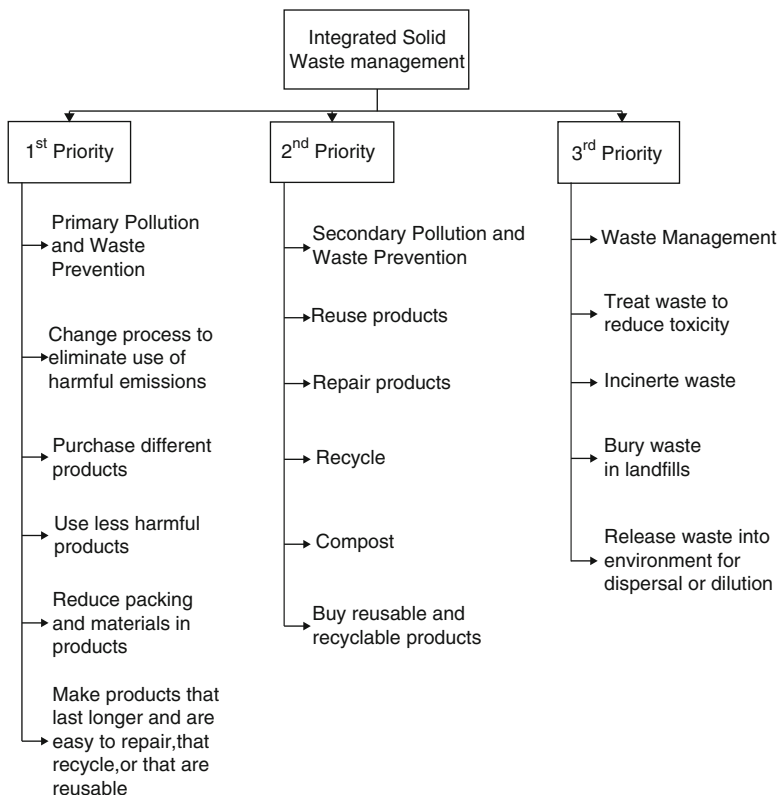
Fig. 13.3 Integrated solid waste management system

13.5.2 Landfills

Landfill is a site for disposing the waste by burying it into the ground in an organized manner without affecting public health or safety. Refuse or garbage is spread and compacted in thin layers within a small area. This layered structure is usually referred to as a cell. To allow for proper compaction, the cell depth should not exceed about 2 m. The cell is then covered with a layer of soil which is spread uniformly and then compacted. To provide an adequate seal the cover should normally be at least 0.2 m thick.

13.5.3 Incineration

Incineration process is the direct burning of wastes in the presence of excess air (oxygen) at high temperatures (about 800 °C) liberating heat energy, ash, inert
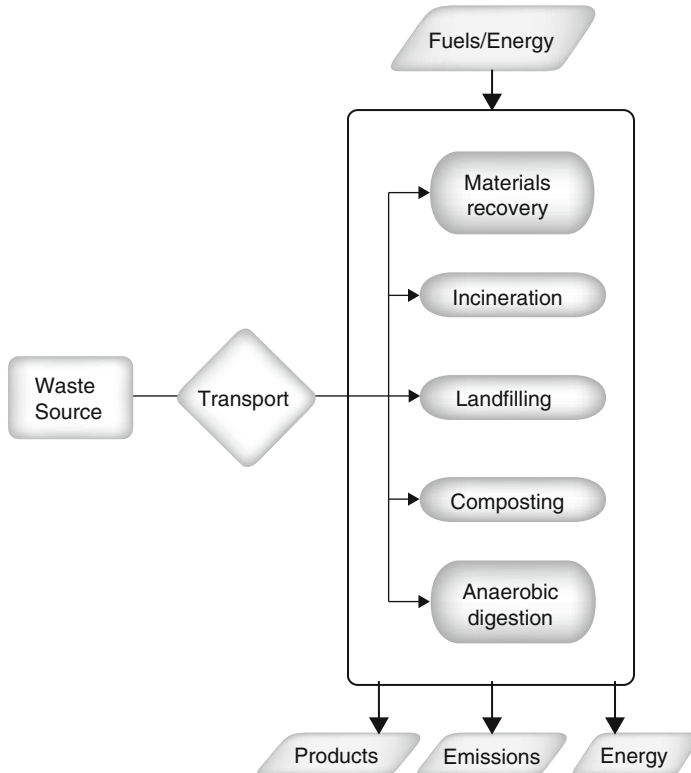
Fig. 13.4 A general model of material and energy flows in a typical waste management system (Eriksson and Carlsson 2005)

gases, metals, glass and unburned combustibles. The residue still needs to be disposed off in some manner which otherwise may lead to air pollution. Incineration can reduce volume by 90 % which would otherwise be disposed at landfilling sites. The liberated heat energy can be used for steam generation and electricity production. High incineration temperature can reduce hazardous waste and pathogens. The major concerns of incineration process include: emissions – particularly dioxins from plastic incineration, requirement of scrubbers, ash disposal, toxic material in ash.

13.5.4   Composting

Composting is a natural occurring process of allowing the waste to decompose under controlled conditions. The decomposition is performed primarily by aerobic bacteria, fungi and yeast, helping in the cooler initial and ending phases by organisms such as springtails, oligochaete worms, ants and nematodes. Composting

can be either done by anaerobic decomposition or aerobic decomposition. In anaerobic composting, decomposition is done in absence of oxygen developing intermediate compounds like hydrogen sulphide, organic acids, methane and other substances, which cannot be metabolized any further. This process takes place at low temperature leaving pathogens intact. Aerobic decomposition of organic matter takes place in the presence of oxygen by microorganisms producing carbon dioxide, ammonia, water and heat. Intermediate compounds produced during this process are allowed to decompose. Aerobic decomposition occurs at higher temperatures and processing time is relatively shorter. Microbes resulting in the reduction of its volume by 50 % metabolize organic waste material. This stabilized product is known as compost. The steps taking place in this process are sorting/separating, size reduction, and digestion of the garbage. To ensure a reasonable composting, temperature ranging from 25 to 50 °C and pH ranging from 5 to 8 has to be maintained. The phases of composting are (a) Mesophilic (35–45 °C) and (b) Thermopholic (45–65 °C). Composting provides nutrients to plants and improves fertility of the soil. It also helps in increasing beneficial soil organisms such as centipedes and worms, which can supress certain plant diseases.

13.5.5   Recycling

Recycling is the process of converting potentially resourceful waste material into new products reducing the need of consumption of fresh raw material as well as air and water pollution. This process also helps in reducing the quantity of waste to be disposed. Materials that can be recycled are collected separately by using dedicated bins for particularly specified type of wastes and collection vehicles. The major recycling products include copper from electrical wires, aluminum from beverage cans, polyethylene from plastic bags, consumer packing and bottles, steel from food and aerosol cans, old steel furnishing or equipment, glass bottles and jars, clothing, newspapers, magazines and light paper. Recycling process plays a major role in reducing the emission of many greenhouse gases and waste pollutants into atmosphere. It helps in conserving future resources by supplying valuable raw materials to industries and saves energy.

13.6   Waste to Energy

Waste-to-Energy conversion is a process of recovering energy from waste materials to generate electricity or heat by incineration/combustion. World energy consumption is rapidly increasing with a present approximation of about 559 EJ in both developed and developing nations (Key World Energy Statistic. IEA 2014). Electricity generation is essentially dominated by combustion of fossil fuels with the major growth in the energy sector. The energy consumption patterns and

environmental trends show a significant potential for extracting energy from Waste or Opportunity Fuels (OF). Opportunity Fuels or waste materials such as wood residues and saw dust, rice husks, spent pulping liquors, petroleum coke, refinery gas, landfill and wastewater treatment gases, combustible hazardous wastes from cement kilns and other unusual combustible wastes make a significant contribution to the industrial sectors with heat applications. Opportunity Fuels (Wastes) can be used productively in the generation of electricity as combustible resources that are outside the mainstream of fuels of commerce (Tillman and Harding 2004). The OFs are categorized as: Low grade wastes, washery wastes, cultivated fuels and derived from wastes.

13.6.1 Low Grade Wastes

The low grade wastes usually include sawdust, rice husks, oat husks, petroleum coke, hogged wooden pieces, edible pig lard from rendering plants, spent pulping liquor, unusable hays, wheat straws and other straws from agricultural activities, and a host of other solid materials. Apart from the solid waste residues, gases such as refinery off-gases, coke oven gas and blast furnace gas can also be considered as OF which are often used in process industries.

13.6.2 Washery Wastes

This category of OF includes the wastes such as slack, gob, anthracite culm and other coal mining wastes which have been recovered and reprocessed at power industries as well as other industrial sectors.

13.6.3 Cultivated Fuels

Crops grown for energy purposes such as Switchgrass, Miscanthus, Willow and hybrid poplar also could be considered in this category. These fuels referred as CO_2 neutral and renewable energy sources.

13.6.4 Derived from Waste

These types of wastes constitute the materials derived from wastes such as landfill gas, fuel derived from tires and plastics, waste oil and re-refined oil, sewage sludge, paper and refuse derived fuel, selected hazardous wastes and wastewater treatment gas.

   Depending upon their sources, the range of opportunity fuels can be as broad as local opportunities of recycling and reusing, rather than their disposal.

13.7   Waste to Energy Conversion Technologies

"Waste to Energy (WTE)" is a process by which energy contained in the waste materials is extracted in the form of heat or electric power, which can then be used for process applications. The most suitable methods generate both electricity as well as process heat in co-generation plants, improving the energy efficiency which gradually results in reduction of greenhouse gas emissions. Now-a-days, extracting energy from municipal solid waste (MSW) is considered as the best strategy for reducing the quantity of MSW to be disposed. Recycling process of MSW is well recognized in the developing countries like India.

   Increasing levels of wastes products across the globe has led to the development of various waste-to-energy conversion technologies to convert residual wastes to useful energy rather than disposing them at dumping sites. Energy recovery from biomass in the form of heat, hydrogen, biogas and electricity can be done using these technologies (Reddy and Kolar 2005). The thermal treatment of solid waste can be done by the energy conversion processes such as (a) Gasification, (b) Incineration/Combustion and (c) Densification. Different by-products are obtained by the application of these technologies and various energy as well as potential material recovery systems can be used to treat these. A detailed description of various energy conversion processes are also discussed in Chap. 9.

13.7.1   Gasification

Gasification is a kind of unique process to convert any solid or liquid carbon- based material (feedstocks) into useful energy without burning it. In this process, a thermo-chemical reaction occurs in the presence of a gasification agent to obtain a clean combustible gas. This thermo-chemical reaction of carbon-based materials with a little amount of oxygen breaks them down into simple molecules liberating heat energy. The gasification agent (oxygen) allows a quick conversion of feedstock into the gas by means of different heterogeneous reactions. The combustible gas is primarily a mixture of CO, H_2 and impurities such as CO_2, CH_4, H_2O, trace amounts of higher hydrocarbons, inert gases present in the gasification agent and other particle impurities such as char, ash and tars. For a correct and efficient gasification process, a sufficiently homogeneous carbon-based material is required. Before entering the gasifier, MSW is shredded or ground into fine particles. An air separation chamber is provided in the gasifier to inject a specific amount of oxygen for maintaining a controlled reaction. Therefore, not all kinds of wastes are treated in the gasification process as such; some types are extensively pre-treated before

gasification. Pre-treatment of solid waste is necessary to sort out some recyclables such as metal and glass. Some of the most suitable waste materials for this process are agricultural residues, paper mills waste, mixed plastic waste and forest industry waste (Singh and Tyagi 2011). The combustible gas, after removing the impurities, can be sent to a turbine or internal combustion engine to generate power or to a chemical industry for further processing. Gasifiers can be operated on a smaller scale compared with an incineration plant, and can also be hybridized to suit a range of different scales of operation.

13.7.2   Incineration

The incineration/combustion process is a waste-to-energy conversion method by burning out all possible waste material to ashes at very high temperatures. Heat energy liberated during the burning process is recovered to generate electricity or to use it in process heat applications. Some industries make use of co-incineration process in which solid waste is mixed up with small amount of fossil fuels resulting in improved calorific value. As much as 90 % of volume of waste can be reduced in incinerators, a significant reduction in the quantity of waste which would otherwise be disposed at landfilling sites. Incineration taking place at higher temperatures will also help neutralize some of the toxic compounds and pathogens in medical and other hazardous wastes. The incinerator design is based on the type of fuel that is being burnt in it, although refused derived fuel (RDF) fired systems are popular for accommodating the variations in the kinds of fuel burnt. The relative advantages of incineration are (i) best suitable process for using high calorific value waste materials like sawdust and plastics, (ii) relatively noiseless and odourless plant operation and (iii) least land area requirement.

Incineration systems can be categorized into mass burn and RDF facilities. In mass burn systems, solid wastes are continuously fed to boilers with very little pre-processing treatment to remove oversized items like refrigerators or sofa sets and without separation of non-combustible matter. High temperatures are attained and waste consumption of each incineration unit range between 50 and 1000 tons (SSWM 2010). Whereas in refuse derived fuel facilities, recyclable/reusable as well as non-combustible materials like metals are separated from the fuel content improving its heating value. Separation process involved in RDF facilities increases the building and operating cost. A few RDF facilities are available across the world in operational condition as many facilities have commercially failed to compete with a conventional mass burn incinerator. The major concern of solid waste incinerators is the potential emission of the contaminants into air and into water. In order to supress the environmental risks, modern pollution control equipment like fabric filter, electromagnetic precipitators are installed in these facilities to prevent any kind of toxic emissions such as metals like mercury and lead, carbon monoxide and nitrogen oxides. However, Incineration has certain distinct limitations: (i) least suitable for high moisture content/low heating

value wastes, (ii) requires auxiliary fuel to sustained combustion and (iii) possibility of high concentration toxic materials in ash.

13.7.3 Densification

One of the major barriers of using solid waste as fuel is the low energy content compared to conventional fuels of same quantity. Densification is a process of segregating, crushing, mixing high and low calorific value organic wastes and solidifying it to generate bulk fuel blocks or pellets. This process helps to overcome the challenge of handling, storing and transportation of low density waste material. The calorific value of RDF is about 16.7 MJ/kg and it depends upon the content of combustible organic materials in the waste, additives and binder materials, if any, used in the process. The main advantages of densification process include the uniform combustion in boilers and high calorific value of pellets (16.7 MJ/kg) against that of unsorted garbage (3.8 MJ/kg) whereas the limitation is the cost associated with it. The main advantages include better storage and transportation. But, the densification may not be effective during the rainy season, as the garbage will be too wet. High moisture content of MSW increases the cost of drying. It also requires efficient combustion mechanism in order to reduce harmful emissions.

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Chapter 14
Air and Water Pollution

14.1 Trade-Off Between Energy And Environment

In energy conversion process, some energy is rejected into surroundings causing certain degradation of environment. The main task is to increase energy supply to meet the demand with minimum degradation. The present trend is to have a trade-off between Energy and Environment for development of renewable and environmental friendly technologies. One of the factors that affect the degradation of the environment is population growth. The impact of population on environment can be assessed based on growth of world population. The world's current growth rate is about 1.3 %, representing a doubling time of 54 years (Population Growth Rates 2015). We can expect the world's population of 6 billion to become 12 billion by 2054 if current growth continues. The world's growth rate peaked in the 1960s at 2 % and a doubling time of 35 years. Many Asian and African countries have high growth rates. Some difficulties faced with coal fired thermal power plants are emission of dust, SO_X, NO_X and deforestation in plant area. Earthquake possibilities, submersion of forest and agricultural land and deforestation in plant area are the difficulties with hydro electric power plants. Similarly, the difficulties involved with other sectors are as follows:

Nuclear power plants: radiation hazards, problem of nuclear waste disposal.

Solar thermal power plants: thermal unbalance in reflector/heliostat field, deforestation in plant area.

Wind power: windmills may interfere with radio, TV broadcasts and kill birds; windmill farms require large tracts of land and farms may degrade scenic resources.

Industries and transportation: chemical waste discharged in rivers, lakes and atmosphere.

Global: depletion of ozone layer, global warming, acid rains, environmental imbalance, deforestation, soil decay and growth of deserts.

14.2   Pollution

An undesirable change in the physical, chemical or biological characteristics of air, water, soil or food that can adversely affect the health, survival or activities of humans or other living organisms is called pollution. In other words, any atmospheric condition in which certain substances are present in such concentrations that they can produce undesirable effects on man and his environment is pollution. The substances include gases like SO_x, NO_x, CO, CO_2, HCs etc., particulate matter (smoke, dust, fumes, aerosols) and radioactive materials etc.

14.3   Air Pollution

Air pollution is said to exist if the levels of gases, solids or liquids present in the atmosphere are high enough to harm humans, other organisms or materials. Human activities such as industrialisation, transportation, crop residue burning, emissions from thermal power plant, mining etc. are some sources of air pollution. Beside these, air pollution could also have natural causes like forest fire, storms or eruption of volcano.

14.3.1   Causes of Air Pollution

(a) *Incomplete Combustion*

Hydrocarbon when combines with oxygen releases energy which is nothing but combustion and is given by Eq. 14.1. If combustion is complete, all carbon is used up and there is no air pollution.

$$C_xH_x + O_2 \rightarrow CO_2 + H_2O + \text{Heat} \tag{14.1}$$
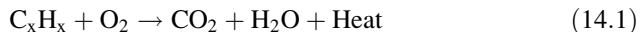
If not enough oxygen is present, carbon monoxide i.e. CO is produced instead of carbon dioxide CO_2. Particles of smoke and soot (unconsumed carbon) are emitted. Poly-nuclear Aromatic Hydrocarbons (PAH) are partially consumed hydrocarbons formed into a variety of ring shapes – probably carcinogenic.

Impurities in combustion are as follows:

(i) Sulphur can be found in lower grade coal (bituminous, sub-bituminous, lignite)

$$S + O_2 + \text{heat} \rightarrow SO_2 \text{ (sulphur dioxide)} \tag{14.2}$$

$$SO_2 + H_2O \rightarrow H_2SO_3 + H_2SO_4 \text{ (sulphurous and sulphuric acid)} \tag{14.3}$$
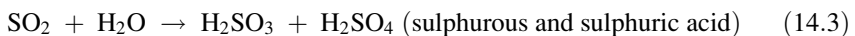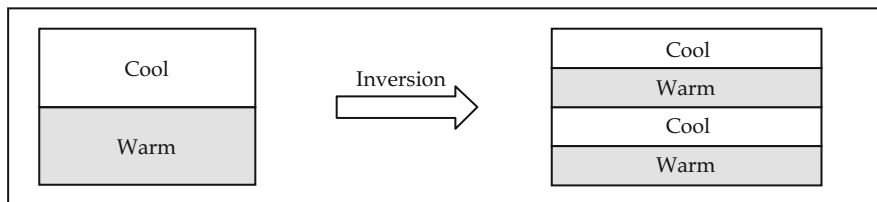
Fig. 14.1 Temperature inversion

(ii) Nitrogen – from the air

$$N_2 \ + \ O_2 \ + \ heat \ \rightarrow \ NO_2 \ (Nitrogen \ dioxide) \tag{14.4}$$

$$NO_2 \ + \ H_2O \ \rightarrow \ H_2NO_3 \ (nitric \ acid) \tag{14.5}$$
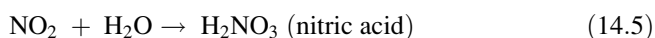
(b) *Thermal/Temperature Inversion*

Normally, the air is cooler at high altitudes. So warm air from surface rises and heat dissipates. Warm air layer forms above cool layer and thus trapping gases. Occasionally a layer of warm air will trap a pocket of cold air in a valley or against a mountain. So pollution gets trapped under this inversion layer and builds up to dangerous levels.

After sunset, the ground cools quickly by radiation heat transfer and the lower layer of air in contact with the surface loses sensible heat through conduction and small scale mixing. Consequently, a temperature inversion is set up between the cool low-level air and warmer air above the surface as shown in Fig. 14.1.

14.3.2   Sources of Air Pollution

Air pollution can occur due to disasters like earthquakes, volcanic eruptions, etc., or it could be due to pesticides, building materials, etc. The sources of air pollution can be due to (a) outdoor and (b) indoor pollution.

(a) *Sources of Outdoor Air Pollution*

The main sources of outdoor air pollution are the combustion of gasoline and other hydrocarbon fuels in cars, trucks, and airplanes and burning of fossil fuels (oil, coal etc.). Dust from mining activities, constructional sites and residual agricultural waste also lead to outdoor air pollution.

Natural disasters like dust storms, earthquakes, eruptions, volcano, leak of gases, armed conflicts, etc. are also the sources of air pollution. Automobiles and

industries are by far the main contributors to the outdoor air pollution across the globe. Even festivals can create air pollution.

(b) *Sources of Indoor Pollution*

Most attention is given to outdoor air pollution, but we do not realize that indoor pollution can also be equally damaging the environment. Mosquito repellents, cleaning agents, pesticides etc. used in urban households can cause toxic conditions. Materials like asbestos, glass fibre, paints, glues, and varnishes are all health hazards. Cigarette smoke, gases from stoves, formaldehyde (from carpets and furniture), ozone (from photocopiers) are the most common pollutants in urban interiors. Organisms like viruses, bacteria, fungi, dust mites and pollen also exist in the ducts found in office buildings.

Following are the other sources of air pollution:

Stationary sources: These are those sources of air pollution which have relatively fixed location.
Point sources: These are those sources of air pollution which have discrete, controllable site (i.e. smokestacks of power plant).
Fugitive sources: These are open areas exposed to wind (i.e. dirt roads, construction sites, farmlands, surface mines).
Area sources: They emit from several different sources within a constrained area (i.e. urban communities, large industrial plants).
Mobile sources: They move from place to place while yielding pollutants (i.e. cars, airplanes).

14.3.3 Classification of Pollutants

Air pollutants can be categorized into primary and secondary pollutants. The primary pollutants are the harmful chemicals that are directly released from a source into the atmosphere. The secondary pollutants are those that are formed in the atmosphere by chemical interactions among primary pollutants and normal atmospheric constituents.

Primary pollutants present in sufficient concentrations to be immediate concern are particulate matter, sulphur oxides, oxides of nitrogen, Olefinic and aromatic hydrocarbons and Radioactive compounds. Particulate matter includes ash, smoke, dust, fumes, mist and spray. Inorganic gases like SO_X, H_2S, NO_X, NH_3, CO, CO_2, and H_2F also come under primary pollutants.

Secondary pollutants are formed from chemical and photochemical reactions in the atmosphere. Pollutants such as sulphur trioxide, PAN (peroxyacetylnitrate), ozone, aldehydes, ketones, and various sulphate and nitrate salts are included in this category (Rao 1994).

14.3.4   *Air Pollution Control Methods and Equipment*

Preventing the formation of pollutants or minimizing their emission at the source itself is the most effective means of reducing air pollution. In the case of industrial pollutants, it can be achieved by investigating various approaches at an early stage of process design and development. Selecting those methods which do not contribute to air pollution or having the minimum air pollution are known as source correction methods (Crawford 1976). Control of the pollutant at the source can be accomplished in several ways through raw material and operational changes, modification or replacement of process equipment and by more effective operation of existing equipment. Effluent gas cleaning techniques are used when source correction methods cannot achieve the desired goal of air pollution control.

14.3.4.1   Source Correction Methods

 (i) **Raw Material Changes (materials substitution and re-use)**: By using pure grade of raw material, the formation of undesirable impurities and byproducts can be reduced. Though it is difficult to remove sulpur from fuels, de-sulphurization of fuels is an attractive solution to reduce pollution. Use of low sulphur fuel in the place of high-sulphur ones and replacing of natural fuel by synthetic fuel can contribute to low pollution. Ore handling operations usually result in the emission of large quantities of dust into the atmosphere. So, raw ore can be replaced by pelleted sintered ore.
 (ii) **Process Changes**: Process Changes involving new or modified techniques offer reduction in atmospheric pollutant emissions. Changes in chemical and petroleum refining industries helps in the volatile substances to be recovered by condensation, the non-condensable gases to be recycled for additional reactions and H_2S that was once flared in refineries, is now recycled and used in Claus process to recover elemental sulphur. Kilns in cement plant are highly responsible for dust generation. It leads to reduction of gas velocities within kiln, modification of the rate and location of feed introduction and employment of a dense curtain of light-weight chain at the discharge end of the kiln. In the steel Industry, the sulphur bearing fuel, limestone and air are injected into a molten iron bath and it is retained back in iron bath and forms a slag with limestone.
(iii) **Equipment Modification/Replacement**: From the design perspective products, buildings and manufacturing systems can be made resource-efficient throughout their life cycle by incorporating environmental considerations into their design. For example, in petroleum refineries, temperature changes, direct evaporation and displacement during filling will lead to release of hydrocarbon vapours into atmosphere from the storage tanks. So, designing the tanks with floating roof covers or by pressurizing tanks could be one of the solutions.

Using energy, water and other production inputs more efficiently, will help in keeping air and water clean, reduces emissions of greenhouse gases, cuts operating costs, and improves productivity. Rethinking day-to-day operations and maintenance activities can help managers root out wasteful management practices that drive up costs and cause pollution.

14.3.4.2   Effluent Gas Cleaning

When source correction methods cannot achieve the desired goal of air pollution control, use is made of effluent gas cleaning. The cleaning techniques are applied to those cases where emissions of pollutants cannot be prevented and pollution control equipment control is necessary to remove them from main gas stream. So pollution control at the "end of the pipe" after it has been created. These techniques used alone or in conjunction with source correction methods form the basis of present day air resource management concepts. The effluent gas cleaning includes removal of particulate pollutants and cleaning of gaseous effluents.

14.3.5   Air Pollution Control

Air pollution emission control equipment can be classified into particulate control and gases control. The particulate control comprises the wet and dry absorption methods whereas gases control include methods depending on the chemical alteration of the pollutant, usually through combustion or catalytic incineration (Brauer and Varma 1981). Various ways of controlling the air pollution are described below.

14.3.5.1   Particulate Emission Control

Particulate matter emitted in gaseous streams consists of discrete and minute suspended particles. Generally, particle sizes range from 0.1 μm to 100 μm. The choice of collection devices depends upon particulate size and concentration in the gas, volume of particulates to be handled, physical and chemical characteristics of particulates, temperature and humidity of gaseous medium, toxicity and inflammability.

The major controlling performance parameters are particle size, weight, shape, particle velocity, gas temperature/density, solubility and pH, system pressure drop and mass transfer conditions, particle size distribution, gas viscosity, humidity level, chemical stoichiometry and residence time.

14.3.5.2 Particulate Control Mechanisms

Gravitational Settling, Centrifugal Impaction, Inertial Impaction, Direct Interception, Diffusion and Electrostatic Precipitation are the basic mechanisms of removing particulate matter from gas streams. Particulate Control Equipment includes the Gravitational Settling Chambers, Cyclone Separators, Fabric Filters, Electrostatic Precipitator and Wet Collectors (Scrubbers).

The gravitational settling chambers and cyclone separators will not generally achieve high efficiencies for removing small size particles. For most practical applications, only fabric filters, electrostatic precipitators and high energy scrubbers are capable of meeting the rigorous air pollution control regulations.

(i) **Gravitational Settling Chambers**: These are used to remove large abrasive particles (>50 µm) from gas steams. They offer low pressure drop and require low maintenance. Their efficiency is quite low for particles < 50 µm and are used as pre-cleaners (Rao 1994). A simple model of horizontal type gravitational settling chamber is shown in Fig. 14.2.

One of the Gravitational Settling Chambers is Howard Type in which collection efficiency can be improved by inserting several trays. In Gravitational Settling Chamber particles with velocities greater than v_t are completely removed and particles with velocities less than v_t are partially removed (Fig. 14.3).

Analysis: (*e.g.* Rao 1994)

Let

Q – Volumetric flow rate of gas steam
n – No. of trays of L × W × H
ρ_p and ρ_g – densities of particle and gas respectively
v is the velocity inside the chamber

$$v = Q/(nW\Delta H)$$

Here, the driving force is gravity.
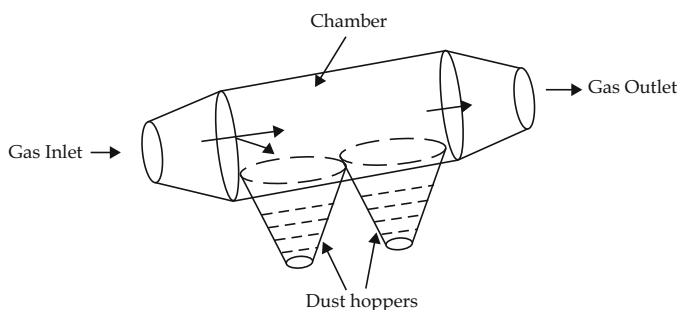
Fig. 14.2 Horizontal gravitational settling chamber
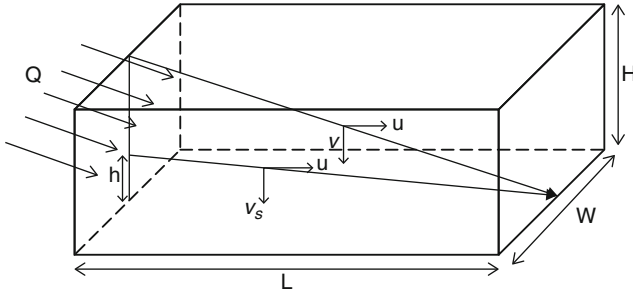
Fig. 14.3 Flow of particulate matter in Gravitational Settling Chamber

Characteristics of the particles are: (a) good efficiency for particles with high settling velocities, (b) low efficiency for $dp < 10$'s of μm (c) typically laminar flow to allow for settling and (d) simple.

If Re_p is in the range of 3–400, then Drag force is given by

$$F_D = C_D \left(\frac{\pi}{4}d_p^2\right)\left(\frac{1}{2}\rho_g v_t^2\right) \tag{14.6}$$

Buoyancy is given by

$$F_b = \pi \frac{d^3}{6}\left(\rho_p - \rho_p\right)g \tag{14.7}$$

where C_D is a drag coefficient (a particle friction factor).

At steady state, forces are equal; particle falls at constant velocity. Equating the drag force F_D to the buoyant force F_b, the terminal settling velocity of the particles,

$$v_t = \sqrt{\frac{4d_p\left(\rho_p - \rho_g\right)g}{3C_D\rho_g}} \tag{14.8}$$

If a particle with settling velocity $< v$ enters the settling chamber, then, it will be removed only if it is at a height h, such that

$$h = v_s t_0 \tag{14.9}$$

For laminar conditions i.e. $Re < 2300$ with the trays.
The collection efficiency is given by

$$\eta(d_p) = \frac{v_t \cdot A}{Q} \tag{14.10}$$

Where

$$A = n \cdot L \cdot W \tag{14.11}$$

$$t_0 = \frac{L}{u} \tag{14.12}$$

$$v = \frac{H}{t_o} = \frac{Hu}{L} = \frac{HuW}{LW} = \frac{Q}{A} \tag{14.13}$$

The minimum particle size that can be removed from the gas with 100 % efficiency is

$$d_{p\,\min} = \sqrt{\frac{18Q}{nWLg\left(\rho_p - \rho_g\right)}} \tag{14.14}$$

The flow in the settling chamber will probably be turbulent rather than laminar.
   The collection efficiency is expressed as:

$$\eta = 1 - \exp\left(-\frac{nWLv_t}{Q}\right) \tag{14.15}$$

(ii) **Cyclones:** These operate to collect relatively large size particulate matter from a gaseous stream through the use of centrifugal forces. Dust laden gas is made to rotate in a decreasing diameter pathway forcing solids to the outer edge of the gas stream for deposition into the bottom of the cyclone (Fig. 14.4). The particles lose K.E. in cyclone and are separated from the gas stream. Particles are then overcome by gravitational force and collected. Centrifugal and grav-itational forces are both responsible for particle collection in a cyclone. Effi-ciencies of 90 % in particle sizes of 10 microns or greater are possible with cyclones (Stairmand 1951).

   Driving forces are gravity and centrifugal force. It works on the principle to increase efficiency by imparting an additional centrifugal force on the particles. Its characteristics are: (a) no moving parts, (b) generally for dp of 10 microns or greater and (c) 90° input to axis of cyclone

$$\eta(d_p) = \frac{\pi \cdot d_p^2 \cdot \rho_p \cdot Q \cdot N_e}{9 \cdot \mu_g \cdot H \cdot W^2} \tag{14.16}$$

$$Ne = \text{number of turns of vortex} N_e = \frac{1}{H} \cdot \left(L_b + \frac{L_c}{2}\right) \tag{14.17}$$

Its efficiency depends on particle diameter, number of vortex turns (length of cyclone) and inlet velocity and inversely dependent on cyclone inlet width.

Fig. 14.4 Cyclone separator
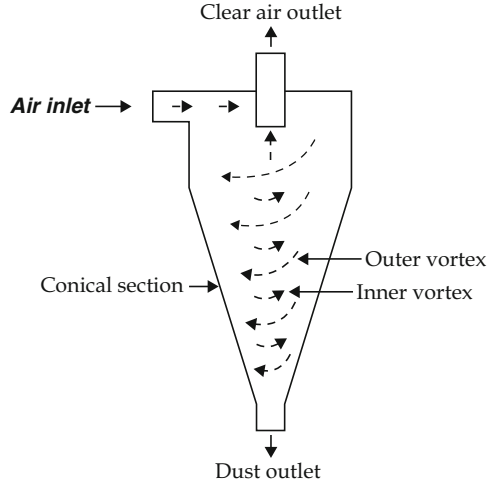
Lapple ([1951](#)) correlated collection efficiency in terms of the cut size d_{pc}. Particles $> d_{pc}$ will have a collection efficiency greater than 50 % and particles with $< d_{pc}$ will be collected with lesser efficiency. The cut size is given by,

$$d_{pc} = \left[\frac{9\mu_g W}{\pi N_e \rho_p V_g} \right]^{\frac{1}{2}} \tag{14.18}$$

Primary operating costs are due to pressure drop. The pressure drop may be estimated as (Shepherd and Lapple [1931](#)),

$$\Delta P = \frac{K \rho_g v_g^2 HW}{2 D_e^2} \tag{14.19}$$

where K is a constant and ranges from 7.5 to 18.5; D_e, W and H are cyclone dimensions and V_g is inlet gas velocity.

Multiple Cyclones (Multi Clone) The smaller particles need lower air flow rate to separate and multiple cyclones allow lower air flow rate and capture particles to 2 μm.

(iii) **Baghouses (Fabric filters):**

Particulate Control – Filtration
The basic principle of filtration is to increase efficiency by retaining particles smaller than filter openings as shown in Fig. 14.5. Its characteristics are commonly used for small-particle collection with typical efficiency of 98–99.9 %. There are filters cleaned of particulate cake when pressure drop through filter exceeds preset value and pressure drop can be predicted by knowing filter and cake characteristics.
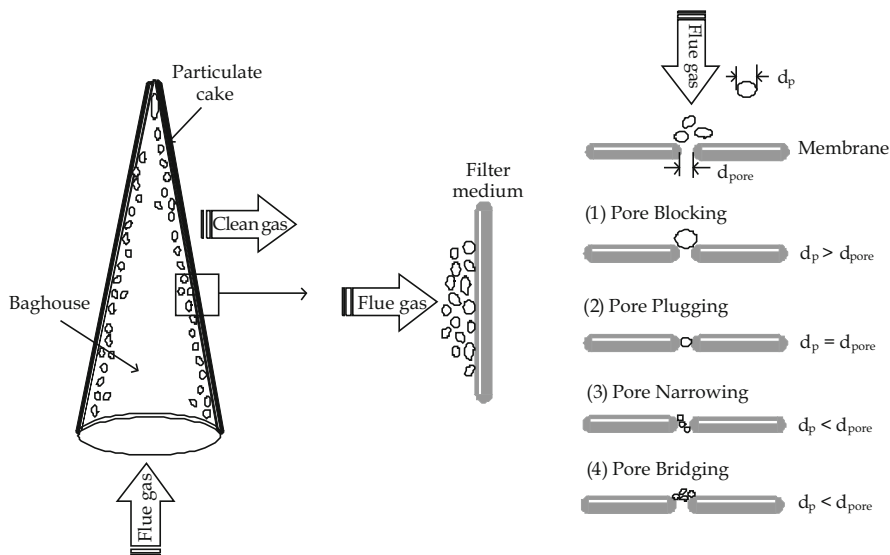
Fig. 14.5   Filtration process for particulate removal

The typical arrangements of multiple socks in a compartment includes baghouses with high removal efficiency for < 5 mm particles and highly sensitive to moisture content but is least efficient for 0.1–0.3 micron range.

The particles are trapped in Fabric Filters due to the mechanisms: (a) inertial impaction, (b) direct interception (sieving), (c) diffusion (agglomeration) and (d) electrostatic filtration. Inertial impaction occurs when the particle with high inertial follows a fluid streamline. Theoretical investigations based on potential flow theory and experimental results reveal the collection efficiency.

During direct interception (sieving), particles have less inertia and almost follow the streamlines around the obstruction. The particles clear the obstacle but their outer peripheries come in contact with the fiber. The particle will touch the fiber and will be intercepted. The combined mechanisms of impaction and interception usually account more than 99.9 % of the collection of the particles <1 μm. Diffusion (agglomeration) mechanism is important for particles that are in the submicron range – particularly for the particles sub-micron range 0.001–0.05 μm. These particles usually do not follow the gas streamlines surrounding the fiber because of individual motion. This zigzag random Brownian motion causes the particles to impinge and adhere to the surface fiber. In practice the collection mechanisms of impaction, interception and diffusion are not independent and hence, all three mechanisms must be combined. In electrostatic filtration, the electrostatic forces between particles and fibers increase the collection efficiency. The generation of electrostatic charges in filter fabrics may be due to friction between gas and fabrics as well as particles and fabrics at high gas velocities (1.5–2.0 m/s). The increase in

efficiency on account of electrostatic forces becomes greater with increase in the strength of the electric charge.

Fabric Filter Systems

Fabric filter systems typically consist of a tubular bag or an envelope, suspended or mounted in such a manner that the collected particles fall into a hopper when dislodged from the fabric. The structure in which the bags hang is known as baghouse. Generally, particle-laden gas enters the bag at the bottom and passes through the fabric while the particles are deposited in the bag. Mechanical shaking, reverse air flow and pulse jet cleaning are the general cleaning methods used. Several fabric types are primarily chosen depending on chemical, thermal and mechanical resistance.

The following advantages make fabric filters the best choice in many cases: (i) retention of finest particles, (ii) relatively low pressure drop, (iii) very high efficiencies, and (iv) collection of particulates in dry form.

(iv) **Electrostatic Precipitators (ESPs):** These are the most widely used devices for controlling the particulate emissions at various installations like power plants, cement and paper mills, oil refineries etc. Mostly, the particulates to be collected are by-products of combustion. Electrostatic precipitation is a physical process, under the influence of electric field, in which the particles suspended in gas stream are electrically charged and separated.

At a very high DC voltage, of the order of 50 kV, a corona discharge occurs close to the negative electrode, setting up an electric field between the emitter and grounded surface. The particle-laden gas enters near the bottom and flows upward. The gas close to the negative electrode is thus ionized upon passing the corona. As the negative ions and electrons migrate towards the grounded surface, they in turn charge the passing particles. The electrostatic field then draws the particles to the collector where they are deposited. By rapping or vibrating the collector, the collected particles then must be removed from the collecting surface as shown in Fig. 14.6. High collection efficiencies are possible, but efficiency may drastically change with changes in operating parameters.

Here, the driving forces are gravitational and electrical forces. The main characteristics of these systems are complex electrical systems, laminar or turbulent
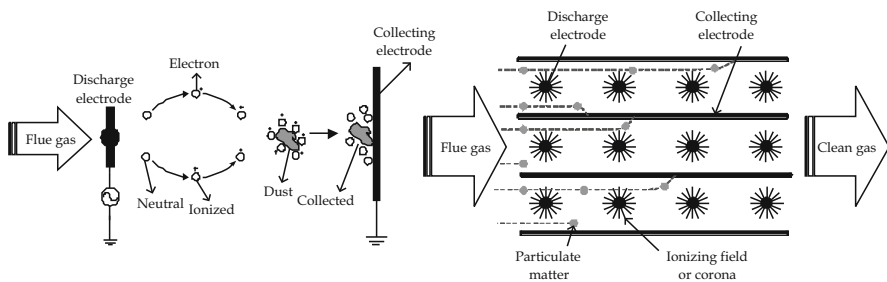
Fig. 14.6 Electrostatic precipitation of dust particles

flow, sensitive to moisture content, least efficient for 0.2–0.5 micron and generally used for d_p ranging less than 1–10's of microns.

The variable parameters in these systems are electric field strength which is based on applied voltage and distance between collecting plate and electrode, maximum voltage (with minimum sparking), cleaning frequency and intensity, particulate resistivity (very low resistive particles are good conductors and will lose charge).

(v) **Wet scrubbers**: Wet scrubbers provides contact between the scrubbing liquid, usually water and the particulate to be collected. This can be achieved in various ways as the particles are confronted with so called impaction targets – which can be wetted surfaces or individual droplets. By introducing a water spray, smaller dry particles turn into larger wet particles, thus increasing efficiency of the system. The removal of gases and particulate matter is done by causing the gaseous contamination to become dissolved into the liquid stream and the solids to be entrained in the liquid. Simultaneous removal of particles and gaseous pollutants is possible. The rate of gas transfer into the liquid is dependent upon solubility, mass transfer mechanism and equilibrium concentration of the gas in solution. Gas collection efficiencies in the range of 99 % are possible.

The rate of particulate matter collection at constant pressure drops is inversely proportional to aerodynamic mean diameter of the particulate matter as well as scrubber droplet size. The collection methods are similar to that of filters which were discussed earlier.

Generally, impaction and interception are the predominant mechanisms for particles of diameter above 0.3 μm, and diffusion begins to prevail for particles of diameter below 0.3 μm. Because of the inertia, the particles cannot follow the streamlines around the droplets and as a result, impact into the droplet. The particles become trapped in the larger drops which allows them to be more easily collected. Diffusiophorectic deposition is significant when the mass transfer within the scrubber, caused by condensation of water vapour from the gas onto a cold liquid surface, exerts force upon the particles and causes to get deposited on the surface (Kraemer and Johnstone 1995).

The characteristics of wet scrubbers are: they can be applied in conjunction with settling chamber or cyclone and can also be used to remove gaseous pollutants. Wet scrubbers can be configured into co-current, cross-current and counter-current.

Many designs of scrubber are available where the contact between the scrubbing liquid and the particles is achieved in various ways. The different types of design are: (a) Spray towers, (b) Centrifugal scrubbers, (c) Venturi scrubbers and (d) Packed Tower Absorbers.

(a) **Spray Towers**: Spray tower is the simplest type in which water is introduced by means of spray nozzles. Due to inertial impaction and interception on the droplets, polluted gas flows upward and the particle collection is done. The efficiency of a spray tower is a complex function of droplet size, flow velocity

of the gas, liquid to gas ratio and droplet trajectories (Stairmand 1950). The low energy scrubbers (spray towers) are used to handle large particles of 5–10 µm dia. The effectiveness of the conventional spray tower ranges from 94 % for 5 µm particles to 99 % for 25 µm particles.

(b) **Centrifugal Scrubbers:** The collection efficiency for particles smaller than those recovered in spray towers can be increased through the use of centrifugal scrubbers. The simplest one of these scrubbers as shown in Fig. 14.7 can be constructed by inserting banks of nozzles inside a conventional dry cyclone. As the spray acts on the particles in the outer vortex, the droplets loaded with particles are thrown outward against the wet inner wall of the cyclone. The particle cut diameter for centrifugal spray scrubbers is between 2 and 3 µm. Commercial scrubber have operating efficiencies of 97 % or better for particles larger than 1 µm. The centrifugal acceleration involved may range from 25 to 300 g (Johnstone and Roberts 1949).

(c) **Venturi Scrubbers:** They offer high performance collection of fine particles (2–3 µm diameter). They are particularly suitable when the particulate matter is sticky, flammable or high corrosive. The high speed action atomizes the feed liquid which is introduced in a uniform fashion across the throat through several low pressure spray nozzles directed radially inward. The droplets accelerate in the throat section and due to the velocity difference between the particles and the droplets, the particles are impacted against the slow-moving droplets. The gas–liquid mixture is then sent into a separation device such as cyclone separator where the droplets carrying the particulate matter are separated from the gas stream. The high performance of venture scrubber is achieved by accelerating the gas stream to very high velocities of the order 60–120 m/s.

The mechanisms affecting the collection of particulates are inertial impaction, diffusion, electrostatic-phenomenon, condensation and agglomeration.

Fig. 14.7 Centrifugal scrubber
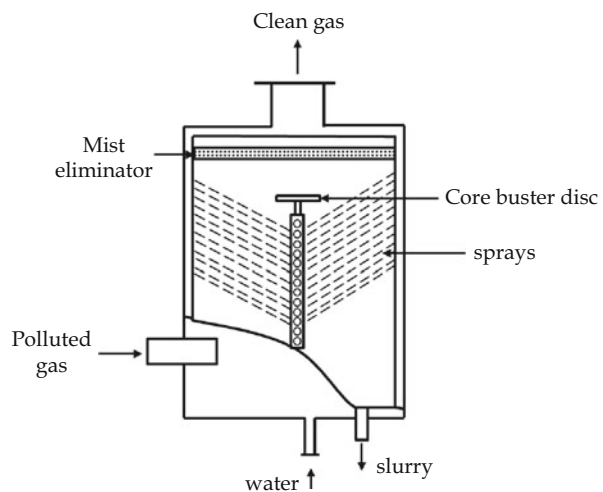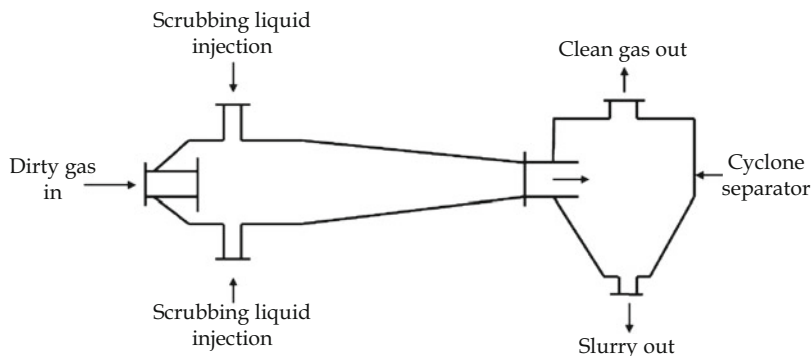
Fig. 14.8   Venturi scrubber followed to cyclone separator

Although condensation plays a part in the effectiveness of the scrubber by helping the particles to agglomerate, the predominant mechanism is inertial impaction (Johnstone et al. 1954). The high energy venturi scrubber as shown in Fig. 14.8, is very effective in collecting fine particles (<3 μm).

(d) **Packed Tower Absorbers:** These systems utilize principles of mass transfer to transfer the contaminant from gas phase to liquid phase. The ability to transfer the gas into the liquid is commonly referred to as the mass transfer coefficient.

In a vertical counter-flow, gas flows vertically upward through the scrubber whereas scrubbing liquid flows downward from the top of the scrubber. Vessel is filled with packing (dump or structured) that provides high surface area with low density per unit volume.

Typical features of vertical cross-flow system are: (a) Multi-beam packing support plate (provides 140 % of the actual vessel cross-section), (b) Target gas superficial velocity of between 5 and 8 fps of saturated gas flow rate, (c) Recirculation rates of 15–20 gpm of liquid per 1000 cfm (saturated) of flue gas and (d) Capacities from 100 cfm to 200,000 cfm.

In a horizontal cross-flow, gas flows horizontally through the vessel and scrubbing liquid flows downward at a 90° angle to the gas flow. Vessel is also filled with packing. The typical features for horizontal cross-flow system are as follows:

(a) Packing is installed on a slope because of horizontal gas flow conditions in the unit.
(b) Integral liquid recirculation tank or externally mounted tank system.
(c) Superficial gas velocities are the same as for vertical counter-flow system.
(d) Liquid recirculation rates are typically higher (20–30 gal per 1000 cfm saturated).
(e) Liquid distribution is critical design factor and as a result proper determination of the vessel height, width and length is essential (vertical packing depth is usually 125 % of the packing width).

14.4   Water Pollution

Water is necessary to live on earth and is an important natural resource which is essential for many purposes which include drinking, domestic use, irrigation, industrial cooling, power generation, transportation and waste disposal.

Water pollution is the contamination of water resources including ponds, lakes, rivers, ground water. Water pollution occurs when pollutants are discharged directly into the water bodies without removing harmful compounds. Plants and animals require water, that is moderately pure, and they cannot survive if the water is loaded with toxic chemicals. Pollution makes streams, lakes and coastal waters unpleasant. People who ingest polluted water can become very ill.

14.4.1   Sources

Solid wastes, nutrient oversupply, toxic chemicals, pesticides/herbicides and nuclear waste are the main sources of water pollutants. They can be categorized into point sources and non-point sources.

Specific places which discharge pollutants through pipes, sewers, or ditches like sewage treatment plants and factories are point sources. These are easy to identify, monitor and regulate through reduction or treatment at end of pipe. Point sources are regulated through laws and rules.

Non-point sources are those, where pollutants enter the water over large areas than at a single point. This is the case where rain water flows along the soil, picks up the pollutants, and carries them into water bodies. Municipal waste, sediments, acid rain, soil erosion, surface runoff comes under non-point resources. These are poorly defined and difficult to control but can be treated through source reduction.

14.4.2   Pollution Categories

Present day, the discharge of domestic and industrial wastes into aquatic systems has become the most serious water pollution problem in the country. About 75 % of India's population is exposed to unsafe drinking water which results in enteric diseases that devastate various parts of the country. The origin of these problems attributes to many types of pollutants. Water pollutants can be often classified (Rao 1994) as follows:

(a)   Oxygen Demand Waste
(b)   Pathogens
(c)   Synthetic Organic Compounds
(d)   Plant Nutrients
(e)   Inorganic Chemicals and Minerals

(f) Sediments
(g) Thermal Discharges
(h) Oil

Pollution of the waterways is often caused by a combination of the above categories which can severely compound the problem. Each of these categories are discussed in detail below.

(a) **Oxygen Demand Waste**: Dissolved Oxygen (DO) is essential for sustaining the plant and animal life in any aquatic system whose level if drops below the level necessary for normal life sustainability, then the aquatic system is said to be polluted. For example, warm water fish requires a minimum DO level of at least 5 mg/l.

As organics are broken down, decomposers use up oxygen, which is about 10 ppm in water (compared to 200,000 ppm in air). Dissolved Oxygen (DO) in the water is depleted during decomposition of organic wastes.

The four processes that affect the DO content in the water are reaeration, photosynthesis, respiration and oxidation of wastes. Reaeration is the process by which oxygen transfer takes place from the atmosphere to water. The solubility of oxygen in fresh water at saturation point decreases with an increase in temperature. When DO falls below the saturation value oxygen diffuses from the atmosphere at a rate which is proportional to the deficit. The combination of the three effects of respiration, photosynthesis, and reaeration results in a diurnal variation in DO concentration. The DO level in the water exceed the saturation during the day. At night the algae and the micro-organisms compete with each other for both dissolved oxygen and organic compounds. This bacterial and algal respiration is responsible for production of CO_2 and subsequent depletion of DO.

Biological Oxygen Demand (BOD) is a measure of the oxygen demand utilized by microorganisms during the oxidation of organic materials. It is the most widely used measure for assessing the water pollution level of a given organic waste. Drinking water usually has a BOD of less than 1 mg/l, and water is considered fairly pure with BOD of 3 mg/l. But when BOD value reaches 5 mg/l, the purity of water is doubtful. A comparison of these BOD levels with the range of values encountered in industrial waste waters indicates the seriousness of the problem.

(b) **Pathogens (Disease-causing agents)**: Water is a potential carrier of pathogenic microorganisms which are carried into water bodies by sewage and wastes from farms and various industries, especially meat packing and tanning industries.

Various water borne pathogens (Smith 1976) are described as follows:

Bacteria

   (i) *Salmonella* sp. – causative agents of salmonellosis and typhoid fever.
  (ii) *Vibrio* sp. – causative agents of asiatic cholera and shellfish poisoning.
 (iii) *Leptospira interrogans* – causative agent of leptospirosis.

    (iv) *Toxigenic Escherichia coli* – causative agent of potentially fatal gastroenteritis.

    (v) *Shighella dysenteriae* – causative agent of bacterial dysentery.

    (vi) *Campylobacter jejuni* – causative agent of campylobacteriosis.

Protozoa

    (i) *Entamoeba histolytica* – causative agent of amoebic dysentery.

    (ii) *Giardia lamblia* – causative agent of giardiasis.

    (iii) *Ballantidium coli* – causative agent of ballantidiasis.

    (iv) *Cryptosporidium* sp. – causative agent of potentially life threatening gastroenteritis.

Metazoa

    Schistosoma mansoni – causative agent of schistosomiasis (ilharzias).

Viruses

    (i) *Hepatitis A* – causative agent of infectious hepatitis.

    (ii) *Polio virus* – causative agent of poliomyelitis.

    (iii) *Rotavirus* – causative agent of one form of gastroenteritis.

    (iv) *Norwalk virus* – causative agent of one form of gastroenteritis.

Safety measures to avoid these disease causing agents are purification of public water supply, sanitary collection/treatment of sewage, sanitary practices when processing food and personal hygiene.

(c) **Synthetic Organic Compounds**: These include pesticides, synthetic organic chemicals and detergents. Some of these compounds are not biodegradable and may persist for long periods. These are of great concern to the environment because they are accumulative toxic poisons and ultimately may reach objectionable levels in water or in aquatic life.

    The chlorinated organic pesticides like DDT, dieldrin and aldrin are hazardous mainly due to their concentration in the food chain (Zajic 1971). They have substantial solubility in oils and fats. Detergent comprises a surfactant, polyphosphate salts and other ingredients such as optical whiteners in small amounts. The presence of surfactants reduces the rate of oxygen absorption in water.

(d) **Nutrients**: For maintaining the growth and metabolism of plants and animals, nitrogen and phosphorous are essential elements. Small amounts of nitrites and phosphates present in aquatic systems are sufficient to maintain a balanced biological growth. These nutrients are present in abundance in the form of phosphates, ammonia, nitrates, etc., which may enter the water bodies directly from the manufacture and use of fertilizers. Large concentration of these nutrients in water bodies produces an unsightly green slime layer over the surface that leads to eutrophication. This slime layer reduces light penetration and restricts atmospheric reoxygenation of water. High concentrations of

nitrates in drinking water causes adverse effects in human body by reducing to nitrites.

(e) **Inorganic Chemicals and Minerals**: Inorganic salts, metal compounds, mineral acids and finely divided metals come under the category of water pollutants. These are toxic and are capable of killing living organisms which can enter the water bodies from municipal and industrial waste water. Increased acidity in natural waters cause corrosion of metals and concrete and can be fatal to fish. Alkalies discharged by industries can also destroy aquatic life. Heavy metal compounds produce physiological poisoning by becoming attached to the tissues of aquatic organisms whose concentrations can build up in food chain. Mercury has proved to be the most toxic aquatic pollutant because of its rapid methylation in the aquatic environment.

(f) **Sediments:** Sediments include soil, sand and mineral particles washed into water bodies by storms and flood waters. Human activities such as deforestation, sewage sludge, ranching, mining sites, construction sites, roads and various industrial solids can all lead to increased sediment loads by disposing them into rivers and marine waters. Particle size affects velocity of sediments transport. Transportation takes place through the following:

  (i) *Solution* or dissolved load
 (ii) *Suspended* load of fine-grained particles
(iii) *Traction* (dragging) of bed load of coarse material
(iv) *Saltation* (bouncing) of bed load of coarse material

Effects of sediments on stream ecology are poor light penetration, loss of hiding-resting places for small fish and attached aquatic organisms scoured from the rocks and sand. Through *flocculation*, some toxics attach to sediment.

(g) **Thermal Pollution**: This term refers to heated water discharges from various sources such as industrial effluents (especially from the electric power industry), irrigation return water, overflow of epilimnial water from lakes and reservoir and natural sources such as thermal springs. Cutting of riparian vegetation may also significantly raise stream temperatures. Thermal pollution may produce a variety of undesirable biological effects. Among these are:

  (i) Water temperatures may exceed the thermal tolerance limits of organisms, killing them directly.
 (ii) Warm water cause aquatic organisms to breed or emerge (aquatic insects) at inappropriate times.
(iii) Oxygen is less soluble in water at elevated temperatures.
(iv) Elevated temperatures tend to increase the metabolic rates (and thus oxygen needs) of aquatic life.
 (v) Elevated temperatures tend to potentiate the effects of toxic substances on aquatic life.
(vi) Sudden discontinuation of thermal discharges may cause "thermal shock" to aquatic life.

(h) **Oil**: Oil and oil wastes enter rivers and other water bodies from several sources like industrial effluents, oil refineries and storage tanks, automobile waste oil and petroleum plants. An oil slick on the surface of water will prevent oxygen transfer from the atmosphere and lead to very low DO levels in the water due to microbial oxidative attack on the hydrocarbon molecules. By the action of wind and tides oil may accumulate along the shore line where they pose aesthetic problems.

14.5   Water Treatment

Removal of the contaminants from water is the purpose of wastewater treatment. Quality standards depend upon the reusability of water. Waste water treatment processes can be broadly classified into physical, chemical and biological. Combinations of these processes are used depending on the influent concentration, composition and condition and specifications of the effluent.

Sedimentation, flotation, screening and filtration are the basic physical processes. Commonly used chemical processes are precipitation, coagulation and disinfection. Other processes like membrane processes (reverse osmosis and electrodialysis), oxidation and reduction, carbon absorption, ion exchange process etc. are also important in particular cases (Barnes et al. 1981; Metcalf and Eddy 1972).

Usually the waste water can be treated in the following ways:

 (i) Treated in-house and discharged to water body
 (ii) Discharged to sewer and treated at wastewater treatment plant.
(iii) Pretreated in-house, discharged to sewer, and fully treated at wastewater treatment plant. Methods (i) and (ii) are most common. Method (i) is most demanding in terms of regulatory standards**.**

14.5.1   Physical Treatment

(a) *Pretreatment*

The preliminary treatment facilitates pretreatment process and sedimentation process. In the pretreatment process, removal of large floating and suspended solids which could interfere with the subsequent treatment processes. Depending on the nature of the solids to be removed, screens of various sizes are used where cleaning is done either manually or mechanically. After screening, the waste water enters the grit chamber for the removal of inorganic grit consisting of sand, gravel, cinders and pebbles. Grit can be removed by scrappers.

(b) *Sedimentation*

Under quiescent condition suspended solid concentration can be reduced by gravitational settling. The sludge formed at the bottom of the tank can be removed by using a vacuum suction or by placing a discharge point at bottom of the tank for withdrawal. After settling, the top layer of water should not contain any settleable matter.

In rectangular, horizontal flow type tank, feed is introduced at one end along the width of the tank while the sludge is collected at the other of the tank. In circular radial flow tanks the feed is introduced through a center well whereas sludge removal is done by using a rotary sludge scrapper which forces it down a slopping bottom into a central hopper. In vertical flow tanks the feed is applied at a point along the bottom and clarified effluent is collected at the top.

Two types of particle behaviour can be distinguished in sedimentation. These are the discrete and flocculent particle behaviour. The setting of particles depends upon their concentration and the types of settling (Rao 1994) can be categorized into

1. Discrete
2. Flocculent
3. Zone

Discrete Settling   In discrete settling, particles do not interfere with one another, and their sizes, shapes and masses remain constant during settling. Sedimentation of a particle is undisturbed by the presence of other settling particles and it depends only on the properties of the fluid and the particle under question. When such a particle is placed in a liquid of lower density, it will accelerate until a limiting terminal velocity is reached. The typical example of this type is the settling of sand particles in grit chamber.

The tank is designed in such a way that all particles with settling velocity greater than the terminal velocity will be removed. The rate of removal for a given discharge is independent of the depth of tank but, it is directly related to surface area of the tank.

Flocculent Settling   In Flocculent settling the particles agglomerate during settling and do not have constant characteristics. This process takes place when settling velocity of the particles increases due to coalescence with the other particles. Coalescence increases with an increase in bed depth, as a result the particle removal efficiency depends on both the overflow and the bed depth. An analysis can be performed by placing the test suspension in a column that has the same depth as that of the sedimentation tank to determine the percentage removal of suspended solids at each time interval and depth can be obtained. The path followed by flocculent particle is different from that of discrete particles.

Zone Settling   Zone settling takes place in the secondary clarifier of the activates sludge process where the suspension is dense and the particles are so closely spaced that the velocity fields of the fluid displaced by the adjacent particles during settling overlap. There is an upward displacement of the fluid with a reduction in the settling

velocities of the particles, and this effect is known as hindered settling. The most commonly encountered form of hindered settling occurs at very high particle concentrations where the suspension tends to settle enmasse with distinct interface between the settling solids and the clear liquid above it. This is termed as zone settling. initially the solids concentration is uniform but as the time passes a clear liquid forms at the top and an interface develops between the zones.

(c) *Floatation*

Particles of density very close to that of water are very difficult to settle in normal sedimentation tanks and take a long time for separation. In such cases, the separation can be speeded up by aerating the effluent whereby air bubbles are attached to the suspended matter. This has the effect of increasing the buoyancy of the particles, as a result the particles float to the surface where they can be readily removed. To aid in the flotation process, chemical coagulants such as aluminum and ferric salts or polymer coagulant-aids are often used.

Floatation technique is used in the paper industry to recover fine fibres from the screened effluent and the oil industry for the clarification of oil bearing waste. It is also used for treating effluents from tannery, metal finishing, cold rolling and pharmaceutical industries.

In dispersed air floatation air is introduced directly into the liquid through diffusers. The generated air bubbles cause turbulence which breaks up fragile flow particles. So, this technique is not favourable for the treatment of municipal waste water although it has limited applications in treating industrial wastes.

In dissolved air floatation process as shown in Fig. 14.9, liquid is saturated with compressed air to dissolve the air in the pressurized tank. Later, in the flotation tank, liquid containing dissolved air is released at a lower pressure, generating micro bubbles (10–40 μm) that rise and carry suspended solids to the surface. Then the solids are skimmed from top of the flotation tank. This technique is effective in separating very small particles that cannot be separated by ordinary air flotation.
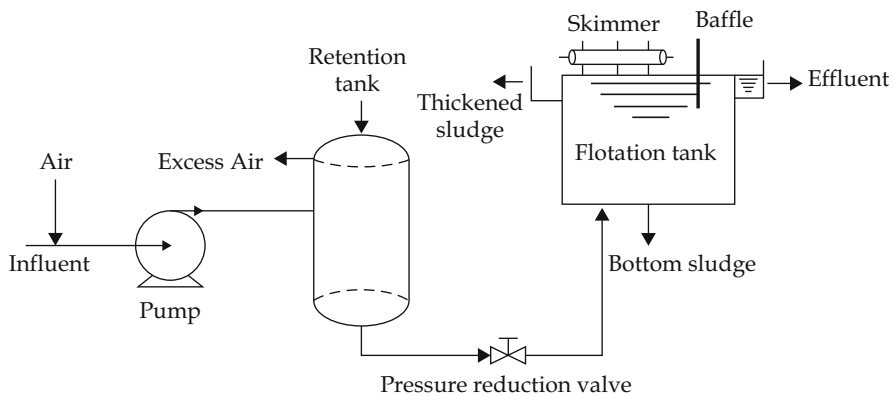
Fig. 14.9 Dissolved air flotation process

Flotation is typically used for removing oils after pH adjustment/chemical treatment in manufacturing facilities and also in biological treatment for removing thickening sludge.

(d) *Coagulation*

Coagulation is the method in which certain chemicals are rapidly dispersed in wastewater to change the characteristics of the suspended particles so that they coalesce and form flocs which sink rapidly. Coagulation is done by the addition of positive ions, e.g., Al^{3+}, which reduce the electrokinetic repulsion between the particles. Coagulation is employed to remove negatively charged colloidal suspensions which do not normally settle out and cannot be removed by conventional physical treatment.

In industrial wastewater treatment, coagulation is frequently used for oily emulsions and non-settleable solids. The most widely used coagulants for wastewater treatment are aluminium and iron salts such as ferric sulphate, aluminium sulpahte (alum), and ferric chloride.

(e) *Filtration*

In the filtration process, flocs formed during the coagulation process are removed using beds of porous media such as sand or coal. The filter consists of fine garnet in the bottom layer, silica sand in the middle layer and coarse coal in the top layer. This type of filter allows both surface straining and in-depth filtration without causing surface plugging or solid fractures.

(f) *Membrane Separation*

Membrane separation process can be extensively used to remove hardness and salts like iron, manganese etc. from drinking water supplies. It can also be used to remove specific impurities and to recover valuable trace metals. The principle involved in this process is to use membrane to filter wastewaters containing substances much smaller than those in comparison with the substance removed during conventional filtration. The characteristics of membrane separation process are high pressure requirements and slow filtration. Some of the examples are reverse osmosis, ion exchange, ultra-filtration, microfiltration, etc.

14.5.2   Chemical Treatment

Chemical treatment involves three steps: (a) Neutralization, (b) Precipitation and (c) Adsorption. Neutralization is a process that is done to adjust the pH of a wastewater to fall within an acceptable range by adding acid or alkaline materials to water which controls the level of pH. Typically the pH range should be 5–9. By constructing a titration curve required amount of acid or alkali that has to be added can be determined. For an example, NaOH can be used to control the pH of acid rinse water. Removal of soluble pollutants is done

by forcing them to transform to an insoluble form by adding chemicals to cause precipitation of the pollutant. This process can take advantage of decreased solubility of pollutants at certain pH values, temperatures, etc. Adsorption is a surface phenomenon wherein the dissolved substances in wastewater are attracted to and adhere to the surface of the adsorbent. Adsorption on activated carbon is probably the most economical and technically attractive method available for removing soluble organics such as phenols, surfactants and colour and odour producing substances from wastewater. Two types of activated carbon commonly used (i) Granular activated carbon (GAC) placed in a bed, through which the wastewater flows and (ii) Powdered activated carbon (PAC) added directly to wastewater, filtered out in a later stage. Adsorption isotherms are constructed to determine activated carbon dosages required to treat the wastewater.

14.5.3   Biological Treatment

Biological treatment is very similar in concept to the natural biodegradation of organic matter by aerobic bacteria which relies on microorganisms to consume the organic pollutants within the wastewater. Two primary classifications of bacteria:

$$\text{(a) aerobic : organics} + O_2 \rightarrow CO_2 + H_2O + \text{energy} \qquad (14.20)$$

$$\text{(b) anaerobic : organics} \rightarrow \text{organic acids} + CH_4 + CO_2 + \text{energy} \quad (14.21)$$
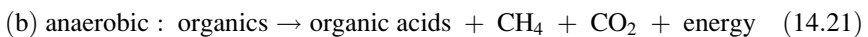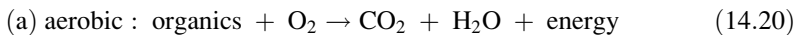
In this treatment oxygen supplied to the bacteria is consumed under controlled conditions so that most of the BOD is removed in the treatment plant rather than in water course. The most commonly used systems are activated sludge and biological film systems.

(a)   *Activated Sludge*

After primary treatment wastewater enters in aeration tank where the organic matter is brought into contact with the sludge from the secondary clarifier. This sludge is heavily laden with microorganisms which are in an active state of growth. The microorganisms utilize the oxygen in the air introduced through diffusers in the form of bubbles and convert the organic matter into stabilized, low energy compounds such as CO_2, NO_3, SO_4 and synthesized new bacterial cells. The sludge which is separated in the settling tank exists without contact with the organic matter and becomes activated. A portion of the sludge is recycled to the aeration tank as a seed. In this sludge system the main design parameter is the amount of organic matter (food) added relative to the microorganisms (activated sludge). This process is typically followed by sedimentation to remove biological floc.

(b) *Biological Films*

In the biological film systems, the wastewater is brought into contact with mixed microbial population in the form of slime attached to the surface of a solid support medium. They normally consist of a rock bed, 1–3 m in depth, with enough openings between rocks to allow air to circulate easily. The influent is sprinkled over the bed packing which is coated with a biological slime. As the liquid trickles over the packing, oxygen and the dissolved organic matter diffuse into the film to be metabolized by the microorganisms in the slime layer. As the microorganisms utilize the organic matter, the thickness of the slime film increases to a point where it can no longer be supported on the solid media and gets detached from the surface. Standard rate filters are suitable for treating weak wastewaters whereas high rate systems are used for partial treatment of wastes before the waste is sent for further treatment.

The main advantages of biological treatment are low capital and operating costs. The disadvantages are large land area requirement, treatment of organics limited by size of pond or land and odours can be a problem

Finally, from all the above processes described earlier, it can be inferred that suspended solids can be removed by sedimentation, filtration etc. whereas heavy metals can be converted to suspended solids and then removed. Similarly, dissolved solids can be separated and removed by membrane filtration, biological treatment, advanced oxidation etc.

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