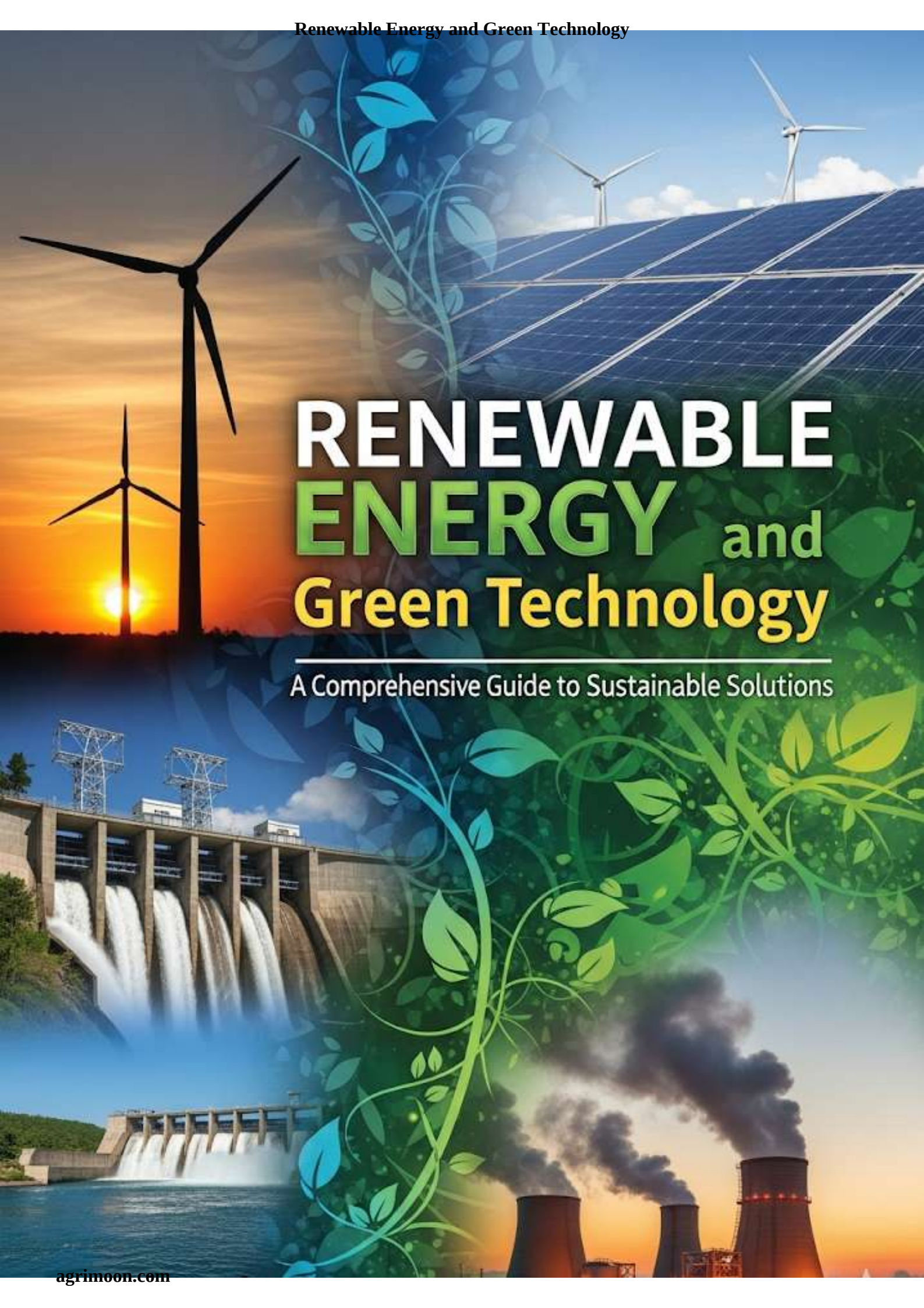




RENEWABLE ENERGY and Green Technology

A Comprehensive Guide to Sustainable Solutions

Renewable Energy and Green Technology

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Chapter 1

Introduction- Energy sources, classification, advantages and disadvantages

1.0 Introduction: With the increase in world population and the rise of living standards, the demand for energy in the world is steadily increasing. Global environmental issues and exhaustion of fossil resources also pose serious problems for energy consumption. Environment friendly energy technology and a shift to non-fossil energy resources such as natural energy and biomass are the need of the day. Energy has been defined as the capacity to do work or capability to produce an effort. It is expressed in N-m or Joules. The energy density is expressed as J/kg.

Consider the following simple model describing the need for commercial and non-commercial energy resources:

$$R = EN \quad (1.1)$$

Here R is the total yearly energy requirement for a population of N people. E is the per capita energy-use averaged over one year, related closely to provision of food and manufactured goods. The unit of E is energy per unit time, i.e. power. On a world scale, the dominant supply of energy is from commercial sources, especially fossil fuels; however, significant use of non-commercial energy may occur (e.g. fuel wood, passive solar heating), which is often absent from most official and company statistics. In terms of total commercial energy use, the average per capita value of E worldwide is about 2 kW; however, regional average values range widely, with North America 9 kW, Europe as a whole 4 kW, and several regions of Central Africa as small as 0.1 kW. The inclusion of non-commercial energy increases all these figures and has the major proportional benefit in countries where the value of E is small.

Standard of living relates in a complex and an ill-defined way to E . Thus per capita gross national product S (a crude measure of standard of living) may be related to E by:

$$S = fE \quad (1.2)$$

Here f is a complex and non-linear coefficient that is itself a function of many factors. It may be considered efficiency for transforming energy into wealth and, by traditional economics, is expected to be as large as possible. However, S does not increase uniformly as E increases. Indeed S may even decrease for large E (e.g. because of pollution or technical inefficiency). Obviously unnecessary waste of energy leads to a lower value of f than would otherwise be possible. Substituting for E in (1.1), the national requirement for energy becomes:

$$R = SN / f \quad (1.3) \text{ resulting in}$$

$$\frac{\Delta R}{R} = \frac{\Delta S}{S} + \frac{\Delta N}{N} - \frac{\Delta f}{f} \quad (1.4)$$

Now consider substituting global values for the parameters in (1.4). In 50 years the world population N increased from 2500 million in 1950 to over 6000 million in 2000. It is now increasing at approximately 2–3% per year so as to double every 20–30 years. Tragically, high infant mortality and low life expectancy tend to hide the intrinsic pressures of population growth in many countries. Conventional economists seek exponential growth of S at 2–5% per year. Thus in (1.4), at constant efficiency f , the growth of total world

energy supply is effectively the sum of population and economic growth, i.e. 4–8% per year. Without new supplies such growth cannot be maintained. Yet at the same time as more energy is required, fossil and nuclear fuels are being depleted and debilitating pollution and climate change increase; so an obvious conclusion to overcome such constraints is to increase renewable energy supplies. Moreover, from (1.3) and (1.4), it is most beneficial to increase the parameter f , i.e. to have a positive value of f . Consequently there is a growth rate in energy efficiency, so that S can increase, while R decreases.

Broadly speaking two main types of energy are heat and work. However, other forms of energy are 1) electrical energy, 2) mechanical energy, 3) chemical energy, 4) heat energy and 5) nuclear energy. Electrical energy is the most convenient form of energy because it can be easily transported, easily controlled and easily converted into other forms of energy at about 100% efficiency. The only short coming of electrical energy is that it can't be stored in large quantities. Out of all the energy resources, fossil fuels have been used the most because of their extremely high energy densities and simplicity of conversion and use. Recent concerns about the environment are expected to increase the use of natural gas for power production. Renewable energy resources, such as solar energy, wind, and biomass, are also expected to increase their share of the energy use. There is a strong sentiment in the world in favor of exploiting renewable energy resources, especially because of environmental concerns.

1.1 Classification of energy resources: For all practical purposes energy supplies can be divided into two classes:

1.1.1 Commercial primary energy resources: Energy obtained from static stores of energy that remain underground unless released by human interaction'. Examples are nuclear fuels and fossil fuels of coal, oil and natural gas. Note that the energy is initially an isolated energy *potential*, and external action is required to initiate the supply of energy for practical purposes. To avoid using the ungainly word 'non-renewable', such energy supplies are called *finite supplies* or *Brown Energy*.

Non-renewable sources of energy or conventional sources of energy are being accumulated in nature for a very long time and can't be replaced if exhausted. Nature gifted resources which are consumed can't be replaced. Eg: coal, petroleum, natural gas, thermal power, hydro power and nuclear power are the main conventional sources of energy.

1.1.2 Renewable sources of energy: Energy obtained from natural and persistent flows of energy occurring in the immediate environment'. An obvious example is solar (sunshine) energy, where 'repetitive' refers to the 24-hour major period. Note that the energy is already passing through the environment as a *current* or *flow*, irrespective of there being a device to intercept and harness this power. Such energy may also be called *Green Energy* or *Sustainable Energy*.

Energy sources which comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished) are known as the renewable sources of energy. About 16% of global final energy consumption comes from renewables, with 10% coming from traditional biomass, which is mainly used for heating, and 3.4% from hydroelectricity. New renewables (small hydro, modern biomass, wind, solar, geothermal, and biofuels) accounted for another 3% and are growing very rapidly. The share of renewables in electricity generation is around 19%, with 16% of global electricity coming from hydroelectricity and 3% from new renewable.

A. Solar Energy Input to the Surface of the Earth

The *solar constant* is defined as the radiation power density at the top of the earth's atmosphere which faces the sun directly. Its value is close to the easily remembered estimate 2 cal/min-cm^2 ; it is about 3% greater than the average value during the summer in the northern hemisphere and about 3% smaller during the winter in the northern hemisphere because the earth's orbit around the sun is not exactly circular. Using 2 cal/min-cm^2 , we may estimate a reasonable average radiant power density for the earth as a whole by proceeding as follows. We first multiply the approximate value 2 cal/min-cm^2 by factors of unity in order to convert the solar constant to the power density in watts per square meter (W/m^2), viz., $=2.0 (\text{cal/min-cm}^2) \times (10^4 \text{ cm}^2/\text{m}^2) \times (1 \text{ J}/0.24 \text{ cal}) \times (1 \text{ min}/60 \text{ sec}) \times (1 \text{ W-sec}/\text{J})$ or $= 1389 \text{ W/m}^2$. The approximate average *solar radiation power density at the top of the earth's atmosphere* is obtained from the solar constant by dividing by 4 to allow for variations of seasons and times of day around the globe. The resulting *global average radiant solar power density* is then about 345 W/m^2 . Since the mean radius of the earth is $r_e = 6.371 \times 10^6 \text{ m}$ and its surface area is approximately $4\pi r_e^2 = 5.10 \times 10^{14} \text{ m}^2$, the *radiant power incident on the entire surface of the earth* becomes $(345 \text{ W/m}^2) \times (5.10 \times 10^{14} \text{ m}^2) = 1.77 \times 10^{17} \text{ W} \times (10^7 \text{ erg}/1 \text{ W-sec}) \times (3.154 \times 10^7 \text{ sec/year}) \approx 5 \times 10^{31} \text{ erg/year}$, where we have slightly reduced the calculated value of $5.6 \times 10^{31} \text{ erg/year}$ and neglected the small difference between the radius of the earth and the radial distance to the top of the atmosphere from the center of earth. It should be noted that local solar radiant power inputs are variable not only because of seasonal and diurnal changes but also because of variability of optical properties of the atmosphere (changes in water vapor concentration, clouds, and particulate concentrations) and of surface reflectivities of the earth. The number $5 \times 10^{31} \text{ erg/year}$ provides a reasonable resource estimate for a discussion of solar energy availability over the entire planetary surface.

B. Wind, Geothermal, Hydroelectric, and Tidal Energy

The numerical value listed for the worldwide windenergy potential results from the estimate that $2 \times (10 \times 10^{10} \text{ MW})$ are available if the average winds are the same in the northern and southern hemispheres, which corresponds to $2 \times 10 \times 10^{10} \text{ MW} \times (106 \text{ W/MW}) \times (10^7 \text{ erg}/2.78 \times 10^{-4} \text{ W-hr}) \times (8.76 \times 10^3 \text{ hr/year}) = 6 \times 10^{31} \text{ W/yr}$. The listed value for the outward flow of heat from the core of the earth equals $8 \times 10^{17} \text{ Btu/yr} = 8 \times 10^{27} \text{ erg/year}$ and includes heat flow to the large areas covered by the earth's oceans; at locations where this geothermal heat flow is usable, the conversion efficiency to electricity is not likely to exceed about 25%. The limiting worldwide potential for hydroelectric energy is $2.86 \times 10^6 \text{ MW} \times [106 \text{ W/MW}] \times (10^7 \text{ erg}/2.78 \times 10^{-4} \text{ W-hr}) \times (8.76 \times$

$10^3 \text{ hr/yr} = 9 \times 10^{26} \text{ erg/year}$; the fossil-fuel equivalent for this resource base as a source of electric energy is about three times larger or about $3 \times 10^{27} \text{ erg/year}$. Based on the increase in the length of the day during the last 100 years, the total tidal energy has been estimated to be about $3 \times 10^6 \text{ MW} = 3 \times 10^{12} \text{ W} \times (107 \text{ erg} / 2.78 \times 10^{-4} \text{ W-hr}) \times (8.76 \times 10^3 \text{ hr/year}) = 1 \times 10^{27} \text{ erg/year}$. The achieved conversion efficiencies for tidal to electrical energy are in the range of 10–20%.

C. Ocean Thermal Energy Conversion [OTEC]

OTEC is a technology that converts solar heat stored in the upper layers of the oceans into mechanical and electrical energy. OTEC is an important energy option because it offers a practical way to provide clean, renewable fuels and electricity in quantities large enough to replace all fossil fuel and nuclear energy sources. A total assessment of the worldwide potential for energy recovery using OTEC is around $1.82 \times 10^{14} \text{ kWeh/yr}$. Assuming 33% conversion efficiency to electricity, the thermal fossil-energy equivalent becomes $(1.82 \times 10^{14} \text{ kWeh/yr}) \times (3 \text{ kW/kWe}) \times (10^7 \text{ erg} / 2.78 \times 10^{-7} \text{ kWh}) = 1.96 \times 10^{28} \text{ erg/yr}$. The worldwide potential is probably at least 20 times greater, i.e. $> 4 \times 10^{29} \text{ erg/year}$, and hence may represent a complete, sustainable solution to the world's energy needs at the estimated steady-state requirement beyond 2050 for 5% recovery of the worldwide ocean thermal energy conversion potential.

1.2 Advantages of renewable energy

- a) Renewable energies are renewable, or almost infinite sources of energy from nature that are not perishable
- b) The power plants based on renewable sources of energy don't have any fuel cost and hence negligible running and maintenance costs, which makes renewable energy affordable for the individual.
- c) Renewable is more sites specific and is used for local processing and application. There is no need for transmission and distribution of power.
- d) Renewable have low energy density and more or less there is no pollution or ecological balance problem.
- e) Most of the devices and plants used with the renewable are simple in design and construction which are made from local materials, local skills and by local people. The use of renewable energy can help to save foreign exchange and generate local employment.
- f) The rural areas and remote villages can be better served with locally available renewable sources of energy. There will be huge savings from transporting fuels or transmitting electricity from long distances.
- g) The more technology grows, the easier these energies will be able to be harnessed by the individual, perhaps saving lots of money on electric bills.
- h) It is clean energy, most renewable energies do not negatively affect the environment. (Nuclear energy perhaps being one major exception)
- i) At any geographic location all or most of these renewable energy sources can be found.

1.3 Disadvantages of renewable energy

- Low energy density of renewable sources of energy need large sizes of plant resulting in increased cost of delivered energy.
- Intermittency and lack of dependability are the main disadvantages of renewable energy sources.
- Low energy density also results in lower operating temperatures and hence low efficiencies.
- Although renewables are essentially free, there is definite cost effectiveness associated with its conversion and utilization.
- Much of the construction materials used for renewable energy devices are themselves very energy intensive.
- The low efficiency of these plants can result in large heat rejections and hence thermal pollution.
- The renewable energy plants use larger land masses.

1.4 New sources of energy: The new sources of energy are available for local exploitation. In many cases, autonomous and small power plants can be built to avoid transmission losses. Most prominent new sources of energy are tidal energy, ocean waves, OTEC, peat, tar sand, oil shales, coal tar, geo thermal energy, draught animals, agricultural residues etc., The total energy production in India is 14559×10^{15} joules. 93% of India's requirement of commercial energy is being met by fossil fuels, with coal contributing 56%, and oil and natural gas contributing 37%. Water power and nuclear power contributing only 7% of total energy production. Comparing the total energy production in India from commercial sources with that of world, it is only 3.5% of total world production.

Comparison between different energy resources

	Fossil Fuels with Sequestration	Renewables (including biofuels)	Nuclear
Description	Fossil fuels (principally coal) are extracted, converted to electricity and/or hydrogen, resulting CO ₂ byproduct is captured and sequestered.	Renewable energy sources are converted to electricity and/or hydrogen. Biofuels may also be converted directly to mechanical power in vehicles.	Energy released from fissile materials or from nuclear fusion.
Long-term availability	200–300 years worldwide, assuming aggressive efforts to improve end-use efficiency.	Indefinite. Climate change may lead to changes in output (positive or negative) in specific locations.	In the case of deuterium-based fusion, almost indefinite, nearly as long as expected lifetime of planet earth.

Economic cost Considerations	Combustion side is mature technology, inexpensive and reliable. Large-scale sequestration is not yet developed, cost unknown but likely to add significantly to life cycle cost.	High cost per unit of energy, due to low capacity factors, low concentration of energy. Need for storage system due to intermittency increases cost (except for biofuels and geothermal). New technologies may reduce cost in future.	Capital costs higher relative to fossil fuel combustion; variable cost for fuel may be lower at present. Long-term disposal cost and cost of fusion technology, breeder reactor technology for U-238 are unknown.
Environmental cost considerations	Negative effect of extraction of coal on land and water resources, natural habitat, and so on.	Land requirements, solid waste issues with large-scale construction of infrastructure	Effect of extraction of uranium; disposal of radioactive waste and decommissioned infrastructure.
Suitability as an energy source for transportation	Requires conversion to electricity or hydrogen, unless means can be found to extract large amount of CO ₂ from atmosphere.	Requires conversion to electricity or hydrogen, except for biofuels.	Requires conversion to electricity or hydrogen.

1.5 Definitions:

Fossil fuels Coals, petroleums, natural gases, oils from shales and tar sands, methane hydrates, and any other supplies from which hydrocarbons for energy applications may be extracted.

Fuels for nuclear breeder reactors These include U-238 and Th-232, which may be converted to fissile isotopes (e.g., U-233, U-235, Pu-239, and Pu-241) as the result of neutron capture.

Fuels for (nuclear) fission reactors The naturally occurring fissile isotope U-235, as well as Pu-239 and Pu-241 produced by neutron capture in U-238 and U-233 from Th-232.

Nonrenewable resources (nonrenewables) Resources located on the planet with estimable times for exhaustion at allowable costs and use rates.

Renewable resources (renewables) Usually defined as extraterrestrial energy supplies such as solar resources, but some authors include energy supplies of such types and magnitudes that they will be available for the estimated duration of human habitation on the planet.

Reserves Energy supplies which are immediately usable at or very close to current prices.

Resources The totality of energy supplies of specified types that include reserves and may become usable in time at competitive prices with improved technologies

Chapter 2

Source of power availability in agriculture. Use of conventional and non-conventional sources of energy for agriculture.

2.1 Introduction

Power is needed on the farm for operating different tools, implements and during various farm operations. While mobile power is used for doing different field jobs, the stationary power is used for lifting water and operating irrigation equipment; operating threshers, shellers/deorticators, cleaners, graders and for other post-harvest operations. The mobile farm power comes from human, draught animals, power tillers, tractors and self-propelled machines, whereas the stationary power is obtained from oil engines (diesel, petrol, kerosene) and electric motors and in certain cases renewable sources.

Availability of adequate farm power is very crucial for timely farm operations for increasing production and productivity and handling the crop produce to reduce losses. With the increase in intensity of cropping the turnaround time is drastically reduced and it is not possible to harvest and thresh the standing crop, on one hand, and prepare seed bed and do timely sowing operations of subsequent crop, on the other hand, in the limited time available, unless adequate farm power is available.

Similarly for precision farming, increasing area under irrigation, conservation tillage, straw management and diversification in agriculture, more power is required for water lifting and precision placement/application of agricultural inputs—seed, fertilizer, irrigation water, plant protection chemicals etc and meeting the requirements of diversified agriculture. There has been close nexus between farm power availability and increased productivity. Those states where availability of farm power is more have, in general, higher productivity as compared to others.

2.2 Sources of Farm Power

The different sources of power available on the farm for doing various mobile and stationary operations are as under:

Mobile Power

1. Human (men, women, children)
2. Draught animals (bullocks, buffaloes, camels, horses and ponies, mules and donkeys)
3. Tractors
4. Power tillers
5. Self propelled machines (combines, dozers, reapers, sprayers etc.)

Stationary Power

1. Diesel/oil engines (for pump sets, threshers, sprayers and other stationary operations)
2. Electric motors (for pump sets, threshers, sprayers and other stationary operations)
3. Renewable energy

2.2.1 Human Power

The average power availability, in sustained working, from a male agricultural worker is considered as 60 watts (0.06 kW) while for a female worker it is considered as 48 watts (0.048 kW) and for child worker as 30 watts (0.030 kW), which are 80% and 50% respectively, compared to male worker. While the population of agricultural workers as percentage of rural population has gone down from about 69.4% in 1951 to about 58.4% in 2001 but in absolute terms, due to increase in overall population, the number of agricultural workers available in rural areas has increased from about 97.2 million numbers in 1951 to about 235.1 million numbers in 2001. These agricultural workers are engaged in different farm operations and depend on agriculture for their livelihood, even when they are not fully employed throughout the year. Due to too much involvement of labour in different farm operations, the cost of production of most of the crops in our country is quite high as compared to developed countries. On an average, a man develops nearly 0.1 horse power (hp).

Advantages: Easily available and used for all types of work.

Disadvantages: Costliest power compared to all other forms of power, very low efficiency, requires full maintenance when not in use and affected by weather condition and seasons

2.2.2 Draught Animal Power

Draught animals, particularly bullocks, are still the predominant source of mobile power on about 60% of the cultivated area consisting of about 85 million ha. They are very versatile and dependable source of power and are used in sun and rain under muddy and rough field conditions. They are born and reared in the village system and maintained on the feed and fodder available locally. They are ideal for rural transport where proper roads are not available. They reduce dependence on mechanical sources of power and save scarce petroleum products. Their dung and urine are also used as indirect source of

energy—farmyard manure, biogas. They also help in maintaining ecological balance. Under Indian conditions where majority of the people are vegetarian and even amongst non-vegetarians, majority of them don't eat beef, draught animals as by-product of milch animals, will continue to be available for draught purposes in future also. About 4-5 decades back most of the farm operations, water lifting, rural transport, oil extraction, sugarcane crushing, chaff cutting etc, were being done using draught animals only. But with the modernization of agriculture, development of pucca roads connecting village and availability of electricity in those villages, most of the jobs earlier being done using draught animals, except field operations, are now being done using other convenient and cheaper options. Over the years the annual use of draught animals is going down. While earlier a pair of animals was being used for about 1200-1800 hours annually, their average annual use has now come down to about 250-500 h only, that too for tillage, sowing, weeding a little bit of rural transport on kuchha roads. It has been observed that on an average a tractor is replacing about 5 pairs and power tiller about 2 pairs of animals.

The power available from draught animals is related to its body weight. The maximum draft available from different animals, in sustained working, on whole day basis (in two shifts) using local yokes/harnesses have been found as under:

Bullocks : 10-12% of body weight in summer and 12-14% in winter

Buffaloes : 12% of body weight in all seasons

Camels : 18% of body weight up to 7 h, 26% up to 6 h following 2 h work + 2 h rest schedule.

Donkeys : 32% of body weight up to 6 h and 36% up to 4 h in two shifts.

On the basis of the body weight draught animals are categorized as small (200-300 kg), medium (300-400 kg), large (400-500 kg) and heavy (above 500 kg.) animal. From a good pair of animals weighing between 900-1000 kg we can get about 0.75-0.78 kW power. But in most of the States the pair weight of draught animals ranges between 600-800 kg/pair and power availability from them is only about 0.50-0.55 kW/pair.

Advantages: Easily available, Used for all types of work, Low initial investment, Supplies manure to the field and fuels to farmers, Live on farm produce.

Disadvantages: Not very efficient, Seasons and weather affect the efficiency, Cannot work at a stretch, Require full maintenance when there is no farm work, Creates unhealthy and dirty atmosphere near the residence, Very slow in doing work.

2.2.3 Mobile Power from Tractors, Power Tillers and Self-Propelled Reapers and Combines

For meeting the increased demand of mobile power for timely farm operations and increased intensity of cropping, additional power is available mainly from tractors and power tillers. Self propelled reapers and combines also provide mobile power specially for harvesting operations. In India tractor and power tiller production started in 1960 and today the annual production has crossed over 250,000 and 17,000 numbers, respectively and India has emerged as number one producer of small tractors in the world. While the demand of tractors has increased steeply, the demand of power tillers has not grown that fast. The demand of tractors that has been increasing steadily has helped in providing additional mobile power on the farm for timely farm operations and has helped in increasing agricultural production and productivity. There are 14 manufacturers of tractors in the country producing about 60 models of tractors in different hp ranges. About 56.73% of the tractors produced are in the range of 23.12-29.84 kW (31-40 hp), about 17.16% in the range of 30.38-37.3 kW (41-50 hp) and about 21.50% in the range of 15.66- 23.38 kW (21-30 hp). Only about 4.46% tractors are produced in the range of above 37.30 kW (above 50 hp) and 0.15% in the range of less than 14.92 kW (20 hp) range. For calculating power availability from tractors on the farm, a weighted average of 26.1 kW per tractor has been taken.

There are mainly 2 manufacturers of power tillers in the country producing about 6 models in the range of 5.97-8.95 kW (8-12 hp). In addition to them there are 4 other manufacturers who are importing Chinese make of power tillers and selling in the country. The total sale of power tillers in the country during 2001 was 16018 numbers. For calculating power availability from power tillers on the farm, a weighted average of 7.0 kW per unit has been taken.

Advantages: Efficiency is high; not affected by weather; requires less space and cheaper form of power.

Disadvantages: Initial capital investment is high; cannot run at a stretch; fuel is costly and repairs and maintenance needs technical knowledge.

2.2.4 Stationary Power from Diesel Engines and Electric Motors

Stationary power sources in agriculture comprise of diesel engines and electric motors used for irrigation equipment, operating threshers and other stationary machines. For calculation purposes the average weighted power of diesel engines has been taken as 5.6 kW and for electric motors as 3.7 kW and 7.46 kW for small pump sets and submersible pumps respectively. On an average, about 1/10th of the total electrical power generated in India, is consumed for the farm work, approximately it is 4600 megawatt.

Advantages: Very cheap form of power; high efficiency; can work at a stretch; maintenance and operating cost is very low and not affected by weather conditions.

Disadvantages: Initial capital investment is high; require good amount of technical knowledge and it causes great danger, if handled without care.

2.2.5 Renewable energy

It is the energy mainly obtained from biomass; biogas, solar and wind are mainly used in agriculture for power generation and various agricultural processing operations. It can be used for lighting, power generation, water heating, drying, greenhouse heating, water distillation, refrigeration and diesel engine operation. This type of energy is inexhaustible in nature. The availability of wind energy for farm work is quite limited. Where the wind velocity is more than 32 kmph, wind mills can be used for lifting water. Main limitation for this source is uncertainty. Average capacity of a wind mill would be about 0.5 hp. There are about 2540 windmills in India. It is the cheapest sources of farm power available in India.

Chapter 3

Familiarization with biomass utilization for biofuel production and their application

3.0 Introduction: Plant matter created by the process of photosynthesis is called biomass (or) all organic materials such as plants, trees and crops are potential sources of energy and are collectively called biomass. Photosynthesis is a naturally occurring process which derives its energy requirement from solar radiation. The plants may be grown on land (terrestrial plants) or grown on water (aquatic plants). Biomass also includes forest crops and residues after processing. The residues include crop residues (such as straw, stalks, leaves, roots etc.,) and agro-processing residues (such as oilseed shells, groundnut shells, husk, bagasse, molasses, coconut shells, saw dust, wood chips etc.,). The term biomass is also generally understood to include human waste, and organic fractions of sewage sludge, industrial effluents and household wastes. The biomass sources are highly dispersed and bulky and contain large amounts of water (50 to 90%). Thus, it is not economical to transport them over long distances, and conversion into usable energy must take place close to source, which is limited to particular regions.

3.1 Availability of biomass

The total terrestrial crop alone is about 2×10^{12} metric tones. These include sugar crops, herbaceous crops and silviculture plants. The terrestrial crops have an energy potential of 3×10^{22} joules. At present only 1% of world biomass is used for energy conversion. The estimated production of agricultural residue in India is 200 million tones per year and that of wood is 130 million tones. At an average heating value of 18 MJ / kg db, a total potential of energy from agricultural residue is 6×10^{12} MJ/ Year. At a power conversion rate of 35%, total useful potential is about 75,000 MW. This can supply all our villages with power at a rate of 30,000 kWh per day per village against the present meager consumption of only 150 kWh per day per village. The cattle production in India is nearly 237 million. Assuming the average wet dung obtained per animal per day to be 10 kg and a collection rate of 66%, the total availability of wet dung in the country would be 575 million tons per annum. This itself would enable to produce 22,425 million m³ of biogas, which can replace kerosene oil to an extent of 13, 904 million litres per year. In a biogas plant, apart from the gas that is produced, enriched manure is also obtained as a by-product. It is estimated that, 206 million tons of organic manure per annum would be produced in biogas plants, which would replace 1.4 million tons of nitrogen, 1.3 million tons of phosphate and 0.9 million tons of potash.

3.2 Biomass Conversion

Biomass can either be utilized directly as a fuel, or can be converted into liquid or gaseous fuels, which can also be as feedstock for industries. Most biomass in dry state can be burned directly to produce heat, steam or electricity. On the other hand biological conversion technologies utilize natural anaerobic decay processes to produce high quality fuels from biomass. Various possible conversion technologies for getting different products from biomass is broadly classified into three groups, viz. (i) thermo-chemical conversion, (ii) bio-chemical conversion and (iii) oil extraction. These alternative technologies for biomass conversion offer sound and alternative options for meeting the future fuels, chemicals, food and feed requirements. Three main approaches can be adopted for generation and utilization of biomass:

- (i) Collection of urban and industrial wastes as supplementary fuel in boilers and as a feed stock for producing methane and some liquid fuels.
- (ii) Collection of agricultural and forest residues to produce fuels, organic manures and chemical feed stock.
- (iii) Growth of some specific energy plants for use as energy feedstock and cultivation of commercial forestry, aquatic and marine plants for different products.

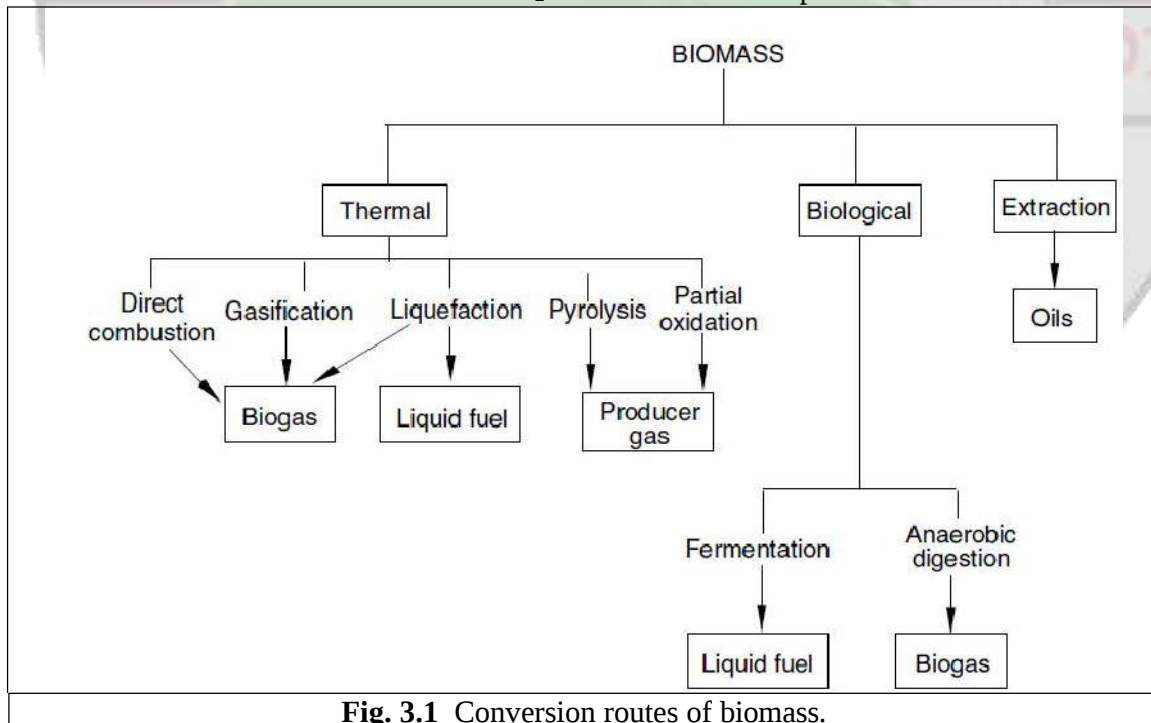
Thermo-chemical conversion includes processes like combustion, gasification and pyrolysis. **Combustion** refers to the conversion of biomass to heat and power by directly burning it, as occurs in boilers. **Gasification** is the process of converting solid biomass with a limited quantity of air into producer gas, while **pyrolysis** is the thermal decomposition of biomass in the absence of oxygen. The products of pyrolysis are charcoal, condensable liquid and gaseous products.

Biochemical conversion includes anaerobic digestion to produce biogas and fermentation to obtain alcohol fuels. The third approach is oil extraction. Edible and non-edible oils can be extracted from a variety of grains and seeds. They can be directly used as fuels by transesterification process to produce bio-diesel, which is a good substitute for conventional diesel oil. Thermal conversion processes for biomass involve some or all of the following processes (Fig. 3.1):

Pyrolysis: Biomass + heat $\rightarrow$ charcoal , gas and oil

Gasification: Biomass + limited oxygen $\rightarrow$ fuel gas

Combustion: Biomass + stoichiometric $O_2 \rightarrow$ hot combustion products



3.3 Principles of combustion

In general, the term combustion refers to the process of release of heat by the exothermic heat of reaction for the oxidation of the combustible constituents of the fuel. Practically the combustion process is an interaction amongst fuel, energy and the environment. Fuel may be defined as a combustible substance available in bulk, which on burning in presence of atmospheric air generates heat that can be economically utilized for domestic and industrial purposes. The common fuels are compounds of carbon and hydrogen; in addition, variable percentages of oxygen and small percentages of sulphur and nitrogen are also present. Biomass fuels are normally thermally degradable solids. Combustion of organic materials not only generates natural components of air such as carbon dioxide and water but also produces carbonaceous residues, smoke and tar and gases of carbonyl derivatives, and carbon monoxide. The important parameters affecting combustion are moisture, organic compounds and minerals (ash).

Combustion Process The pyrolysis and subsequent combustion of biomass fuels proceed by two alternative pathways. In the first pathway, which operates at higher temperatures, pyrolysis or thermal decomposition of the biomass provides a mixture of combustible gases. These gases mix with air to fuel the flaming combustion that could rapidly spread in the gas phase. In the second pathway, which dominates at lower temperatures, pyrolysis produces mainly carbonaceous char and a gas mixture containing water and carbon dioxide. That is not flammable. Oxidation of the resulting active char then provides glowing or smouldering combustion. This type of combustion proceeds as a front in the solid phase at a lower rate.

Principles of pyrolysis The pyrolysis of solid wastes strictly refers to the thermal decomposition of the wastes in an inert atmosphere. In this process, a mixture of gaseous products, tars, water insoluble oils, and an aqueous solution of acetic acid, methanol and other organic compounds is evolved and a solid residue composed of the inert content of the waste and a char is produced. The amounts of the various products generated are dependent upon the rate of heating and the final temperature to which the wastes are subjected. In general, the higher the heating rate, and higher the final temperature, greater the fraction of the initial wastes that is converted into the gaseous and liquid products. The yield of gaseous products is highly variable but is about 25% of the refuse on dry ash-free basis. The yield of char is about 15 to 25% by weight of the refuse.

Pyrolysis or charring of a biomass fuel has three main objectives: (i) production of a less smoky, clean burning fuel without generation of any tar; (ii) production of a fuel with a high calorific value than that of the initial feed material; (iii) production of a more reactive fuel. As the biomass is subjected to thermal treatment, it decomposes and volatilizes some of the volatile matters, leaving a carbonaceous residue containing the mineral components. The volatile products consist of a gaseous fraction containing CO, CO₂, some hydrocarbons and H₂; a considerable fraction containing water and organic compounds of lower molecular weights such as acids, alcohols, aldehydes, and ketones, and a tar fraction. Fine airborne particles of tar and charred materials constitute smoke. The amounts of volatiles matter formed, the residue left, and the weight loss occurred can be determined by the thermogravimetric analysis (TGA) and its derivative is called

differential thermogravimetry (DTG). The change in enthalpy, ΔH can be measured by differential thermal analysis (DTA). All these analysis are called thermal analysis. The energy released during pyrolysis and combustion can be measured as a function of time or temperature by thermal evolution analysis (TEA).

Principles of gasification Gasification is a process for converting carbonaceous materials to a combustible or synthetic gas (e.g., H_2 , CO, CO_2 , CH_4). Gasification is an environmentally sound way to transform any carbon-based material, such as coal, refinery byproducts, biomass, or even trash, into energy without burning it. Instead, gasification produces a gas by creating a chemical reaction that combines those carbon-based materials (feedstocks) with air or oxygen, breaking them down into molecules and removing pollutants and impurities. What's left is a clean "synthesis gas" (syngas) that can be converted into electricity and valuable products, such as transportation fuels, fertilizers, substitute natural gas, or chemicals.

The equivalence ratio, ϕ is defined as the ratio of the actual air supplied to the theoretical air required. The efficiency, η of a gasifier is defined as the ratio of chemical energy output in the dry producer gas at 150 °C to the energy input from the biomass. The total energy in the gaseous phase increases with the increase of equivalence ratio, ϕ . The important parameters affecting the fixed bed gasification are:

- Shape and size of the biomass fuel and fuel bed structure,
- Moisture content
- Volatile matter content
- Ash content
- Ash composition, its moisture content and
- Energy content.

In the course of gasification, a number of thermochemical reactions take place. The quality of the fuel gas is dependent upon the equilibrium constants of the reactions. In gasification, the quantity of air that is supplied to the gasifier is always sub-stoichiometric. A gasification process that produces pyrolytic oil and char can achieve an overall thermal efficiency in excess of 70%. It may be noted that the products of combustion are generally CO_2 , H_2O , N_2 and excess O_2 and those of gasification are CO_2 , CO, H_2 , CH_4 , C_2H_4 , C_3H_6 , NH_3 , H_2S , N_2 , H_2O and tar vapours and low molecular weight organic liquids.

A comparison of gasification and combustion technologies has been shown in tabular form below (Table 3.1).

Table 3.1: Comparison of Gasification and Combustion Technologies		
Features	Gasification	Combustion
Purpose	Creation of valuable, usable products from waste or lower value material	Generation of heat or destruction of waste
Process type	Thermal and chemical conversion using no or limited	Complete combustion using excess oxygen (air)

	oxygen	
Raw Gas Composition (before gas cleanup)	H ₂ , CO, H ₂ S, NH ₃ , and particulates	CO ₂ , H ₂ O, SO ₂ , NO _x , and particulates
Gas Cleanup	Syngas cleanup at atmospheric to high pressures depending on the gasifier design Treated syngas used for chemical, fuels, or power generation Recovers sulfur species in the fuel as sulfur or sulfuric acid Clean syngas primarily consists of H₂ and CO.	Flue gas cleanup at atmospheric pressure Treated flue gas is discharged to atmosphere Any sulfur in the fuel is converted to SO₂ that must be removed using flue gas cleanup systems, generating a waste that must be landfilled. Clean flue gas primarily consists of CO₂ and H₂O
Solid by-products/products	Char or slag	Bottom ash
Ash/char or slag handling	Low temperature processes produce a char that can be sold as fuel. High temperature processes produce a slag, a non-leachable, non-hazardous material suitable for use as construction materials. Fine particulates are recycled to gasifier. In some cases fine particulates may be processed to recover valuable metals.	Bottom ash and fly ash are collected, treated, and disposed as hazardous waste in most cases.
Temperature	1300°F – 2700°F	1500°F – 1800°F
Pressure	Atmospheric to high	Atmospheric

3.4 Biomass Applications and Processes

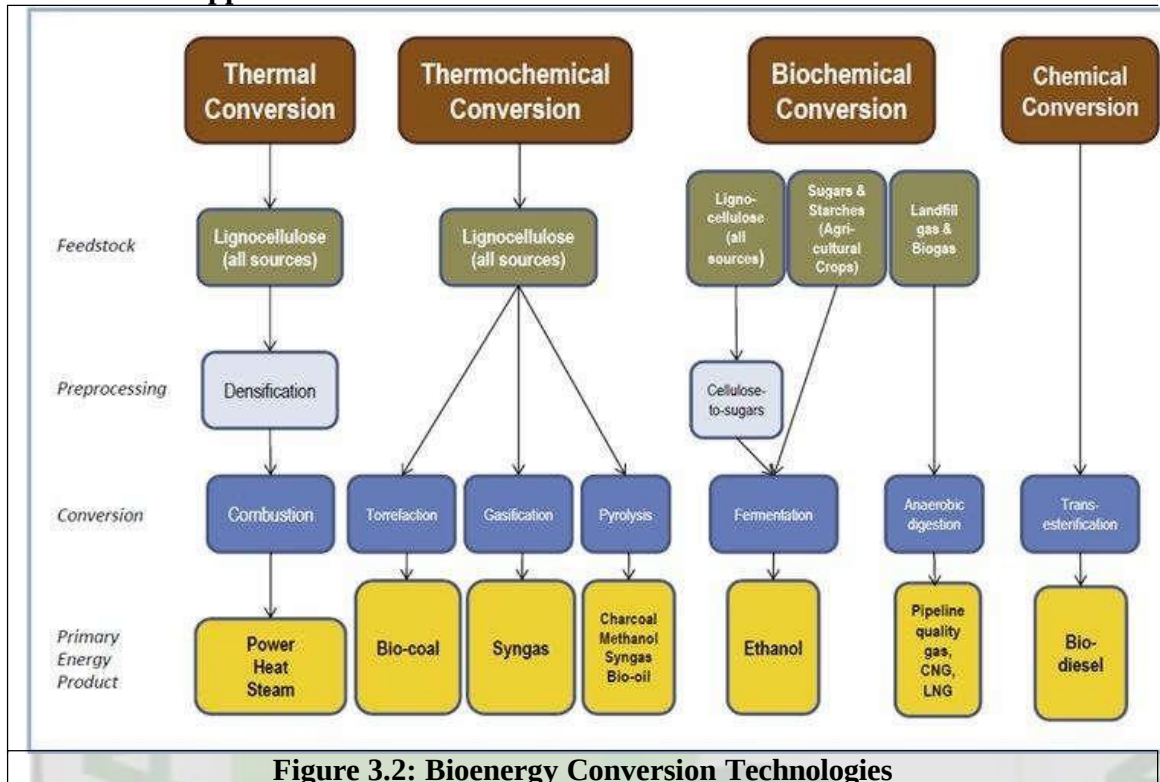


Diagram examines bioenergy conversion technologies of various different energies. F stands for Feedstock. PP stands for Preprocessing, C stands for conversion and PEP stands for primary energy product.

Thermal Conversion

F: Lignocellulose (all sources)
 PP: Densification
 C: Combustion
 PEP: Power, Heat, Steam

Chemical Conversion

F: N/A
 PP: N/A
 C: Transesterification
 PEP: Bio-diesel

Thermochemical Conversion

F: Lignocellulose (all sources)
 PP: N/A
 C: Torrefaction
 PEP: Bio-coal
 C: Gasification
 PEP: Syngas

C: Pyrolysis

PEP: Charcoal, methanol, syngas, bio-oil

Biochemical conversion

F: Lignocellulose (all sources)

PP: Cellulose to Sugars

C: Fermentation

PEP: Ethanol

F: Sugars & Starches (Agricultural Crops)

PP: N/A

C: Fermentation

PEP: Ethanol

F: Land Fill gas & Biogas

PP: N/A

C: Anaerobic Digestion

PEP: Pipeline quality gas, CNG, LNG

3.5 Definition:

Bio-chemical conversion This involves biological processes. The most important to date are alcohol production from biomass containing sugar, starch and/or celluloses and biogas production from organic waste material (like animal or human waste). Both technologies are state of the art and widely used for fuel making in developing as well as in industrialized countries. Additionally heat can be produced during composting of biomass waste, although this heat is difficult to tap economically.

Biofuel Biomass used as fuel. Sometimes used to refer to processed liquid, solid, or gaseous fuels derived originally from biomass.

Biomass This term is used somewhat more narrowly than its common use in ecology, where it refers to all living matter. Biomass refers to organic material produced initially by photosynthesis with or without human support.

Herbaceous biomass refers to all types of biomass with a grassy nature, such as cereal and hay. Such biomass is provided mainly by agriculture. Compared to wood herbaceous biomass it is more difficult to burn such types of biomass in an environmentally sound way due to a higher amount of trace elements like chlorine and a lower ash melting point.

Lower heating value (LHV) The LHV (net calorific value) characterizes the energy released during complete oxidation of dry biomass without counting the latent heat of the water produced. If the water vapor in the flue gas produced from fuel hydrogen during oxidization is condensed within the conversion device, additional energy is released. The higher heating value (HHV—gross calorific value) includes this energy as well.

Physico-chemical conversion This may be used to produce liquid fuel by physical (e.g., pressing) or chemical (e.g., esterification) means. The only important process with a certain market potential so far is vegetable oil production from oil seed and esterification of this vegetable oil to fatty acid methyl ester as a substitute for diesel fuel. This technology is used to some extent in Europe.

Thermo-chemical conversion This is used to convert biomass into a solid, liquid, or gaseous fuel by heating under various conditions with some access to air. Gasification, pyrolysis, and charcoal production are the main examples. Of these, only charcoal

production is widely used to date, but gasification in connection with electricity production seems to be promising in both developed and developing countries. Biomass gasification also shows advantages in developing countries for production of process heat in small-scale industrial applications such as food drying, silk manufacture, and cremation. Pyrolysis for production of liquid fuel useable in engines is a future option.

Woody biomass This can be produced by forestry (i.e., firewood from natural or intensively managed forests), agriculture (i.e., short-rotation plantations of fastgrowing trees such as poplar or willow), or as residues from wood production for nonfuel purposes such as lumber. Compared to herbaceous biomass, it is a more promising source of energy. Besides the fact that the content of trace elements in wood is lower compared with herbaceous biomass, the ash melting point is also usually higher. Therefore from an environmental point of view wood is more promising as a solid biofuel compared to straw or hay.



Chapter 4

Familiarization with biogas and types of biogas plants

4.0 Introduction: Biomass is organic matter from plants, animals and microorganisms grown on land and in water and their derivatives. Biomass includes forest crops, crops from agricultural fields, animal manure, urban and rural organic wastes etc. Fossil fuels are derived from biomass but are not renewable and hence not called biomass. Biomass can be converted into gaseous and liquid fuels called biogas and biochemicals respectively, by anaerobic decomposition. Biogas and biochemicals can be transported over long distances and then used as secondary sources of energy. Biogas and biochemicals have higher energy density (J/ Kg) than that of raw biomass. Most of the biomasses are used as fuels either directly or after obtaining biogas/biochemicals. Thus biomass is an important renewable source for obtaining organic fuels.

Biogas is a mixture of methane, carbon dioxide, hydrogen and hydrogen sulphide, the major constituent being methane. Biogas is produced by anaerobic degradation of animal wastes (sometimes plant wastes) in the presence of water. Anaerobic degradation means break down of organic matter by bacteria in the absence of oxygen. Biogas is a non-polluting, clean and low cost fuel which is very useful for rural areas where a lot of animal waste and agricultural waste are available. India has the largest cattle population in the world (240 million) and has tremendous potential for biogas production. From cattle dung alone, we can produce biogas of a magnitude of 22,500 Mm³ annually. A sixty cubic feet gobar gas plant can serve the needs of one average family. The calorific value of biogas ranges from 5000 to 5500 Kcal/Kg (18.8 to 26.4 MJ /m³). The biogas can be upgraded to synthetic natural gas (SNG) by removing CO₂ and H₂S.

Biogas has the following main advantages: It is clean, nonpolluting and cheap. There is direct supply of gas from the plant and there is no storage problem. The sludge left over is a rich fertilizer containing bacterial biomass with most of the nutrients preserved as such. Air-tight digestion/degradation of the animal wastes is safe as it eliminates health hazards which normally occur in case of direct use of dung due to direct exposure to faecal pathogens and parasites.

4.1 Principle of Biogas Plant

Anaerobic fermentation is the fermentation in the absence of air of cellulose containing organic materials, like cattle dung, poultry droppings, pig excreta, human excreta, crop residues etc. This oxygen deficient fermentation results in the production of a combustible gas called biogas. The structural set up in which anaerobic fermentation of cellulose containing organic material occurs, producing biogas that is collected in a gas holder and sent through a pipe line for utilization under suitable pressure, is called the biogas plant. The design of a biogas plant is directly linked to its hydraulic retention time (HRT), which may be defined as the time period during which the mixture of cattle dung and water stays in the digester to produce the biogas before being fully exhausted of its biochemical potential of producing biogas. The HRTs of biogas plants are different for different regions of India. For the majority of the Indian territory, it is 40 days.

Following three anaerobes help in anaerobic decomposition.

- i. Fermentative bacteria: These bacteria perform initial break down of polymeric materials.
- ii. Acid forming bacteria: These produce volatile fatty acids (e. g. acetic acid) and
- iii. Methanogenic bacteria: These produce methane gas.

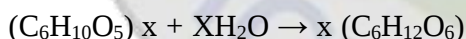
The organic matter consists of carbohydrates, fats, and complex organic compounds. The first stage bacteria convert complex organic matter to simpler organic compounds. These bacteria grow well in the pH range 6-7.

The second group bacteria convert the various sugars, amino acids, and fatty acids to volatile fatty acids, carbon dioxide and hydrogen. Varieties of fatty acids such as lactic acid, acetic acid, and propeonic acids are produced in the second step.

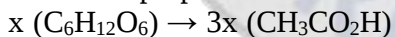
In the third step methanogenic bacteria become active and decompose short chain fatty acids to give carbon dioxide and methane gas. Methanogenic bacteria are active only in the atmosphere of carbon dioxide and inactive in the presence of oxygen. They grow well in the pH range 7-8 (i.e. just greater pH than the first group of bacteria). These are very sensitive to a change of pH.

Any drop in pH decreases the activity of these bacteria, resulting in cessation of methane generation. To maintain pH of slurry lime or ammonia are added to the digester. The whole process of biogas generation can be summarised as follows:

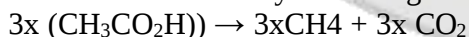
Hydrolysis: The complex organic compounds are converted to low molecular weight soluble substances, primarily carboxylic acids. Here low molecular weight soluble substances pass through the cell membrane of bacteria responsible for anaerobic digestion and extra cellular enzymes are released in medium. These enzymes hydrolyze the sludge particles.



Acid formation: During this process the organic matter is oxidised to volatile acid mainly acetic and propanic acid.



Methane formation: volatile acids produced in previous step are converted to methane and carbon di oxide by Methanogenic bacteria.



4.2 Construction and Operation of Biogas Plant

In order to understand the principle of biogas plant a simple model is shown below (Fig. 4.1).

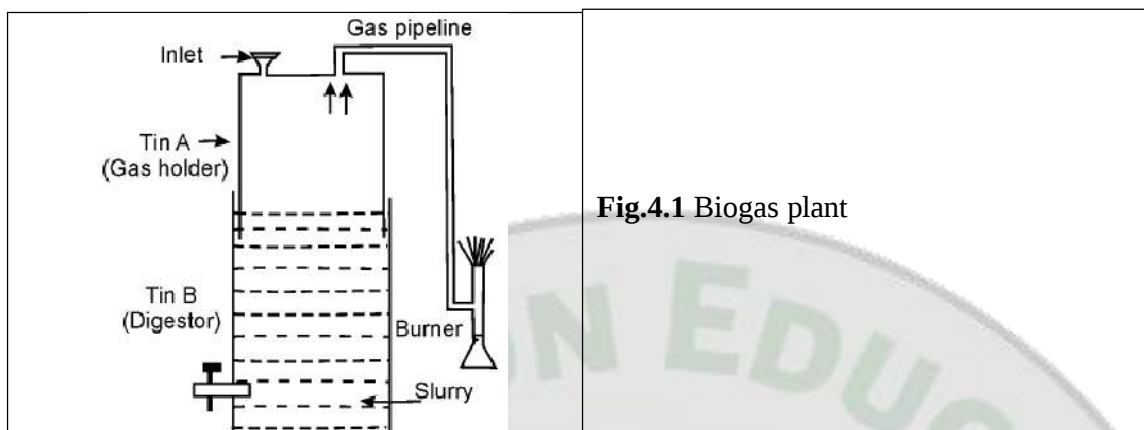


Fig.4.1 Biogas plant

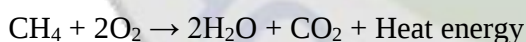
The biogas plant mainly consists of:

- i. Digester ii. Gas holder iii. Distribution pipes iv. Gas appliances

The biogas plant is fabricated simply with two tins (Tin A and Tin B); one of them is slightly smaller than the other, so that they can fit into one another. For the upper tin A, the funnel for inlet and pipes for outlet are fitted. Similarly for Tin B at the bottom, outlet tap is fitted. The Tin A is called gasholder and B is called digester.

The Tin B or digester is completely filled with the slurry; Tin A is pressed downward so that it will tightly fit into lower tin B. After two three weeks the upper tin A starts to move up due to production of biogas. This period varies from few weeks to two months and is known as retention time. The retention time varies with the size of biogas plant and rate of feed.

The approximate composition of gas is as follows 55-60% methane, 35-40 % CO₂, 5 % Hydrogen, H₂S and O₂ traces. The gas burns with a hot blue and smokeless flame. Methane and hydrogen burn with oxygen give heat as follows:



The CO₂ present in biogas does not contribute to heat energy and it is un-favorable to any burning process.

Approximate rules for sizing biogas plants

1. One kg of dry cattle dung produces approximately 1 m³ of biogas.
2. One kg of fresh cattle dung contains 8% dry bio-degradable mass.
3. One kg of fresh cattle dung has a volume of about 0.9 litres.
4. One kg of fresh cattle dung requires an equal volume of water for preparing slurry.
5. Typical retention time of slurry in a biogas plant is 40 days.

4.3 Application of biogas

One cubic meter of biogas can do the following operations:

- (i) It can illuminate a mantle lamp (60 W) for a period of 7 hours.
- (ii) It can be used for cooking three meals for a family of five.
- (iii) It can run 2 hp engine for one hour.
- (iv) It can run 100 lt. capacity refrigerator for 9 hours.
- (v) It can generate electricity of 1.25 KWH.

4.4 Composition of slurry

- i) Nitrogen (N_2): 1.5 %
- ii) Phosphorus (P_2O_5): 0.4 %
- iii) Potash (K_2O): 2.2 %

Number of cattle required for different capacity of plants and family sizes				
S.No.	Size of plant (M^3)	Amount of wet dung required daily (kg.)	Approximate No. of cattle required	Approximate family size
1.	1	25	2-4	1-4
2.	2	50	4-5	5-8
3.	3	75	6-8	9-12
4.	4	100	9-10	13-16
5.	6	150	11-15	17-22
6.	8	200	13-16	23-26
7.	10	250	17-20	27-32

The efficiency of biogas generation depends upon the following factors:

- a) Acid formers and methane fermentors must remain in a state of dynamic equilibrium which can be achieved by proper design of digester.
- b) Anaerobic fermentation of raw cow dung can takes place at any temperature between 8 and 55°C. The value of 35°C is taken as optimum. The rate of biogas formation is very slow at 8°C. For anaerobic digestion, temperature variation should not be more than 2 to 3°C. Methane bacteria work best in the temperature range of 35 and 38°C.
- c) A pH value between 6.8 and 7.8 must be maintained for best fermentation and normal gas production. The pH above 8.5 should not be used as it is difficult for the bacteria to survive above this pH.
- d) A specific ratio of carbon to nitrogen (C/N ration) must be maintained between 25:1 and 30:1 depending upon the raw material used. The ratio of 30:1 is taken as optimum.
- e) The water content should be around 90% of the weight of the total contents. Anaerobic fermentation of cow dung proceeds well if the slurry contains 8 to 9% solid organic matter.
- f) The slurry should be agitated to improve the gas yield.
- g) Loading rate should be optimum. If digester is loaded with too much raw material, acids will accumulate and fermentation will be affected.

4.5 Equivalent Quantity of Fuel for 1 m³ of Bio-Gas

Name of the fuel	Kerosene	Fire-wood	Cow-dung cakes	Charcoal	Soft coke	Butane	Furnance Oil	Electricity
Equivalent quantities to 1 m ³ of Biogas	0.620 lt	3.474 kg	12.296 kg	1.458 kg	1.605 kg	0.433 kg	0.417 lt	4.698 kWh

4.6 Types of Biogas Plants

Depending on nature of gasholder biogas plants are classified into mainly two groups as follows:

1. Floating gasholder biogas plant.
2. Fixed dome gasholder biogas plant.

In floating type biogas plant the gasholder is separated from the digester where as in fixed dome plants the gasholder and digester are combined.

4.6.1 Floating gasholder Biogas Plant: (KVIC Model)

The floating dome biogas plant first developed by Khadi and Village Industries Commission in 1961 and called KVIC Model. These were standardized in 1962 and are used widely even now. Modified version of KVIC model is called Ganesh model. The design consists of deep well-shaped underground digester connected with inlet and outlet pipes at its bottom. The inlet and outlet pipes are separated by a partition wall dividing the 3/4s of the total height into two parts. A mild steel gas storage drum that is inverted over the slurry and goes up and down around a guide pipe with the accumulation and withdrawal of gas. Now FRP (fibre-reinforced plastic) and ferrocement gas holders are also being used in this type of plant. The gas holder is separated from the digester. A partition is provided in the digester to encourage circulation. The floating gas holder provided at the top of the digester helps to keep the pressure constant. The floating gas holder rises when the pressure is increased due to production of gas and allows the generated gas to be let out through the gas supply pipe. It lowers when the pressure is decreased to stop the supply of the biogas (Fig. 4.2).

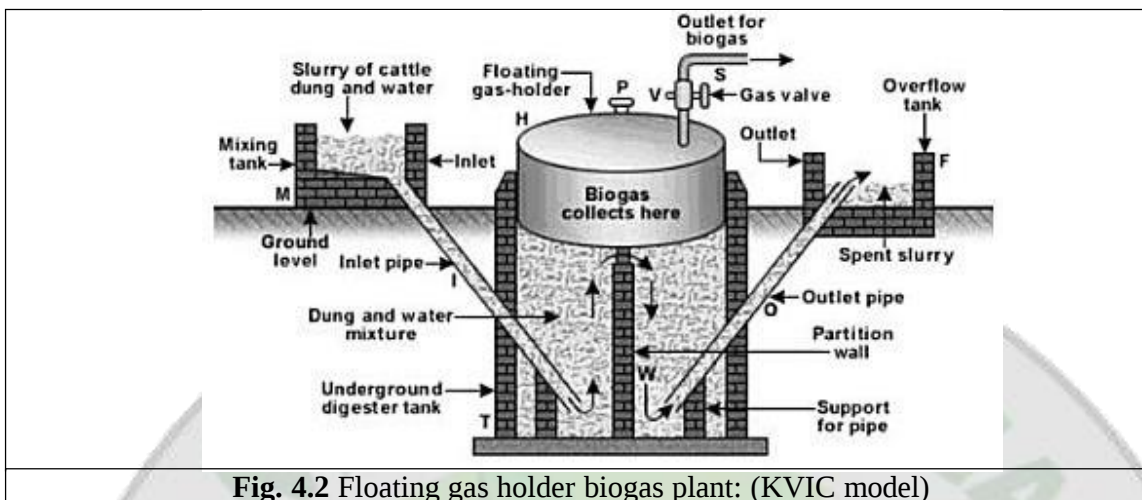


Fig. 4.2 Floating gas holder biogas plant: (KVIC model)

Digester is 3.5-6.5 m in depth and 1.2 to 1.6 m in diameter. The size of the gas holder depends on requirement of gas per day e.g. for cooking the food of one person gas required is 0.24 m^3 therefore for the family of six members total gas required per day is 1.44 m^3 and thus the size of gasholder must be more than this. It should be approximately 2 m^3 . From experimental observations it has been observed that 1 kg of cow dung gives 0.036 m^3 of gas 1 cow or cattle gives 10 kg dung every day. i.e. 0.36 m^3 gas that is produced by the dung of one cattle. Thus to get sufficient biogas we need the dung of 5 cattle.

The size of the digester depends on the retention time and for cow dung it varies from 20-55 days, depending on temperature of location. Thus the size of digester varies from place to place to get same amount of gas. For example, the size of digester of biogas plant having capacity 2 m^3 will be smaller in Maharashtra than in Himachal Pradesh.

4.6.2 Fixed Dome Biogas Plant

In a fixed-dome digester, the gas holder and the digester are combined. Gas is stored in the upper part of the digester. The upper portion of the digester pit itself acts as a gasholder. The displaced level of slurry provides the requisite pressure for the release of gas for its subsequent use. The pressure inside the digester varies as the gas is collected. A fixed-dome digester is usually built below the ground level and is suitable for cold regions. As the plant does not involve any steel parts, it can be built with local materials and hence its construction costs are low.

4.6.2.1 Janata Model

This type of biogas plant was constructed first time in 1978 by the Planning Research and Action Division (PRAD) Lucknow. This model is known as Janata biogas plant and is relative cheaper than KVIC Model. Typical structure of Janata model is shown in Fig. 4.3;

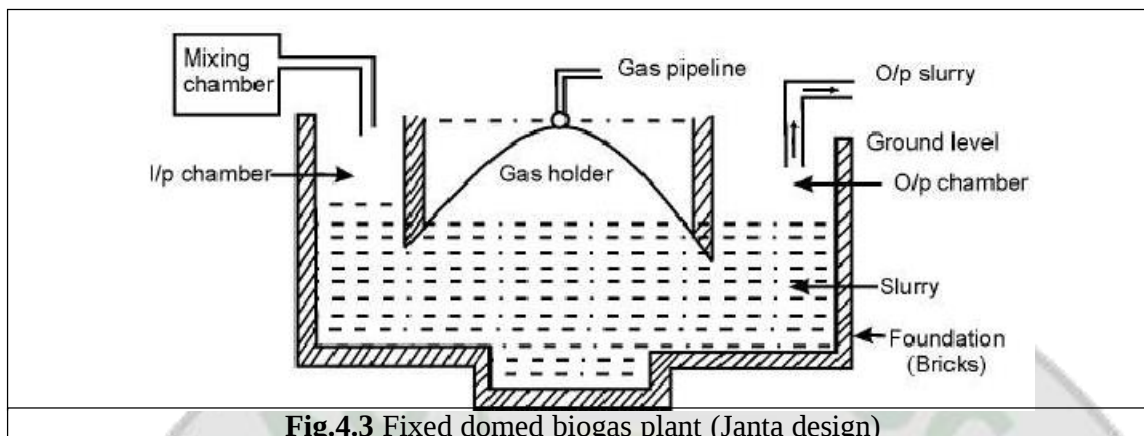


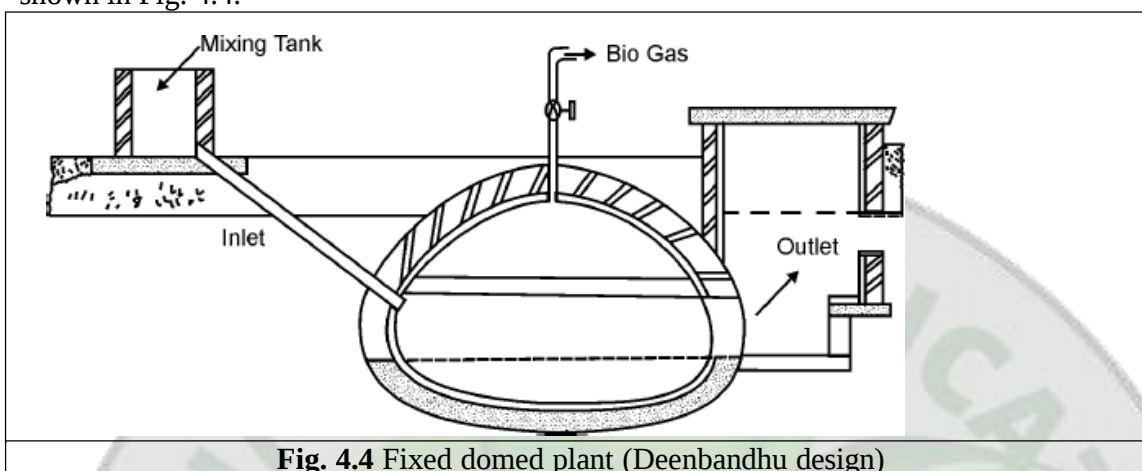
Fig.4.3 Fixed domed biogas plant (Janta design)

In this biogas plant the gasholder is dome type and fixed one. Digester is cylindrical with flat base cemented at bottom. Inlet and outlet chambers are constructed for putting fresh slurry in and to take digested slurry out. The input and output slurry chambers are relatively bigger than KVIC plant. The gas is collected in between the dome and digester. When gas is generated, it develops the pressure within a dome and it suppresses the slurry down. This results in rise in the level of the input (i/p) and output (o/p) slurry chambers. On opening the pipe gas is released due to pressure of the slurry in i/p and o/p chambers. The gas releases till the levels in i/p and o/p chambers and digester become equal. As a result the rate of gas released in this model is not constant and decreases with time. The size of the biogas plant is decided by the gas generated or required every day i.e. 2, 4, 6, 8, 10 m³, accordingly the volume of gas collecting dome is decided. The size of the digester depends on retention time similar to KVIC Model. As retention time increases the volume of digester increases though volume of gasholder remains constant. The construction cost of the Janata model is relatively less than KVIC model. The main feature of this model is that the digester and the gas holder are integrated parts of the brick masonry structure. The digester is made of a shallow well having a dome shaped roof on it. The inlet and outlet chambers are connected with the digester through large chutes. These chambers are above the level of the junction of the dome and the cylindrical well. The gas pipe is fitted on the crown of the masonry dome.

4.6.2.2 Deenbandhu model

The Janta model was further modified and the revised version is called Deenbandhu model, (the friend of poor). The Deenbandhu model was developed by Action for Food Production (AFPRO), New Delhi, India, in 1984. Until now, this model is the cheapest among all the available models of biogas plant. This model is designed on the basis of the principal of minimization of the surface area of a biogas plant to reduce its installation cost without sacrificing the functional efficiency. The design consists of two spheres of different diameters, joined at their bases. The structure thus formed acts as the digester or fermentation chamber, as well as the gas storage chamber. The digester is connected with the inlet pipe and outlet tank. The upper part above the normal slurry level of the outlet tank is designed to accommodate the slurry to be displaced from the digester with the

generation and accumulation of biogas. Schematic diagram of Deenbandhu model is as shown in Fig. 4.4.



The asbestos cement pipe is used for inlet and is embedded in digester wall at fixed position however the structure and nature of dome is same as that of Janta model. The principle and working of Deenbandhu model is similar to that of Janta model. Initially a level of slurry in digester and output slurry chamber is equal. As gas is produced there develops the pressure in the dome and it suppresses the slurry level in the digester with the increase in the level of the o/p chamber. When one opens the gas pipe, due to level difference between digester and o/p chamber, the gas comes out till the levels in both chamber and digester become equal.

4.7 Comparison between KVVC, Janata and Deenbandhu type biogas plants

Sr. No.	KVIC	Janata	Deenbandhu
1.	Installation cost is very high.	It is cheaper than the KVVC type plants.	It is much cheaper than KVVC-and Janta-type plants.
2.	Gas holder is generally made of mild steel. It is inverted into the digester and goes up and down with formation and utilization of gas.	Gas holder is integral part of the masonry structure of the plant. Slurry from the gas storage portion is displaced out of the digester with the formation of gas and comes back when it is used.	Biogas is stored in the same way as it is in Janta plants.
3.	The biogas is available at a constant pressure of about 10 cm of water column.	Gas pressure varies in between 0 to 90 cm of water column.	Gas pressure varies in between 0 to 75 cm of water column.
4.	Gas holder has a short working life.	Gas holder has a long working life.	Gas holder has a long working life.
5.	Inlet and outlet	Inlet and outlet tanks are	Inlet connection is

	connections are provided through PVC pipes.	large masonry structures.	through PVC pipe. Outlet tank is large masonry designed to store displaced slurry.
6.	Volume of the biogas holder governs the gas storage capacity of the plant.	It is combined volumes of the inlet and outlet chambers.	It is the volume of the outlet displacement chamber.
7.	The digester is a deep well-shaped masonry structure. There is a partition in the middle of the digester.	Digester is shallow well-shaped masonry structure. No partition wall is provided.	Digester is made of segments of two spheres one each for the top and bottom.
8.	The floating mild steel gas holder needs regular maintenance to prevent corrosion.	There is no moving part and hence no recurring expenditure.	There is no moving part and hence no recurring expenditure.
9.	Digester can be constructed locally. The gas holder needs sophisticated workshop facilities.	A trained mason using locally available materials can build the entire plant.	Entire plant can be built by a trained mason using locally available materials.

4.8 Points are to be considered in the construction and maintenance of bio-gas plant:

- (1) Locate the bio-gas plant nearer to kitchen to reduce the cost of pipe line.
- (2) While digging the plant, the excavated soil should be kept away at least by one meter.
- (3) Soil around the well should be thoroughly compacted.
- (4) While laying pipe line, provide slight slope towards the kitchen.
- (5) To produce more gas during winter, lay the compost around the digester well to a depth of one meter to warm the digester.
- (6) Paint the gas drum at outside, every alternate year with good quality paint to prevent corrosion.
- (7) Cover the gas drum with paddy straw mat to prevent the drum from cooling in winter.
- (8) Mix three parts of dung and two parts of water to produce more gas.
- (9) The plant should be located 15 m away from the water supply source.
- (10) Avoid construction of plant under waterlogged areas.
- (11) Do not allow the sand particles to enter into the digester.
- (12) If possible, use PVC pipes instead of A.C. (asbestos cement) pipes for inlet and outlet.
- (13) KVIC digester should be initially charged equally through inlet as well as outlet.
- (14) Don't add excess molasses in winter to get more gas, which forms more non-combustible matter.

- (15) Banana stem and water hyacinth should be chopped in 5 - 10 cm pieces before introducing into the respective plants.
- (16) Eucalyptus leaves should be soaked for five days prior to feeding into the plant.
- (17) For composite waste biogas plant, chopped rice straw and banana stem should be mixed with cowdung slurry completely.
- (18) Feeding should preferably be done at mid-day.
- (19) Daily rotate the gas holder and stirrers for 50 times in the morning and 50 times in the evening to break the scum.
- (20) Cowdung should be mixed with water prior to feeding.

4.9 Plant size parameters.

Although size calculations can become very complicated, for domestic application the following parameters suffice to arrive at a practical plant size range

Parameter	Explanation	Values used
Dung/water ratio	Theoretically, the dung / water ratio depends on the total solids (TS) concentration of the dung, whereby optimum fermentation results are claimed at 6 to 7% TS. The TS of dung varies considerably, for livestock in development countries TS values in the 10 to 15% (cattle) and 15 to 20% (pigs) range are reported.	The TS values suggest a dung / water ratio of a little under 1 : 1 for cattle dung and 1 : 2 for pig dung. For practical reasons. A 1 : 1 ratio has the advantage that households can easily measure the amount of required process water.
Specific gas production	The specific gas production of dung depends on the type and quality of dung.	For cattle, typically 1 kg of dung fed to a digester produces about 40 litres of biogas per day. Values for other substrates will differ; pigs, poultry and human excreta typically have higher yields.
Minimum gas production	Depending on construction costs and gas demand pattern, below a certain nominal gas production the investment becomes uninteresting for the household.	One cubic meter of biogas daily will render 2.5 to 3.5 stove hours. This could, depending on family size, suffice for e.g. breakfast and lunch preparation, and would then provide a meaningful

		contribution.
Hydraulic Retention Time	The hydraulic retention time (HRT) is the period the dung/water mix fed to the installation remains in the plant. As the fermentation process works better at higher ambient temperatures, installations in warmer climates can work with a shorter HRT and vice versa. As a longer HRT requires a larger digester volume, plants become more expensive to construct.	Typical HRTs for domestic (simple) biogas plants are 40 to 60 days for warm climates and 50 to 75 days for temperate climates.
Gas storage volume	Biogas is generated more or less continuously, but consumption in households typically takes place during 3 or 4 periods during the day. The generated gas needs to be stored in the installation.	For the gas storage volume, a fixed share of the maximum amount of daily generated gas, 60% is taken

4.10 Digester Sizing

The energy (E) available in MJ from a biogas digester is given by

$$E = \eta H_b V_b$$

where η is the combustion efficiency of burner or boiler. H_b is the heat of combustion per unit volume biogas (20 MJ/m³) at 10 cm water gauge pressure (0.01 atmos) and V_b is the volume of biogas (m³).

It is important to note that some of the heat of combustion of methane is used to heat the CO₂ of the biogas and hence is unavailable for other applications.

Above mentioned equation can also be written in terms of the fraction (f_m) of methane in biogas (0.7) as

$$E = \eta H_m f_m V_b$$

where H_m is the heat of combustion of methane (56 MJ/kg, 28 MJ/m³ at STP). If c is the biogas yield per unit dry mass of whole input (0.2 to 0.4 m³/kg) and m_0 is the mass of dry input (e.g. 9.2 kg per day per cow), then the volume of biogas is given by

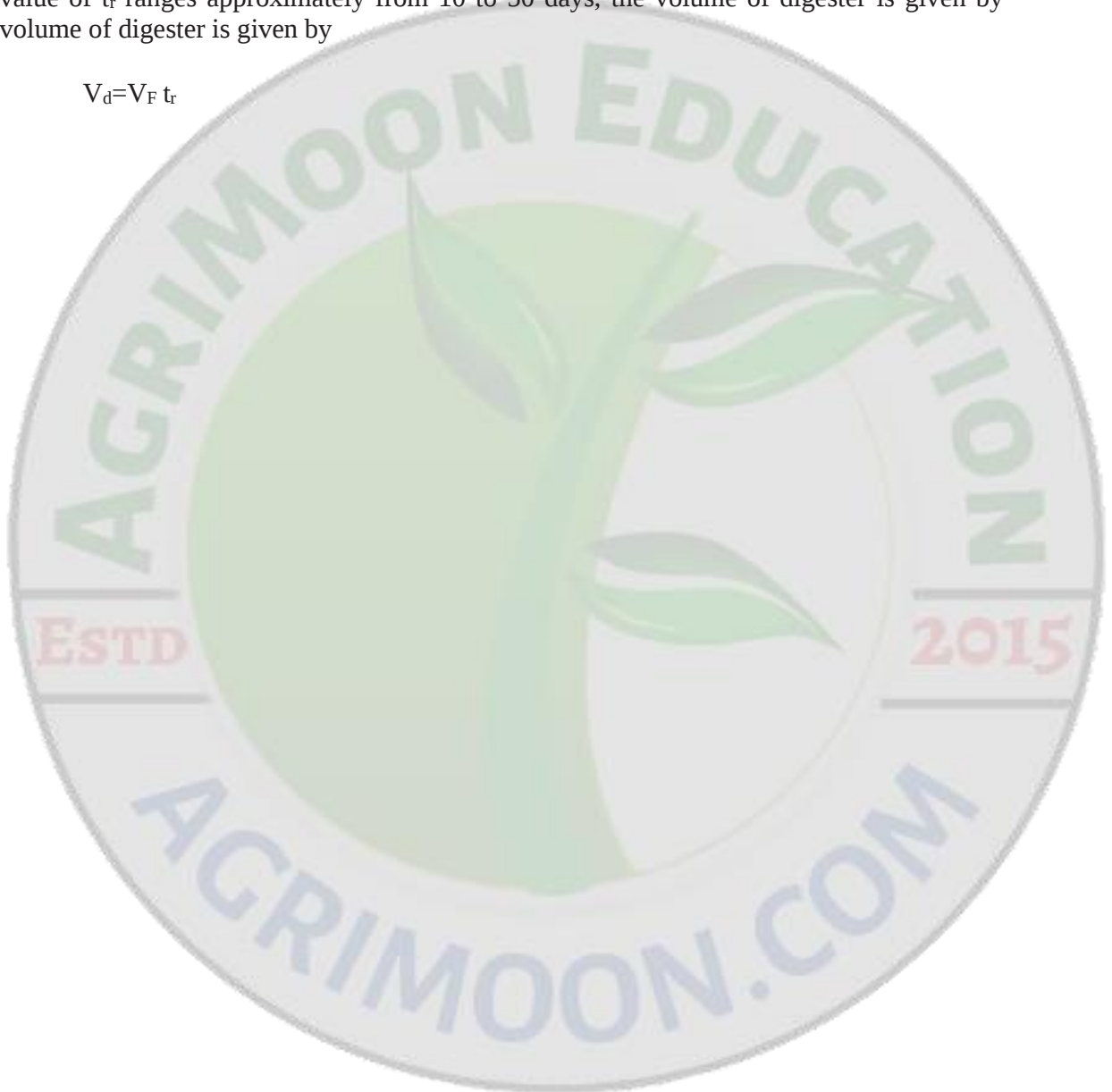
$$V_b = c m_0$$

The volume of fluid per day in the digester can be written as

$$V_F = m_0 / \rho_m$$

where ρ_m is the density of dry matter in the fluid (50 kg/m^3). If V_F is the flow rate of the digester fluid and t_r is the retention period in the digester for anaerobic fermentation. The value of t_r ranges approximately from 10 to 50 days, the volume of digester is given by

$$V_d = V_F t_r$$



Chapter 5

Gasification and types of gasifiers

5.0 Introduction:

Gasification is a process for converting carbonaceous materials to a combustible or synthetic gas (e.g., H_2 , CO , CO_2 , CH_4). In general, gasification involves the reaction of carbon with air, oxygen, steam, carbon dioxide, or a mixture of these gases at 1,300°F or higher to produce a gaseous product that can be used to provide electric power and heat or as a raw material for the synthesis of chemicals, liquid fuels, or other gaseous fuels such as hydrogen (Fig. 5.1).

Once a carbonaceous solid or liquid material is converted to a gaseous state, undesirable substances such as sulfur compounds and ash may be removed from the gas. In contrast to combustion processes, which work with excess air, gasification processes operate at substoichiometric conditions with the oxygen supply controlled (generally 35 percent of the amount of O_2 theoretically required for complete combustion or less) such that both heat and a new gaseous fuel are produced as the feed material is consumed.

Combustion is primarily used to thermally destruct the feed material and to generate heat. In contrast, the objective of gasification is to convert the feed material (forestry products, agricultural residues, and aquatic biomass to municipal solid wastes) into more valuable, environmentally friendly intermediate products that can be used for a variety of purposes including chemical, fuel, and energy production. Elements generally found in a carbonaceous material such as C, H, N, O, S, and Cl are converted to a syngas consisting of CO , H_2 , H_2O , CO_2 , NH_3 , N_2 , CH_4 , H_2S , HCl , COS , HCN , elemental carbon, and traces of heavier hydrocarbon gases. The products of combustion processes are CO_2 , H_2O , SO_2 , NO , NO_2 , and HCl .

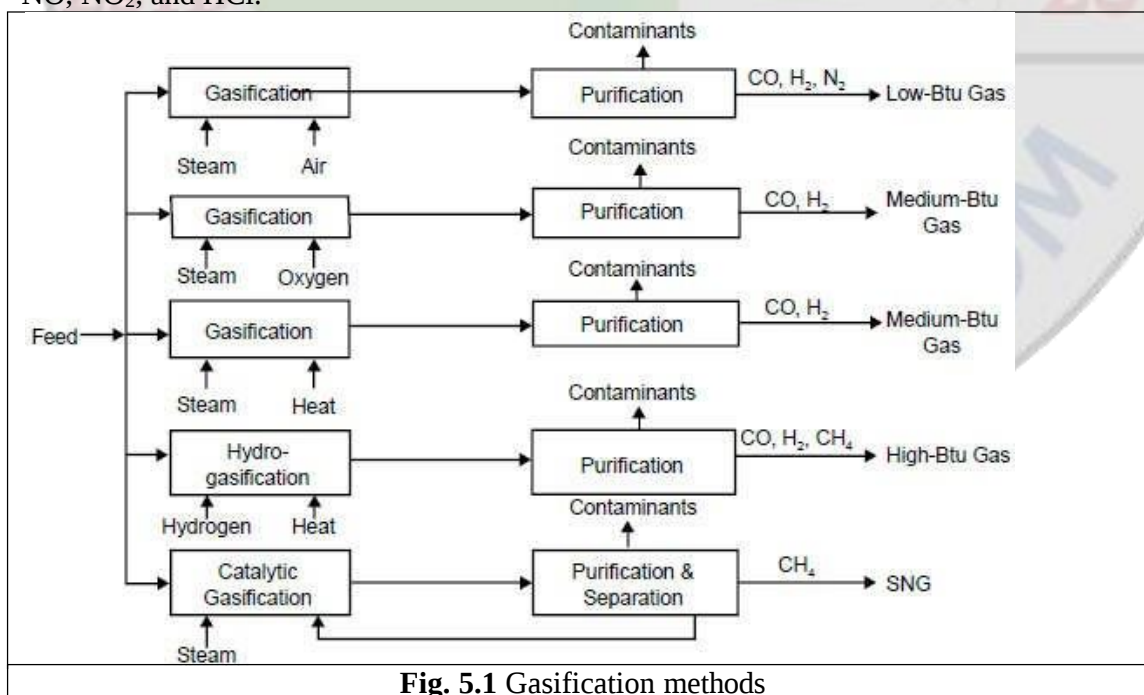


Fig. 5.1 Gasification methods

Some gasification processes also use indirect heating, avoiding combustion of the feed material in the gasification reactor and avoiding the dilution of the product gas with nitrogen and excess CO₂.

When a carbonaceous material is heated, either directly or indirectly, under gasification conditions, it is first pyrolyzed. During pyrolysis light volatile hydrocarbons, rich in hydrogen, are evolved and tars, phenols, and hydrocarbon gases are released. During pyrolysis the feedstock is thermally decomposed to yield solid carbon and a gas product stream that has higher hydrogen content than the original carbonaceous feed material.

5.0.1 Hydrogenation

In a gasification process the feedstock is hydrogenated. This means hydrogen is added to the system directly or indirectly or the feedstock is pyrolyzed to remove carbon to produce a product with a higher hydrogen-to-carbon ratio than the feedstock. These processes may be carried out separately or simultaneously. The more hydrogen that is added or the more carbon removed, the lower the overall efficiency of the synthetic gas production process. In an indirect hydrogenation process, steam is used as a hydrogen source and hydrogen is produced within the gasification reactor.

5.0.2 Stoichiometric Considerations

Depending on the gasification process, reactions that take place in a gasifier include:

- (1) $C + O_2 \rightarrow CO_2$
- (2) $C + 1/2O_2 \rightarrow CO$
- (3) $H_2 + 1/2O_2 \rightarrow H_2O$
- (4) $C + H_2O \rightarrow CO + H_2$
- (5) $C + 2H_2O \rightarrow CO_2 + 2H_2$
- (6) $C + CO_2 \rightarrow 2CO$
- (7) $C + 2H_2 \rightarrow CH_4$
- (8) $CO + H_2O \rightarrow H_2 + CO_2$
- (9) $CO + 3H_2 \rightarrow CH_4 + H_2O$
- (10) $C + H_2O \rightarrow 1/2CH_4 + 1/2CO_2$

Most of the oxygen injected into a gasifier, either as pure oxygen or air, is consumed in reactions (1) through (3) to provide the heat necessary to dry the solid fuel, break up chemical bonds, and raise the reactor temperature to drive gasification reactions (4) through (9).

Reactions (4) and (5), which are known as water-gas reactions, are the principal gasification reactions, are endothermic, and favor high temperatures and low pressures.

Reaction (6), the *Boudourd reaction*, is endothermic and is much slower than the combustion reaction (1) at the same temperature in the absence of a catalyst.

Reaction (7), hydro-gasification, is very slow except at high pressures.

Reaction (8), the *water-gas shift reaction*, can be important if H₂ production is desired. Optimum yield is obtained at low temperatures (up to 500°F) in the presence of a catalyst and pressure has no effect on increasing hydrogen yield.

Reaction (9), the *methanation reaction*, proceeds very slowly at low temperatures in the absence of catalysts.

Reaction (10) is relatively thermal neutral, suggesting that gasification could proceed with little heat input but methane formation is slow relative to reactions (4) and (5) unless catalyzed.

In addition to the gasification agent (air, oxygen, or steam) and the gasifier operating temperature and pressure, other factors affect the chemical composition, heating value, and the end use applications of the gasifier product gas. The following factors affect the quality of the product gas:

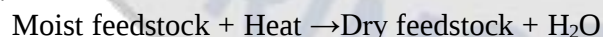
- Feedstock composition
- Feedstock preparation and particle size
- Reactor heating rate
- Residence time
- Plant configuration such as:
 - Feed system - dry or slurry
 - Feedstock-reactant flow geometry
 - Mineral removal system - dry ash or slag
 - Heat generation and transfer method — direct or indirect
 - Syngas cleanup system - low or high temperature and processes used to remove sulfur, nitrogen, particulates, and other compounds that may impact the suitability of the syngas for specific applications (i.e., turbine and fuel cell for electric power generation, hydrogen production, liquid fuel production, or chemical production).

5.0.3 Reactions occurring during gasification:

As feedstock proceeds through a gasification reactor or gasifier, the following physical, chemical, and thermal processes may occur sequentially or simultaneously, depending on the reactor design and the feedstock material.

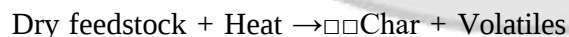
Drying

As the feedstock is heated and its temperature increases, water is the first constituent to evolve.



Devolatilization

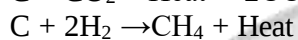
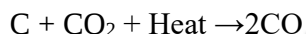
As the temperature of the dry feedstock increases, pyrolysis takes place and the feedstock is converted to char.



Depending on the origin of the feedstock, the volatiles may include H₂O, H₂, N₂, O₂, CO₂, CO, CH₄, H₂S, NH₃, C₂H₆, and very low levels of unsaturated hydrocarbons such as acetylenes, olefins, and aromatics and tars. Char is the residual solids consisting of organic and inorganic materials. After pyrolysis, the char has a higher concentration of carbon than the dry feedstock.

Gasification

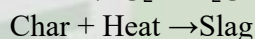
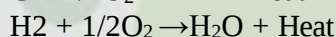
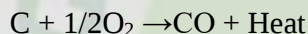
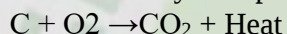
Gasification is the result of chemical reactions between carbon in the char and steam, carbon dioxide, and hydrogen in the gasifier vessel as well as chemical reactions between the resulting gases. Gasification reactions can be represented by:



Depending on the gasification process conditions, the remaining char may or may not have a significant amount of organic content or heating value.

Combustion

The thermal energy that derives gasification reactions must be provided directly, by combusting some of the char or dry feedstock and in some cases the volatiles within the gasifier, or indirectly, by combusting some of the feedstock, char, or clean syngas separately and transferring the required heat to the gasifier. The following chemical and thermal reactions may take place when char or dry feedstock is burned.



Combustion of char or feedstock produces ash, unreacted organic material, which can be melted into liquid slag. Slag can be resolidified to form clinker. In addition to heat, the combustion products are CO_2 and H_2O when clean syngas is burned to provide the required thermal energy.

- CH_4 formation decreases with increasing temperature and increases with increasing pressures.
- CO and H_2 formation increases with increasing temperature and reducing pressures. Maximum concentration of H_2 and CO can be obtained at atmospheric pressure and temperature range of 800 to 1000°C.
- CO_2 concentration increases with increasing pressures and decreases sharply with increasing temperatures.
- Reducing oxygen-to-steam ratio of reactant gases (or reactor inlet streams) increases H_2 and CH_4 formation, while increasing the oxygen-to-steam ratio will increase CO and CO_2 formation.

Therefore, gasifier temperature and pressure can be controlled to maximize the concentration of desired product, CH_4 or H_2 and CO . However, in order to determine the optimum operating conditions other factors such as the gasification kinetic, any catalyst effects, and the mechanism by which reactions occur must also be considered.

5.0.4 Depending on the gasifier system configuration, operating conditions, and gasification agent, four types of synthetic gas can be produced:

- Low heating-value gas (3.5 to 10 MJ/m^3 or 100 to 270 Btu/ft^3) : because of its high nitrogen content and low heating value, it is not well suited as a natural gas replacement or for chemical synthesis.
- Medium heating-value gas (10 to 20 MJ/m^3 or 270 to 540 Btu/ft^3)
- High heating-value gas (20 to 35 MJ/m^3 or 540 to 940 Btu/ft^3).
- SNG or Substitute Natural Gas (over 35 MJ/m^3 or 940 Btu/ft^3) can be easily substituted for natural gas and therefore is suitable for hydrogen and chemical production as well as fuel cell feed.

5.0.5 Attractive features of gasification technology include:

- The ability to produce a consistent product that can be used for the generation of electricity or as primary building blocks for manufacturers of chemicals and transportation fuels.
- The ability to process a wide range of feedstocks including coal, heavy oils, petroleum coke, heavy refinery residuals, refinery wastes, hydrocarbon contaminated soils, biomass, and agricultural wastes.
- The ability to remove contaminants in the feedstock and to produce a clean syngas product.
- The ability to convert wastes or low-value products to higher value products.
- The ability to minimize the amount of solid waste requiring landfill disposal. Solid by-products have a market value can be used as fuel or construction material, and are non-hazardous.

5.0.6 Some important points to be taken into consideration while undertaking any biomass gasification system:

- 1) A gasifier is used either (a) to generate a combustible gas to provide heat or (b) to generate a fuel gas which can be used in an internal combustion engine as a petroleum oil substitute.
- 2) Some of the gaseous, liquid and solid products of combustion are not only harmful to engines and burners, but also to human beings. That is why these gases are not used as cooking gas.
- 3) A gasifier must have an effective gas cleaning train if the gas is to be used for internal combustion engines. A maximum limit of $5\text{-}15 \text{ mg}$ solids and tar per kg of gas may be allowed for the use of the gas in an internal combustion engine.
- 4) A gasification system may not be of much advantage to generate a combustible gas, as far as fossil fuel savings, economies and ease of operation are concerned.

5.1 Preprocessing of raw materials

Preprocessing of raw materials are required for making them acceptable for gasification. Some of the common preprocessing operations are as follows:

- 1) For agricultural products and residues, chipping, drying and densifying operations are carried out.
- 2) For forestry products, shredding, chipping, drying and densifying operations are being followed.
- 3) For municipal solid wastes (MSW), size reduction of the MSW is done by one or two stage shredding only. The ferromagnetic and non ferrous metals are separated by magnetic separation and by eddy current or by any other equivalent device. The glass pieces are removed by air classification, trammeling and screening.

The advantages of preprocessing are: (i) storage and handling of feedstocks are made easier, (ii) uniform distribution of the preprocessed feedstock in the gasifier, (iii) channeling action in the flow paths is prevented, (iv) the gasifier top sealing device can be operated without any accident, (v) uniform gas quality is obtained, and (vi) steady rate of production of ash or char is possible. The disadvantages are: (i) additional capital investment for the preprocessing equipments is necessary, (ii) both operational and maintenance costs are involved, and (iii) total preprocessing costs may be high.

5.2 Types of gasifiers

Gasifiers are generally classified on the basis of the physical conditions of the feed stocks in the reactors. The gasifiers may be classified as (1) Fixed bed gasifiers and (2) Fluidized bed gasifiers.

5.2.1 Fixed Bed Gasifier A fixed bed gasifier is generally a vertical reactor (furnace). The gasifier is fed either from the top or from the side at a certain height. Inside the gasifier the feedstock is supported either on a fixed grate or on a sand bottom. Fixed bed (sometimes called moving bed) gasifiers use a bed of solid fuel particles through which air and gas pass either up or down. They are the simplest type of gasifiers and are suitable for small-scale application only.

5.2.1.1 Updraft or Countercurrent Gasifiers The simplest type of gasifier is the fixed-bed countercurrent gasifier. Here, the biomass is fed at the top of the reactor and moves downward as a result of its conversion and removal of ashes. Air is taken in at the bottom, and gas leaves at the top. The biomass moves counter to the gas flow and passes successively through drying, distillation, reduction, and hearth zones. In the drying zone, the biomass is dried. In the distillation or pyrolyzation zone, it is decomposed into volatile gases and solid char. The heat for pyrolyzation and drying is mainly delivered by the upward-flowing producer gas and partly by radiation from the hearth zone. In the reduction zone, many reactions occur (involving char, carbon dioxide, and water vapor) in which carbon is converted and carbon monoxide and hydrogen are produced as the main component of the producer gas. In the hearth zone, the remaining char is combusted, providing heat, carbon dioxide, and the water vapor for reactions occurring in the reduction zone. The updraft gasifier is widely used for coal gasification and nonvolatile fuels such as charcoal. However, the high rate of tar production (5-20%) makes them impractical for high volatile fuels where a clean gas is required. The major advantages of this type of gasifier are its simplicity, high charcoal burnout, and internal

heat exchange that leads to low gas-exit temperatures and high gasification efficiencies. Because of the internal heat exchange, the fuel is dried at the top of the gasifier. Therefore, fuels with high moisture content (upto 60 percent, wet basis) can be used. Furthermore, this type of gasifier can even process relatively small fuel particles and accepts some size variation in the fuel feedstock. The height to diameter ratio is usually kept at 3:1 (Fig. 5.2).

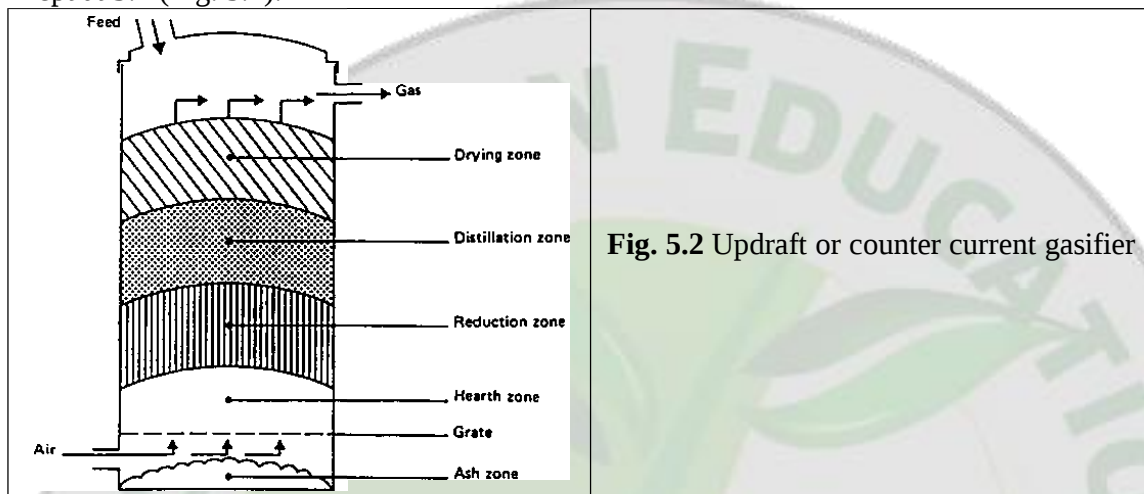


Fig. 5.2 Updraft or counter current gasifier

The drawback of the updraft type is a high rate of oil, tar, and corrosive chemical formation in the pyrolysis zone. This problem is solved by the downdraft version, where such oils and other matter pass through a hot charcoal bed in the lower zone of the reactor and become cracked to simpler gases or char.

5.2.1.2 Downdraft or co-current gasifier

Here, both gas and feed travel downward. The temperature is highest in the downstream combustion zone. The tar is produced after drying at lower temperatures (200–500 °C) close to the feed point. The oxygen in the air, along with the tar, travels downward to the hotter zone. Owing to the availability of oxygen and high temperature, the tar readily burns in a flame, raising the gas temperature to 1000 to 1400 °C. The flame occurs in the interstices between feed particles, which remain at 500 to 700 °C. This phenomenon is called *flaming pyrolysis*. Since the pyrolysis product, tar, contacts oxygen while passing through the highest-temperature zone, it has the greatest opportunity to be converted into noncondensable gases. For this reason, a downdraft gasifier has the lowest tar production ($<1 \text{ g/Nm}^3$). The downdraft gasifier was developed to convert high volatile fuel (wood, biomass) to low tar gas and therefore has proven to be the most successful design for power generation (Fig. 5.3).

5.2.1.3 Cross draft or cross flow gasifier

Cross draft gasifiers are an adaptation for the use of charcoal. Charcoal gasification results in very high temperatures (1500 °C and higher) in the oxidation zone which can lead to material problems. In cross draught gasifiers insulation against these high temperatures is provided by the fuel (charcoal) itself. Advantages of the system lie in the

very small scale at which it can be operated. Installations below 10 kW (shaft power) can under certain conditions be economically feasible. The reason is the very simple gas-cleaning train (only a cyclone and a hot filter) which can be employed when using this type of gasifier in conjunction with small engines. A disadvantage of cross-draught gasifiers is their minimal tar-converting capabilities and the consequent need for high quality (low volatile content) charcoal. It is because of the uncertainty of charcoal quality that a number of charcoal gasifiers employ the downdraught principle, in order to maintain at least a minimal tar-cracking capability (Fig. 5.4).

In a cross-draught gasifier, air is fed into the gasifier through a horizontal nozzle. The resulting fuel gas is discharged through a vertical grate on the opposite side of the air injection location. The biomass can be fed to the gasifier either from the top or from the side. The reactions in the cross-draught gasifier are similar to the downdraught gasifier.

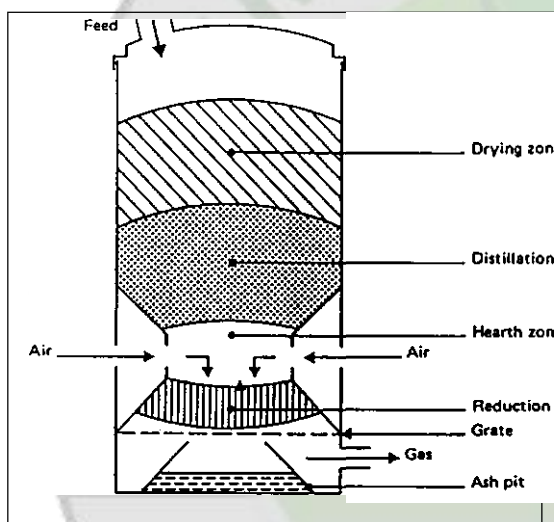


Fig. 5.3 Downdraught or co-current gasifier

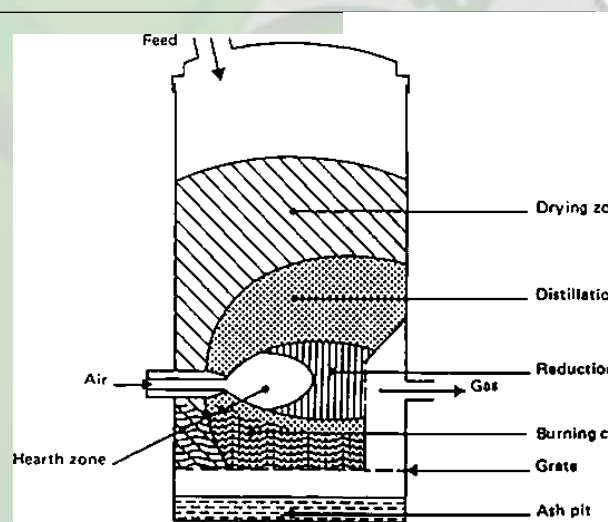


Fig. 5.4 Cross-draught gasifier

5.2.2 Fluidized-Bed Gasifier

In a typical fluidized bed (bubbling or circulating) air enters from the bottom, but is fuel fed from the side or top. In either case, the fuel is immediately mixed throughout the bed owing to its exceptionally high degree of mixing. Thus, the fresh oxygen (in air) entering the grid comes into immediate contact with fresh biomass particles undergoing pyrolysis as well as with spent char particles from the biomass, which has been in the bed for some time. Oxygen's contact with the fresh biomass burns the tar released, while its contact with the spent char particles causes the char to burn. Though the solids are back-mixed, the gases flow upward in plug-flow mode. This means that further up in the bed neither older char particles nor fresh pyrolyzing biomass particles come in contact with the oxygen. Any tar released moves up in the bed and leaves along with the product gas. For this reason, tar generation in a fluidized-bed gasifier is between the two extremes represented by updraft and downdraft gasifiers, averaging about 10 mg/Nm^3 . The bed

temperatures should be lower than 1100-1150 C in order to prevent slagging of the residues, but it should be higher than 850 C to promote partial oxidation of the feed material. Generally the height to diameter ratio of a fluidized bed reactor is 10:1. The fluidized bed reactor may prove superior for large-scale operations, because passage time is smaller. The drawback of this is that ash and tars are carried along with the gas and have to be removed later in cyclones and scrubbers (Fig. 5.5)

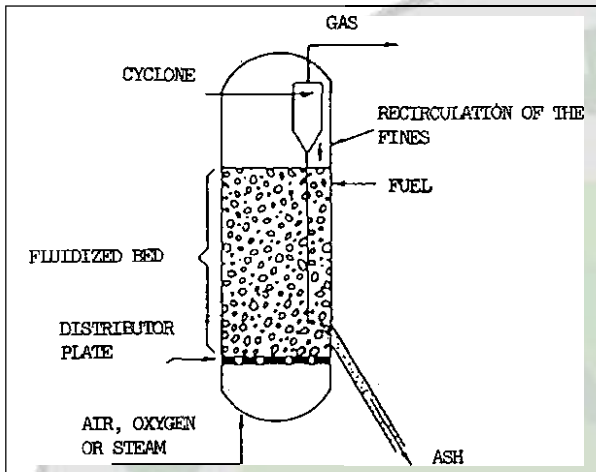


Fig. 5.5 Fluidized bed gasifier

The advantages of fluidized bed reactors in comparison with fixed bed reactors are as follows:

1. Compact construction because of high heat exchange and reaction rates due to intensive mixing in the bed.
2. Flexibility to changes in moisture and ash content and other fuel characteristics, ability to deal with fluffy and fine-grained material that have high ash content, low bulk density, or both.
3. Relatively low ash melting points due to the flow reaction temperatures.

The output of a biomass gasifier can be used for a variety of direct thermal applications such as cooking, drying, heating water, and generating steam. It can also be used as a fuel for I.C. Engines to obtain mechanical shaft power or electrical power. If the producer gas is used in IC engines, it has to be cleaned for complete removal of particulate material and tar. The conversion efficiency of a gasifier is defined as the ratio of the heat content in the producer gas to the heat content in the biomass supplied and is usually around 75%.

Chapter 6 Biooil

6.0 Introduction:

Any material that can be burned to release thermal energy is called a conventional fuel, which consists primarily of hydrogen (H) and carbon (C). They are referred to as hydrocarbon fuels. They are denoted by the general formula C_nH_m . Hydrocarbon fuels exist in all phases, namely coal, petrol and natural gas. The main constituent of coal is carbon. Coal also contains oxygen, hydrogen, nitrogen, sulfur, moisture and ash. It is difficult to give an exact mass analysis of coal since its composition varies considerably from one geographical area to the next. Even within the same geographical location the composition of coal varies. Most liquid hydrocarbon fuels are a mixture of various hydrocarbons namely petrol, kerosene, diesel fuel, fuel oil, etc. These are obtained from crude oil by distillation. The most volatile hydrocarbon vaporises first, which is known as petrol. The less volatile fuels obtained during distillation are kerosene, diesel fuels and fuel oil. The liquid hydrocarbon fuels are mixtures of different hydrocarbons, which are usually considered to be a single hydrocarbon. For example, petrol and diesel fuels are treated as octane (C_8H_{18}) and dodecane ($C_{12}H_{26}$), respectively. The gaseous hydrocarbon fuel, which is a natural gas, is a mixture of methane (CH_4) and smaller amounts of other gases. It is produced from gas/oil wells. On vehicles, it is either in gas phase (CNG, compressed natural gas) at pressures of 150 to 250 atm or in the liquid phase (LNG, liquefied natural gas) at $-162\text{ }^\circ\text{C}$. Liquefied petroleum gas (LPG) is a byproduct of natural gas processing or crude oil refining. LPG consists of mainly propane (over 90 percent). Thus, it is usually referred to as propane. However, it also contains various amounts of butane, propylene and butylenes.

All petroleum-based fuels are the major sources of air pollutants such as nitric oxides (NO), carbon monoxide (CO) and the greenhouse gas (GHG), carbon dioxide (CO_2), when they are used in vehicles. Hence, there is currently a shift in the transportation industry from commercial petroleum-based conventional fuels (petrol and diesel) to the cleaner burning alternative fuels (natural gas, alcohols, ethanol and methanol) which are friendly to the environment. Due to the limited sources of natural gas, researchers have to explore the appropriate renewable source of energy as the fuel for sustainability and pollution-free characteristics with the natural ecology. One such natural resource is biomass. Biofuels are produced through the chemical or biological processes from biomass. The term biomass generally refers to renewable organic matter generated by plants through photosynthesis. The solar energy combines the carbon dioxide and water to form carbohydrate and oxygen in photosynthesis. Materials having combustible organic matter are also referred to as biomass. It contains C, H and O. It is the oxygenated hydrocarbon. Biomass includes forest and mill residues, agricultural crops and wastes, wood and wood wastes, animal wastes, livestock operation residues, aquatic plants, municipal and industrial wastes. Fossil fuels can also be referred to as biomass, since they are the fossilised remains of plants.

Wood was initially the primary biomass fuel for humans. The goal of many biomass conversion processes is to convert solid fuel into more useful forms, i.e. gaseous or liquid

fuels. Examples are (i) conversion of biomass to gaseous fuels include anaerobic digestion of wet biomass to produce methane gas (ii) high-temperature gasification of dry biomass to produce a flammable gas mixture of hydrogen, carbon monoxide and methane (iii) fermentation of sugars to ethanol, thermochemical conversion of biomass to pyrolysis oils (iv) processing of vegetable oils to biodiesel.

The resulting liquid and gaseous fuels can then be used in machinery to produce heat and electrical power. Biomass can also be converted to heat and electrical power by burning it, as occurs in boilers and steam power plants. Biomass is a versatile resource of energy that is expressed in what is termed mixed “f” fields, namely food, feed, fuel, feedstock, fibre and fertiliser. These form the essential ingredients for our survival. It is obvious that the demand for biomass can be defined in a complex field of competitive parameters.

The broad spectrum of natural vegetation and residual deposits from human and animal activities constitute the major sources of biomass. The term “biomass” is therefore related to the quantity of all living matter from the five kingdoms in biology namely plants, animals, fungi, bacteria and algae. All the five kingdoms of life are in a renewable manner. Photosynthesis can occur in algae and bacteria as well as in plants. The term “Bio” is derived from bios (Greek word) meaning life. Biomass is a highly diverse and complex resource.

“Biofuels” are transportation fuels like ethanol and biodiesel that are made from biomass materials. These fuels are usually blended with petroleum fuels namely with gasoline and diesel fuel, but they can also be used on their own. Ethanol and biodiesel are also cleaner burning fuels, producing fewer air pollutants. It has drawn significant attention due to increasing environmental concern and diminishing petroleum reserves. Bio-diesel fuel can be made from renewable vegetable oils, animal fats or recycled cooking oils by transesterification process. Biodiesel is the fastest growing alternative fuel in the world. Ethanol is a alcohol fuel made from the sugars found in grains such as corn, sorghum, and wheat, as well as potato skins, rice, sugarcane, sugar beets and yard clippings by fermentation.

6.1 Characteristics of bio-fuels The following are some of the characters for the efficient bio-diesel: a) Kinematic viscosity b) Density c) Calorific value d) Melt or pour point e) Cloud point f) Flash point g) Acid value h) Iodine value i) Cetane number j) Stability – oxidative, storage and thermal k) Carbon residue l) Ash percentage m) Sulphur percentage

6.1.1 Kinematic viscosity Viscosity represents flow characteristics and the tendency of fluids to deform with stress. Viscosity affects injector lubrication and fuel atomization. Fuels with low viscosity may not provide sufficient lubrication for the precision fit of fuel injection pumps, resulting in leakage or increased wear. Fuel atomization is also affected by fuel viscosity. Diesel fuels with high viscosity tend to form larger droplets on injection which can cause poor combustion, increased exhaust smoke and emissions.

6.1.2 Melt point or Pour point Melt or pour point refers to the temperature at which the oil in solid form starts to melt or pour. In case where the temperatures fall below the melt point, the entire fuel system including all fuel lines and fuel tank will need to be heated.

6.1.3 Cloud point The temperature at which an oil starts to solidify is known as the cloud point. While operating an engine at temperatures below an oil's cloud point, heating will be necessary in order to avoid waxing of the fuel.

6.1.4 Flash point (FP) The flash point temperature of diesel fuel is the minimum temperature at which the fuel will ignite (flash) on application of an ignition source. Flash point varies inversely with the fuel's volatility. Minimum flash point temperatures are required for proper safety and handling of diesel fuel. The flash point determines the flammability of the material. Neat biodiesel has a flash point (150°C) well above the flash point of petroleum based diesel fuel ($\pm 70^\circ\text{C}$).

6.1.5 Acid value The total acid number is an indication of the presence of free fatty acids formed due to oil degradation and combustion. It can also result from improper manufacturing, through remaining catalyst or excessive neutralization.

6.1.6 Iodine value It is an index of the number of double bonds in biodiesel, and therefore is a parameter that quantifies the degree of unsaturation of biodiesel. It is reported in terms of the grams of iodine that will react with 100 grams of a fat or oil under specified condition. It is a value of the amount of iodine, measured in grams, absorbed by 100 grams of given oil. It is commonly used as a measure of the chemical stability properties of different biodiesel fuels against such oxidation.

6.1.7 Aniline point/Cetane number (CN) It is a relative measure of the interval between the beginning of injection and autoignition of the fuel. The higher the cetane number, the shorter the delay interval and the greater its combustibility. Fuels with low Cetane Numbers will result in difficult starting, noise and exhaust smoke. In general, diesel engines will operate better on fuels with Cetane Numbers above 50. Cetane number is usually measured directly using a test engine. Cetane tests provide information on the ignition quality of a diesel fuel. No.2 diesel fuel usually has a cetane rating between 45 and 50 while vegetable oil is 35 to 45. Biodiesel is usually have in between 50 to 60.

6.1.8 Stability Biodiesel ages more quickly than petroleum diesel fuel due to the chemical structure of fatty acids and methyl esters present in biodiesel. Typically there are fourteen types of fatty acid methyl ester in the biodiesel. The individual proportion of presence of these esters in the fuel effects the final properties of biodiesel. Poor oxidation stability can cause fuel thickening, formation of gums and sediments which inturn can cause filter clogging and injector fouling. Thermal degradation occurs at high temperature and degrades hyper peroxide in the fuel more rapidly than oxidative

degradation. Biodiesel and biodiesel blends are much more thermally stable than diesel. Biodiesel and its blends should not be stored in a storage tank or vehicle tank more than 6 months. Depending upon the storage temperature and other conditions suggest the use of appropriate antioxidants.

6.1.9 Carbon residue This indicates the tendency of fuel to form carbon deposits in an engine. An important indicator of the quality of biodiesel is the carbon residue, which corresponds to the content of glycerides, free fatty acids, soaps, polymers and remaining catalyst.

6.1.10 Ash Percentage Ash is a measure of the amount of metals contained in the fuel. High concentrations of these materials can cause injector tip plugging, combustion deposits and injection system wear. The ash content is important for the heating value, as heating value decreases with increasing ash content. Ash content for bio-fuels is typically lower than for most coals, and sulphur content is much lower than for many fossil fuels.

6.1.11 Sulfur percentage The percentage by weight, of sulfur in the fuel sulfur content is limited by law to very small percentages for diesel fuel used in on-road applications. First use vegetable oil and animal fat based biodiesel has less than 15 ppm sulphur. Many researchers claim that pure biodiesel is essentially sulphur free and therefore biodiesel is an ultra-low sulphur fuel.

6.1.12 Density Is the weight per unit volume. Oils that are denser contain more energy. For example, petrol and diesel fuels give comparable energy by weight, but diesel is denser and hence gives more energy per litre. Biodiesel is generally denser than diesel fuel with sample values ranging between 877 kg/m³ to 884 kg/m³ compared with diesel at 835 kg/m³. Thus, density of the final product depends mostly on the feedstock used.

6.1.13 Calorific Value, Heat of combustion Heating Value or Heat of Combustion, is the amount of heating energy released by the combustion of a unit value of fuels. One of the most important determinants of heating value is moisture content. Liquid biofuels however have bulk densities comparable to those for fossile fuels.

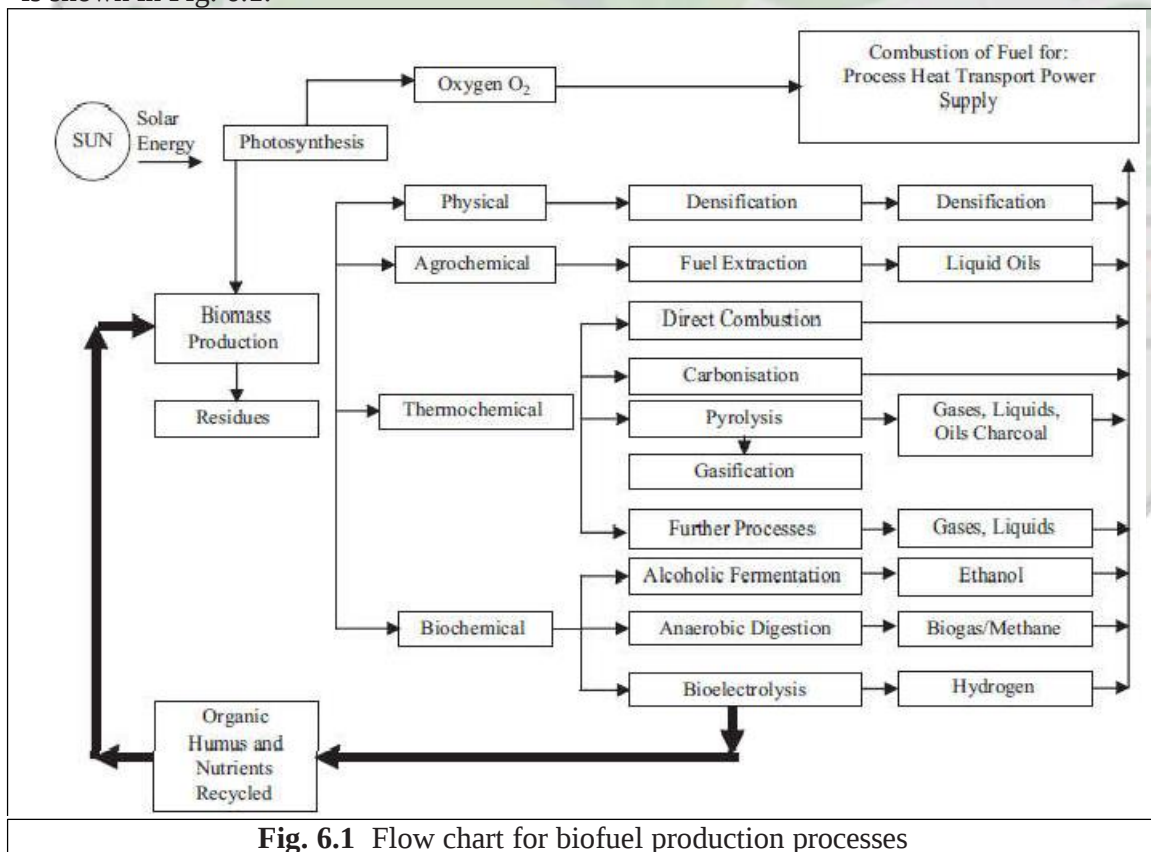
The properties of a few bio-diesel fuels made from edible and non-edible oils are shown in Table 6.1.

Table 6.1. Properties of edible and non-edible oils							
Bio-diesel	Kinematic viscosity at 40°C	Cetane number	Lower heating value (MJ/kg)	Cloud point (°C)	Pour point (°C)	Flash point (°C)	Density (kg/litre)
Edible oils							
Palm	5.7	62	33.5	13		164	0.880
Peanut	4.9	54	33.6			176	0.883
Soyabean	4.5	45	33.5	1	-7	178	0.885
Sunflower	4.6	49	33.5	1		183	0.860

Non-edible oils							
Jatropha	5.2	38	39.2	13		175	0.865
Karanja	4.7	55	37.1	7	4	183	0.876
Diesel	3.06	50	43.8	9	-16	76	0.855
20 % biodiesel blend	3.2	51	43.2		-16	128	0.859

6.2 Biofuel Production Process

Biomass is the primary energy source to produce biofuels. Adequate and specific technologies are required to convert biomass into energy efficient forms (biofuels). This is particularly desirable as the energy content of many biomass feedstocks are very low and converting them into high-energy content ones requires technological advancement. Biomass materials are either burnt directly for heat (thermal energy) or upgraded physically or chemically to produce better fuels, giving a higher calorific value. There is a wide range of production routes. End products are generally obtained through the use of wood as an energy input or feedstock. The flow chart for the biofuel production processes is shown in Fig. 6.1.



Chapter 7

Biodiesel production and their utilization as bioenergy resource

7.0 Introduction: A variety of grains and seeds contain relatively high concentrations of vegetable oils that are of high caloric value. It can be used as liquid fuels. However, the high viscosity of these raw vegetable oils (20 times that of diesel), would lead to serious lubrication oil contamination. On the other hand, chemical modification of vegetable oils to methyl or ethyl esters yields excellent diesel engine fuel without the viscosity problems. Biodiesel is the generic name given to these vegetable oil esters. Hence, biodiesel is defined as the biofuel produced through transesterification. This is a process in which organically derived oils are combined with alcohol (ethanol or methanol) in the presence of a catalyst to form ethyl or methyl ester. The biomass-derived ethyl or methyl esters can be blended with conventional diesel fuel. It is used as a neat fuel (100% biodiesel). Biodiesel can be made from soybean, sunflower, cottonseed, corn, groundnut (peanut), sunflower, rapeseed, waste vegetable oils and animal fats, etc. Therefore, biodiesel is made from renewable biological sources such as vegetable oils and animal fats and as an alternative diesel fuel.

One hundred years ago, Rudolf Diesel tested vegetable oil as a fuel for his engine.¹⁰ With the advent of cheap petroleum, appropriate crude oil fractions were refined to serve as fuel. In the 1930s and 1940s, vegetable oils were used as diesel fuels from time to time. It was usually only in emergency situations. Recently, there has been a renewed focus on vegetable oils and animal fats to make biodiesel fuels due to the increase in crude oil prices, limited resources of fossil oil and environmental concerns. Intensification of local air pollution and magnification of global warming problems caused by CO₂, through continued and increasing use of petroleum can be reduced by the use of biodiesel fuels.

The advantages of vegetable oils as diesel fuel

- (i) liquid-nature portability;
- (ii) heat content (80% of diesel fuel);
- (iii) ready availability and
- (iv) renewability.

The disadvantages are

- (i) higher viscosity; and
- (ii) lower volatility.

It is the action of a fat or oil with an alcohol to form esters and glycerol. In addition to lowering the viscosity of vegetable oils, transesterification improves other characteristics such as (i) total removal of the glycerine (ii) increase in boiling point and (iii) lowering of flash point.

Biodiesel is produced by transesterification of large, branched triglycerides into smaller, straight chain molecules of methyl esters, using an alkali or acid or enzyme as catalyst. Alcohols such as methanol, ethanol, propanol, butanol and amyl alcohol are used in the transesterification process. Methanol and ethanol are used most frequently, especially methanol because of its low cost, and physical and chemical advantages. They can quickly react with triglycerides and sodium hydroxide is easily dissolved in these

alcohols. The most common form uses methanol to produce methyl esters (commonly referred to as Fatty Acid Methyl Ester - **FAME**) as it is the cheapest alcohol available, though ethanol can be used to produce an ethyl ester (commonly referred to as Fatty Acid Ethyl Ester - **FAEE**) biodiesel and higher alcohols such as isopropanol and butanol have also been used.

Chemistry of biodiesel production Transesterification Biodiesel is commonly produced by the transesterification of the vegetable oil or animal fat feedstock. The process involves reacting vegetable oils or animal fats catalytically with a short-chain aliphatic alcohols (typically methanol or ethanol). There are several methods for carrying out this transesterification reaction including the common batch process, supercritical processes, ultrasonic methods, and even microwave methods. A by-product of the transesterification process is the production of glycerol. For every 1 tonne of biodiesel that is manufactured, 100 kg of glycerol are produced.

7.1 Production methods

The production of biodiesel from oil seed is shown in Fig. 7.1. Oil is squeezed from the seed in an oil press. Byproduct meal can be sold as a feed additive. One triglyceride molecule ($GL(FA)_3$) reacts with three methanol molecules ($MeOH$) to produce three ester molecules ($MeFA$) and one glycerol molecule ($GL(OH)_3$). The chemical reaction has been given as



where FA represents the fatty acid component of the ester molecule. The reaction can be catalysed by alkalis, acids or enzymes. catalyst. The reaction takes place at room temperature in about an hour.

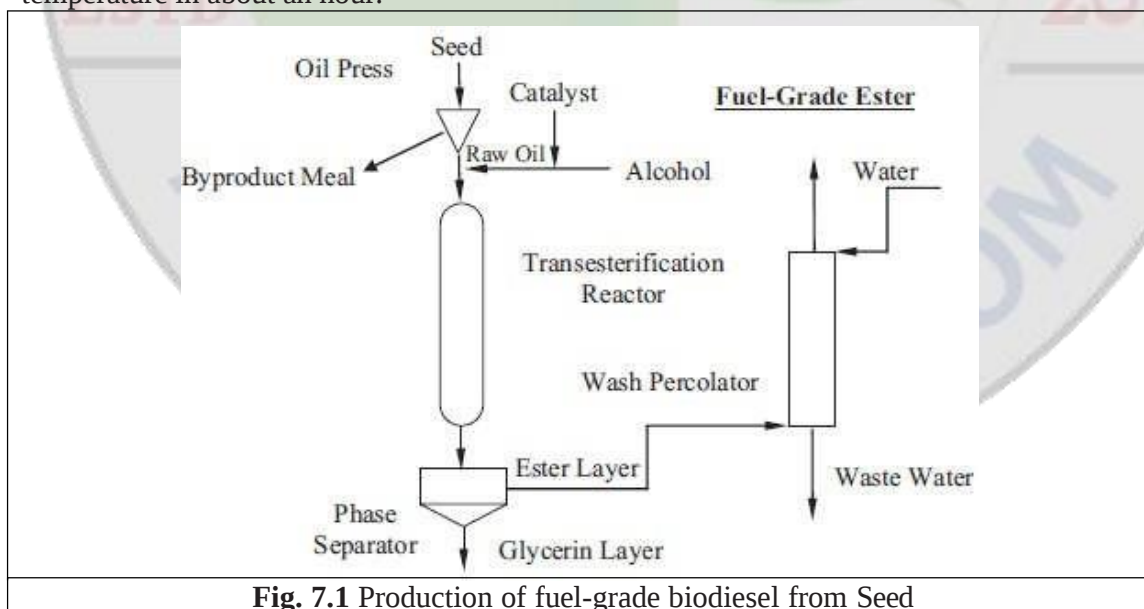


Fig. 7.1 Production of fuel-grade biodiesel from Seed

Small amounts of soap are also produced by the reaction of alkali with fatty acids. Upon completion, the glycerol and soap are removed in a phase separator. Finally, methyl ester

layer is collected as biodiesel. The heat of combustion of biodiesel is within 95 percent by weight of conventional diesel. They burn more efficiently, they have essentially the same fuel value as diesel. Biodiesel can be used in unmodified diesel engines with no excess wear or operational problems.

7.1.1 Batch process

- 1) Preparation: care must be taken to monitor the amount of water and free fatty acids in the incoming biolipid (oil or fat). If the free fatty acid level or water level is too high it may cause problems with soap formation and the separation of the glycerin by-product downstream.
- 2) Catalyst is dissolved in the alcohol using a standard agitator or mixer.
- 3) The alcohol/catalyst mix is then charged into a closed reaction vessel and the biolipid (vegetable or animal oil or fat) is added. The system from here on is totally closed to the atmosphere to prevent the loss of alcohol.
- 4) The reaction mix is kept just above the boiling point of the alcohol (around 70 °C) to speed up the reaction. Some systems recommend the reaction take place anywhere from room temperature to 55 °C for safety reasons. Recommended reaction time varies from 1 to 8 hours; under normal conditions the reaction rate will double with every 10 °C increase in reaction temperature. Excess alcohol is normally used to ensure total conversion of the fat or oil to its esters.
- 5) The glycerin phase is much denser than biodiesel phase and the two can be gravity separated with glycerin simply drawn off the bottom of the settling vessel. In some cases, a centrifuge is used to separate the two materials faster.
- 6) Once the glycerin and biodiesel phases have been separated, the excess alcohol in each phase is removed with a flash evaporation process or by distillation. Care must be taken to ensure no water accumulates in the recovered alcohol stream.
- 7) The by-product (i.e., glycerin) contains unused catalyst and soaps, that are neutralized with an acid and sent to storage as crude glycerin.
- 8) Once separated from the glycerin, the biodiesel is sometimes purified by washing gently with warm water to remove residual catalyst or soaps, dried, and sent to storage.

7.1.2 Supercritical process

It is a catalyst-free method and continuous process. In this method, transesterification process uses supercritical methanol at high temperatures and pressures. In the supercritical state, the oil and methanol are in a single phase, and reaction occurs spontaneously and rapidly. The process can tolerate water in the feedstock. Also the catalyst removal step is eliminated. High temperatures and pressures are required, but energy costs of production are similar or less than catalytic production routes.

7.1.3 Ultra- and high-shear in-line and batch reactors

Ultra- and High Shear in-line or batch reactors allow production of biodiesel continuously, semi- continuously, and in batch-mode. This method drastically reduces production time and increases production volume. The reaction takes place in the high-energetic shear zone of the ultra- and high Shear mixer by reducing the droplet size of the

immiscible liquids such as oil or fats and methanol. Therefore, the smaller the droplet size, the larger the surface area the faster the catalyst can react.

7.1.4 Ultrasonic-reactor method

In the ultrasonic reactor method, the ultrasonic waves cause the reaction mixture to produce and collapse bubbles constantly. This cavitation provides simultaneously the mixing and heating required to carry out the transesterification process. The ultrasonic reactor method for biodiesel production drastically reduces the reaction time, reaction temperatures, and energy input. Industrial scale ultrasonic devices allow for the industrial scale processing of several thousand barrels per day.

7.1.5 Microwave method

Current research is being directed into using commercial microwave ovens to provide the heat needed in the transesterification process. The microwaves provide intense localized heating that may be higher than the recorded temperature of the reaction vessel. A continuous flow process producing 6 liters/minute at a 99% conversion rate has been developed and shown to consume only one-fourth of the energy required in the batch process. Although it is still in the lab-scale, development stage, the microwave method holds great potential to be an efficient and cost-competitive method for commercial-scale biodiesel production.

7.2 Preparation of bio diesel from *Jatropha curcas* In most of the developed countries, biodiesel is produced from soybean, rapeseed, sunflower, peanut, etc., which are essentially edible in Indian context. Among the various vegetable oil sources, non-edible oils are suitable for biodiesel production. Because edible oils are already in demand and too expensive than diesel fuel. Among the non-edible oil sources, *Jatropha curcas* is identified as potential biodiesel source and comparing with other sources, which has added advantages as rapid growth, higher seed productivity, suitable for tropical and subtropical regions of the world. The *Jatropha* plant can reach a height up to 5 m and its seed yield ranges from 7.5 to 12 tonnes per hectare per year, after five years of growth. The oil content of whole *Jatropha* seed is 30-35 % by weight basis. Several properties of the plant including its hardness, rapid growth, easy propagation and wide ranging usefulness have resulted in its spread far beyond its original distribution. Preparation of bio diesel from *Jatropha* requires a two-step approach; the extraction of the *Jatropha* oils from the seed, and the conversion of the extracted oil to Biodiesel, according to the following transesterification reaction. The mechanical extraction was done using a hydraulic press. After dehulling, the *Jatropha* seeds were first pressed to extract oil and then placed inside a soxhlet and brought into contact with a condensed solvent. The solvent dissolves the oil and then it is later separated using a rotor vapor. The obtained *Jatropha* oil was used for Biodiesel production. The transesterification reaction was done using methanol and two basic catalysts. Solvent extraction has higher oil yield than hydraulic press extraction.

7.3 Biodiesel production The process flowchart for biodiesel production from *Jatropha curcas* seeds and by products is shown in Fig. 7.2.

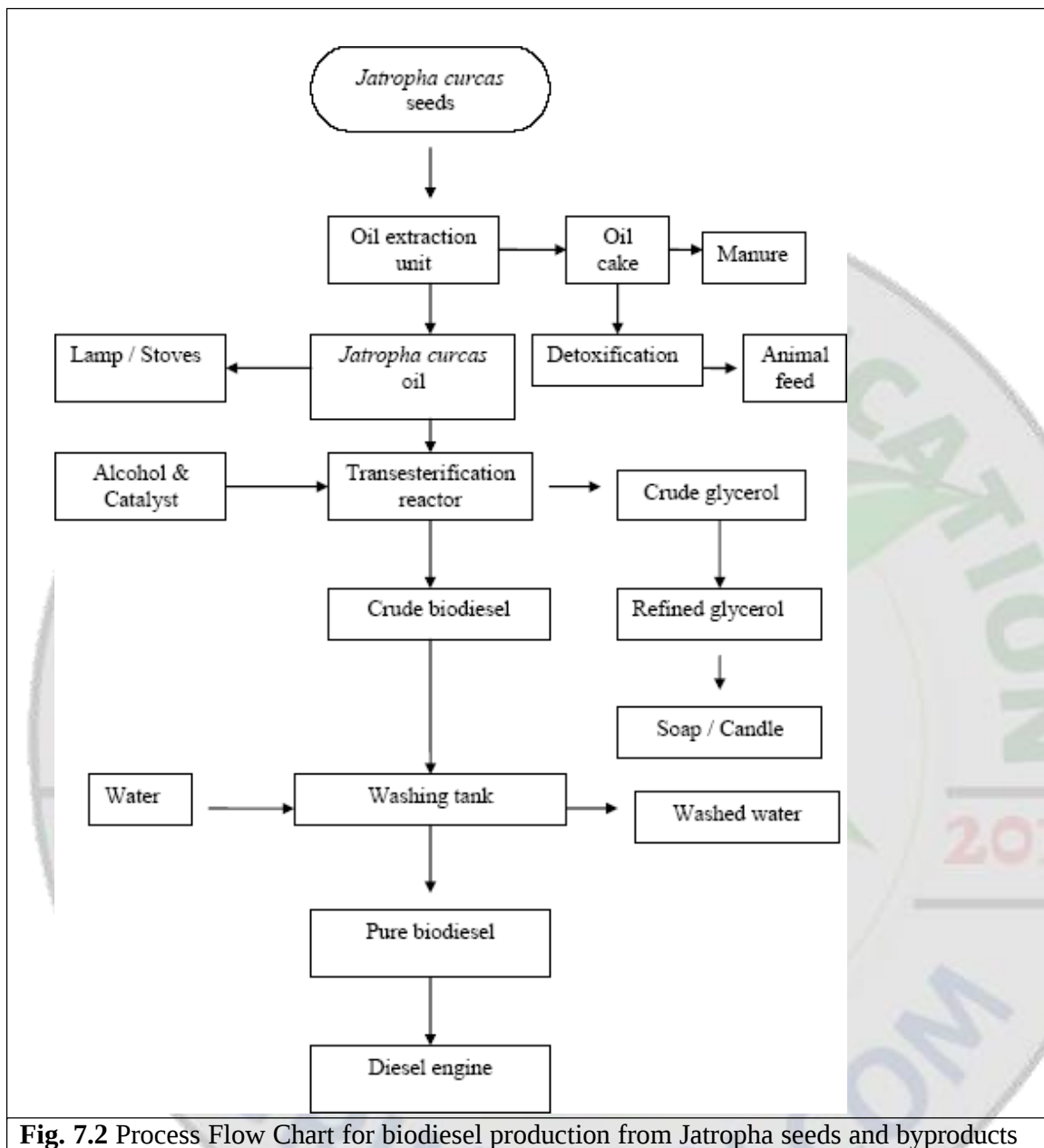


Fig. 7.2 Process Flow Chart for biodiesel production from *Jatropha* seeds and byproducts

7.4 Applications

Biodiesel is the only alternative fuel that can be used directly in any existing unmodified diesel engine, because it has similar properties to diesel fuel. Biodiesel can be used in pure form (B100) or may be blended with petroleum diesel at any concentration in most modern diesel engines. Biodiesel has different solvent properties than petrodiesel, and will degrade natural rubber gaskets and hoses in vehicles (mostly vehicles manufactured before 1992). Biodiesel has been known to break down deposits of residue in the fuel lines where petrodiesel has been used. As a result, fuel filters may become clogged with particulates if a quick transition to pure biodiesel is made. Therefore, it is recommended

to change the fuel filters on engines and heaters shortly after first switching to a biodiesel blend.

Bio diesel has better lubricating properties and much higher cetane ratings than today's lower sulfur diesel fuels. The fuel properties of jatropha oil, jatropha biodiesel and conventional fuel is given in Table 7.1. Bio diesel addition reduces fuel system wear, and in low levels in high pressure systems increases the life of the fuel injection equipment that relies on the fuel for its lubrication.

The calorific value of bio diesel is about 37.27 MJ/L. Bio diesel is a liquid which varies in color - between golden and dark brown - depending on the production feedstock. It is immiscible with water, has a high boiling point and low vapor pressure. The flash point of bio diesel ($>130^{\circ}\text{C}$) is significantly higher than that of petroleum diesel (64°C) or gasoline (-45°C). Bio diesel has a density of $\sim 0.88 \text{ g/cm}^3$, less than that of water (Table 2). Bio diesel has virtually no sulfur content, and it is often used as an additive to Ultra-Low Sulfur Diesel (ULSD) fuel.

Table 7.1 Fuel properties of jatropha oil and its biodiesel Properties			
	Jatropha Oil	Jatropha biodiesel	Diesel
Density, g/ml	0.920	0.865	0.841
Viscosity @ 40°C , Cst	3.5	5.2	4.5
Calorific value, MJ/kg	39.7	39.2	42
Flash point, $^{\circ}\text{C}$	240	175	50

7.5 Economics of biodiesel production

Cost of raw jatropha oil = Rs. 22/litre
 Biodiesel processing cost = Rs. 9/litre
 Cost of production = Rs. 31/litre
 Less return from crude glycerol = Rs. 3/litre
 Net cost of production = Rs. 28/litre
 Dealers margin = Rs. 1/litre Profit = Rs. 3/litre
 Sale price of biodiesel = Rs. 32/litre

Chapter 8 Bio alcohol

8.0 Introduction:

Ethyl alcohol, known as alcohol and technically termed ethanol is a colourless and flammable liquid with a chemical formula C_2H_5OH . It is the alcoholic product of fermenting the sugars in natural raw materials with yeast. The natural raw materials include vegetable matter, growing crops, farm waste, waste organic products (straw and saw dust), molasses, wastes of paper and pulp industries etc. Its use may be regarded as obtaining energy by a direct method from the Sun without the intermediate storage. Plants will perform their synthesis of starch from the abundant carbon dioxide and water as long as the Sun shines. From this annually renewed store of raw materials, ethanol can be readily produced in quantities sufficient to meet the world demand. It thus has attributes of renewal in nature.

Ethanol offers certain advantages if used as an automobile engine fuel. It is an antiknock fuel and has the ability to stand very high compression ratios. It is a high octane, water-free alcohol. Octane rating is defined as the fuel's ability to resist engine knock. Ethanol is both a fuel and an octane enhancer. It is an ideal replacement for lead. It has a high latent heat of vaporisation. This property can be utilised to achieve lower charge temperature during induction for higher charge density. Hence, higher volumetric efficiency is obtained. It tends to produce less carbon deposits than normal petrol and the deposits are softer and easier to remove. Its lower calorific value, higher viscosity, greater surface tension and hygroscopic nature are some of the difficulties in its use as a complete fuel in present day combustion engines. It can, however, be mixed with other fuel or fuel mixtures so as to impart to the resulting blend some of its important properties namely higher compression operation without knock, cleaner combustion and cooler engine operation. Ethanol has the potential as the alternative fuel to solve the problems of limited source of fossil fuels. Ethanol is most commonly used as a 10 percent blend with petrol known as gasohol that can be burned in unmodified automotive engines.

Diesel engines operate on an entirely different combustion principle in comparison to spark ignition engines. It relies on the fuel to self-ignite from an increased pressure and temperature of the compression cycle. The ability of a fuel to self-ignite is measured by its octane rating. Diesel fuel has a high cetane rating. It also has a low octane rating. The converse is true for ethanol, which is the major problem in the use of ethanol in diesel engines. Ethanol can be burned in diesel engines, but because it resists self-ignition, it can have accompanying knock and engine stresses that may be unacceptable due to noise and lower engine life. Cetane-enhancer additives are available but expensive and of questionable performance. Also, phase separation of diesel and ethanol is more pronounced than with petrol blends, which limits its performance during cold weather. Hence, ethanol is not suitable to use as a fuel in diesel engine systems.

8.1 Manufacture of ethanol Ethanol can be produced by the fermentation of any feedstock that contains sugar or starches. It can be produced from cellulose materials that can be converted into fermentable sugar. These three groups of biomasses are as follows:

- (i) sugars (sugar beets, sugarcane, sweet sorghum, fruits);
- (ii) starches (small grains such as corn and wheat, potatoes, cassava); and
- (iii) cellulose (wood, solid waste, agricultural residues).

Sugar crops contain monosaccharide forms of sugar such as glucose. This can readily be fermented into alcohol by yeast with no intermediate processing. Starch crops contain sugar units that are tied together in long chains. Yeast cannot use these disaccharide forms of sugar until the starch chains are converted into individual six-carbon groups such as glucose or fructose. This conversion process can be done fairly simply by the use of cooking in a dilute acid solution or reacting the starch with thermophilic (heat tolerant) enzymes. Cellulose crops contain chemicals called polysaccharides. These chains must be broken down to release the sugar. Breaking the chemical bonds of cellulose is more complicated than breaking down starch to simple sugar. The conversion is typically done physically (milling or heat treatment) or chemically (basic or acid reactions). Ethanol production from various crops is presented in Table 8.1.

	Liters of ethanol per tonne of crop	Liters of ethanol per hectare per year
Sugarcane	70	3500
Cassava	180	2160
Sweet sorghum	86	3010
Sweet potato	125	1875
Corn (maize)	370	2220
Wood	160	3200

Ethanol production proceeds as follows:

- (i) formation of a fermentable sugar solution;
- (ii) fermentation of the sugar solution to ethanol; and
- (iii) separation of ethanol from other process ingredients.

The ethanol production process is outlined as follows:

1. **Milling:** Feedstock is first passed through hammer mills and then it is ground into a fine powder.
2. **Sterilisation:** If distressed or damaged crop are used, sterilisation facilities are included to avoid biological contamination.
3. **Cooking:** Enzymes (alpha-amylase) and water are added to form a mash that is cooked for about 30 min. Heat is applied at this stage to enable liquefaction.
4. **Cooling:** The mash from the cooker is cooled. The secondary enzyme (glucoamylase) is added to convert the liquefied mash to fermentable sugars (dextrose).

5. Fermentation: Yeast is added to the mash to ferment the sugars to ethanol and carbon dioxide. Mash ferments for about 2 days, during which the sugar is converted to alcohol.
6. Distillation: The fermented mash, now called “beer” contains about 10% alcohol as well as the nonfermentable solids. Initially the mass is introduced into the first-stage distillation column that is regulated to maintain a temperature just a little higher than the boiling point of ethanol. Alcohol vaporises and ascends out of the column. Liquid water mixed with residual grain and yeast (distillers grain) flows down and out. The vaporised alcohol (now about 50 percent) is passed through a second distillation column. It concentrates the alcohol content to 95 percent (e.g. 190 proof). Proof is a measure of ethanol content. One percent ethanol content equals 2 proofs.
7. Dehydration: Since the alcohol from the second-stage column contains 5% water, which is unusual for commercial gasohol, it must be totally dehydrated. Benzene and petrol are common additives in a further process to separate the residual water and produce anhydrous ethanol (100 percent or 200 proof alcohol).
8. Denaturing: Ethanol that will be used for fuel is then denatured with a small amount (2–5%) of some product, like petrol, to make it unfit for human consumption.
9. Fuel: The denatured anhydrous alcohol is transported to the gasohol market. It is blended with unleaded petrol at the ratio of 10 percent ethanol to 90 percent petrol.
10. Coproducts: Two primary coproducts of ethanol production are distillers grain and carbon dioxide. Both of which have market value. Distiller grain consists of the protein value of corn, yeast, fibre and water discharge from the first-stage distillation column. The distillers grain has a high protein content of about 27 percent. Therefore, it makes an excellent animal feedstock supplement. It is competitive with soybean meal, which is about 44 percent protein. Carbon dioxide (CO₂) that evolves from the fermentation process can be used in grain storage silos to retard spoilage.

8.1.1 Ethanol from starchy feed stock (grains) Ethanol production from cereal grains such as barley, wheat and corn is a much easier process than from cellulose material. The process includes several steps, a) Milling of grains b) Hydrolysis of starch to sugar units c) Fermentation by yeast d) Distillation e) Removal of water from ethanol

After grinding the raw material, it is mixed with water and enzymes to break down the starch to sugar units. The free sugar can be used by yeast or bacteria and converted to ethanol and carbon dioxide. As the concentration of ethanol increases to about 15%, fermentation is reduced, since high alcohol concentration kills the yeast or bacteria. It is then necessary to separate the ethanol from the other material in the fermentation tanks by distillation. Distillation increases the ethanol concentration up to about 95%. In order to remove the rest of the water from the ethanol solution, it must be dried by different drying agents to a concentration of 99.5% ethanol or absolute ethanol. Extractive distillation with benzene also yields anhydrous ethanol. It is possible to produce 1 litre of absolute ethanol from about 3 kg of wheat. The process flow chart for production of ethanol from grains is shown in Fig.8.1.

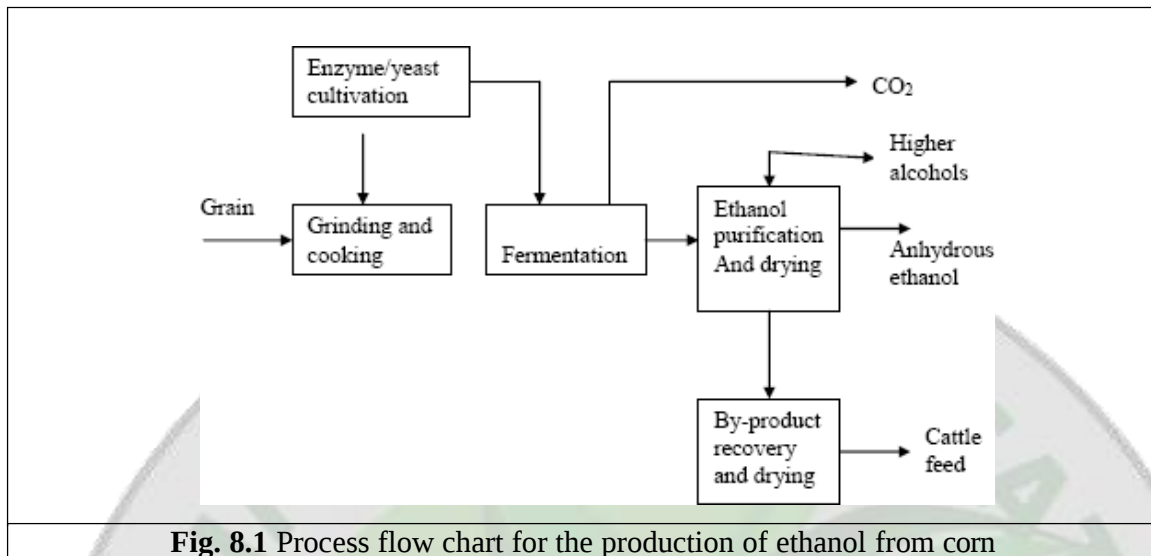


Fig. 8.1 Process flow chart for the production of ethanol from corn

8.1.2 Ethanol from sugarcane Ethanol production from sugarcane is one of the easiest and most efficient processes since sugarcane contains about 15% sucrose. The glycosidic bond in the disaccharide can be broken down into two sugar units, which are free and readily available for fermentation. The cane is cut and the juice is extracted by maceration. After clarification, the juice is concentrated by boiling. The concentrated juice is fermented with yeast to produce raw ethanol. A series of distillation steps including a final extractive distillation with benzene are used to obtain anhydrous ethanol. The normal yield of ethanol is about 8.73 litres of alcohol per tonne of cane. The potential of ethanol production in India is about 475 litres per year. The process flow chart for production of ethanol from sugarcane is shown in Fig.8.2.

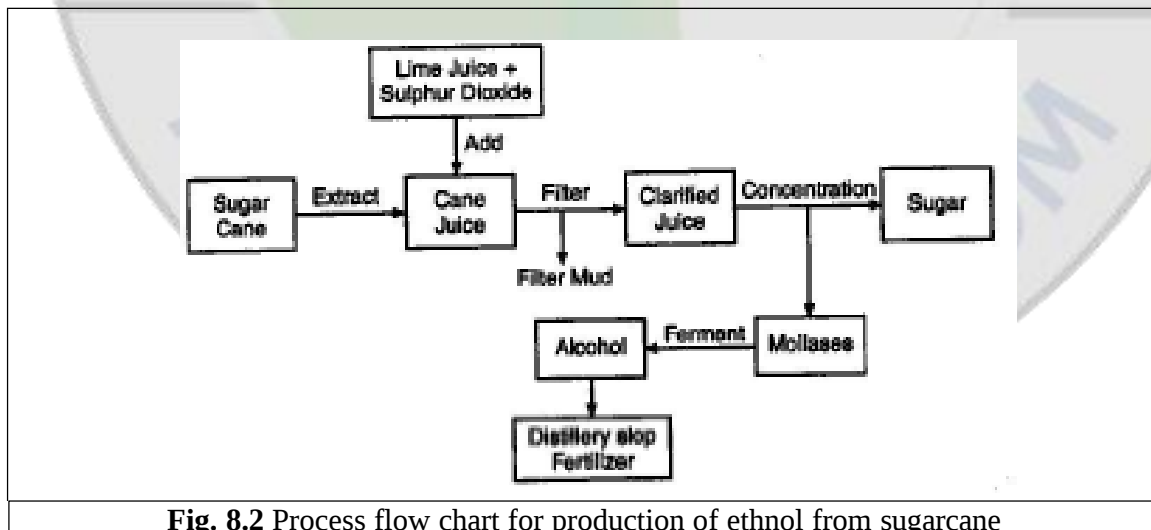


Fig. 8.2 Process flow chart for production of ethanol from sugarcane

Chapter 9

Solar energy

9.0 Introduction: Sunlight, in the broad sense, is the total spectrum of the electromagnetic radiation given off by the Sun. On Earth, Sunlight may be recorded using a sunshine recorder, pyranometer or pyrheliometer. The World Meteorological Organization (WMO) defines sunshine as direct irradiance from the Sun measured on the ground of at least 120Wm^{-2} . Direct sunlight gives about 93 lux of illumination per watt of electromagnetic power, including infrared, visible and ultraviolet. Bright sunlight provides illumination of approximately 100000 lux per square metre at the Earth's surface. Sunlight is a key factor in the process of photosynthesis.

The demand for energy has always been the primary driving force in the development of industrial capability. The invention of the steam engine sparked the industrial revolution and the consequent evolution of an energy economy based on wood and coal. Since then the continuous growth of the energy economy has focused on various sources of energy, such as nuclear, wind, water, oil, and gas. Nuclear energy is very expensive and poses radiation hazards and nuclear waste problems. Electrical energy sources using coal, wood, gas, and oil generate large amounts of pollution or carbon dioxide emissions, thereby posing health risks. All these electrical energy power sources require large capital investments and scheduled maintenance. In case of coal-fired power plants, high capital investment, coal transportation cost, and delivery delay under adverse climatic conditions could pose serious problems. On the other hand, a solar energy source provides pollution-free, self-contained, reliable, quiet, long-term, maintenance-free, and year-round continuous and unlimited operation at moderate costs. Despite all these benefits of solar cells and nearly 55 years after their invention, PV solar cells are generating only 0.04 percent of the world's on-grid electricity due to the high cost of solar cells, which is beyond the reach of the common consumer. Based on the 2007 statistical review of world energy consumption, 30 percent of the electrical energy is generated from coal, 16 percent from natural gas, 15 percent from water generators, 9 percent from oil, 4 percent from nuclear reactors, and only 1 percent from solar cells. In the United States, solar energy of all kinds fulfills less than 0.1 percent of the electrical demand. All industrial and Western countries such as the United States, Germany, Japan, Brazil, Italy, Spain, and other European countries are turning to electrical power generation from solar cells, because of the high capital investments, radiation, and carbon dioxide emissions associated with coal-based, nuclear-based, gas-based, and oil-based power plants.

The power from the sun intercepted by the earth is approximately 1.8×10^{11} MW which is many thousand times larger than the present consumption rate on the earth of all commercial energy sources. Thus, in principle, solar energy could supply all the present and future energy needs of the world on a continuing basis. This makes it one of the most promising of the unconventional energy sources. The advantages of solar energy are (i) environmentally clean source of energy and (ii) freely available in adequate quantities in almost all parts of the world where people live. The main problems associated with solar energy are: (i) dilute source of energy and (ii) availability varies widely with time. India, being tropical country receives solar insolation in the order of $1650\text{--}2100\text{ kwh/m}^2/\text{year}$ for nearly 250-300 days. Solar energy can be used directly or indirectly.

9.1 The Sun

The Sun is the star at the centre of the solar system. The Earth and other matter (including other planets, asteroids, meteoroids, comets and dust) orbit the Sun, which by itself accounts

for about 99.8% of the solar system's mass. Energy from the Sun, in the form of sunlight, supports almost all life on Earth via photosynthesis, and drives the Earth's climate and weather. The Sun has an effective black-body temperature T_s of 5777 K and it is the largest member of the solar system. The Sun is a sphere of intensely hot, gaseous matter with a diameter of 1.392×10^9 m and is, on average, 1.496×10^{11} m (Astronomical Unit) away from the Earth. The Sun is, effectively, a continuous fusion reactor. It is estimated that 90% of the Sun's energy is generated in the region 0 to $0.23R$ (R being the radius of the Sun $= 6.95 \times 10^8$ m); the average density (ρ) and the temperature (T) in this region are 10^5 kg m^{-3} and about 8.40×10^6 K respectively. At a distance of about $0.7R$ from the centre, the temperature drops to about 1.3×10^5 K and the density to 70 kg m^{-3} . Hence for $r > 0.7R$ convection begins to be important and the region $0.7R < r < R$ is known as the convective zone. The outer layer of this zone is called the photosphere. The maximum spectral intensity occurs at about $0.48 \mu\text{m}$ wavelength (λ) in the green portion of the visible spectrum. About 8.73% of the total energy is contained in the ultraviolet region ($\lambda < 0.40 \mu\text{m}$); another 38.15% in the visible region ($0.40 \mu\text{m} < \lambda < 0.70 \mu\text{m}$) and the remaining 53.12% in the infrared region ($\lambda > 0.70 \mu\text{m}$).

9.2 The Earth

The Earth revolves around the Sun once in about a year. Nearly two-thirds of the Earth is covered by water and the remaining one-third is land. Half of the Earth is lit by sunlight at a time. It reflects one-third of the sunlight that falls on it. This is known as Earth's albedo. The Earth is spinning at a constant rate about its axis, inclined at an angle of 23.5° . As a result, the lengths of days and nights are constantly changing. The heat flux at Earth's surface due to heat conduction from the centre is $0.04\text{--}0.06 \text{ W m}^{-2}$ with a temperature gradient of $30\text{--}40^\circ\text{C/km}$.

9.3 Solar Constant

The **solar constant** G_{sc} is the energy from the sun per unit time received on a unit area of surface perpendicular to the direction of propagation of the radiation at mean earth-sun distance outside the atmosphere. The World Radiation Center (WRC) has adopted a value of 1367 W m^{-2} , with an uncertainty of the order of 1%. A value of G_{sc} of 1367 W m^{-2} ($1.960 \text{ cal/cm}^2 \text{ min}$, $433 \text{ Btu/ft}^2 \text{ h}$, or $4.921 \text{ MJ/m}^2 \text{ h}$) may be used.

9.4 Measurement of Solar Radiation on Earth's Surface

The solar radiation reaching the Earth's surface through the atmosphere can be classified into two components: beam and diffuse radiation.

Beam radiation (I_b): The solar radiation propagating along the line joining the receiving surface and the Sun. It is also referred to as direct radiation.

Diffuse radiation (I_d): The solar radiation scattered by aerosols, dust and molecules. It does not have any unique direction.

Total radiation (I_t): The sum of the beam and diffuse radiation, sometimes known as global radiation.

The following instruments are commonly used for measurement of solar radiation on Earth's surface.

(i) Pyrheliometer

The pyrheliometer is a broadband instrument that measures the direct (or beam) component of solar radiation at normal incidence. This means the instrument is always aimed directly at the Sun, via a tracking mechanism that continuously follows the Sun. It is sensitive to

wavelengths in the band from 280 to 3000 nm (0.284 μm to 0.3 μm). Solar irradiance enters the instrument through a sealed crystal-quartz window and the sunlight is directed onto a thermopile which converts heat to an electrical signal that can be recorded. A calibration factor is applied when converting the mV signal to an equivalent radiant energy flux, measured in watts per square metre.

(ii) Pyranometer

A pyranometer is a type of actinometer used to measure broadband solar irradiance on a planar surface and is a sensor that is designed to measure the solar radiation flux density (in watts per metre square) from a field of view of 180 degrees. The working principle of a pyranometer is the same as a pyrliometer except for the fact that a sensitive surface is exposed to the total beam, diffused and reflected from Earth and surrounding radiation. The sensitive surface consists of a circular, blackened (hot junction) multijunction thermopile whose cold junctions are electrically insulated from the basement. The temperature difference between the hot and cold junctions is a function of the radiation falling on the surface.

9.5 Sun–Earth Angles

The energy flux of beam radiation on a surface with arbitrary orientation can be obtained by the flux either on a surface perpendicular to the Sun rays or on a horizontal surface. The various Sun–Earth angles required to understand the solar energy received are as follows.

(i) Zenith Angle (θ_z)

Let P be a point on the surface of the Earth referred to as the position of the observer and PN normal to the horizontal plane as shown in Figure. The direction PN is known as the zenith direction. The zenith angle (θ_z) is the angle of the Sun's ray (SP) away from the zenith direction, which varies from 0° to 90° . When the Sun is either rising or setting the zenith angle is near 90° whereas at noon it is equal to or very near to zero. The zenith angle varies throughout the day with the movement of the Sun (Fig. 6.1).

(ii) Solar Altitude (α)

The solar altitude (α) is the angle between the rays of the Sun (SP) and the horizontal plane under consideration. PS' is the projection of the Sun's rays on a horizontal surface. Thus, PS' represents the horizontal surface. The angle S'PS is the solar altitude, as shown in Figure. Hence $\alpha + \theta_z = 90^\circ$. The altitude angle is zero at sunrise and sunset, whereas at noon it is near to 90° . The altitude angle also varies throughout the day with the movement of the Sun (Fig.9.1).

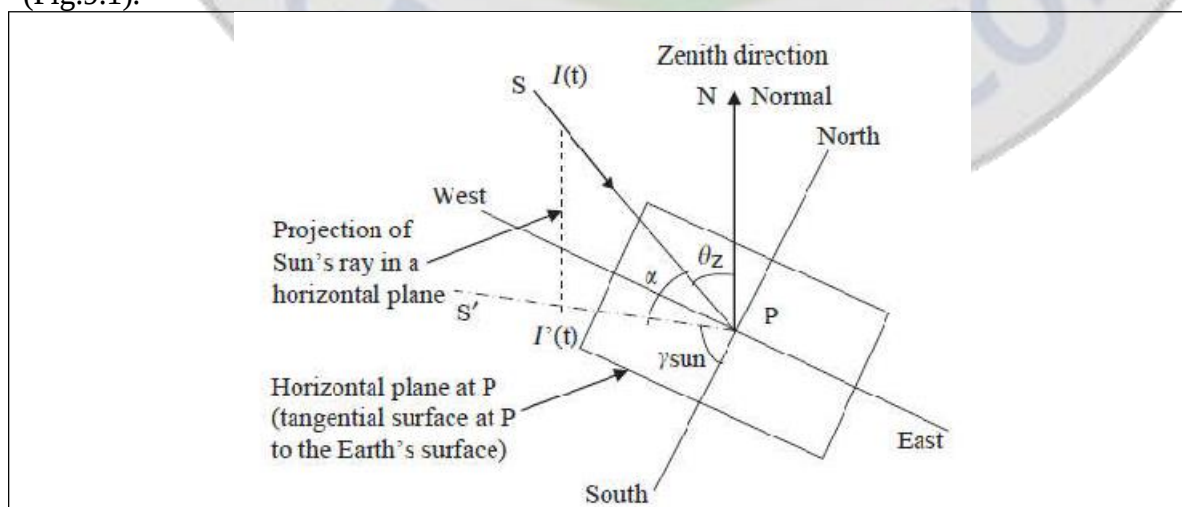


Fig. 9.1 Zenith, solar altitude and solar azimuth angles

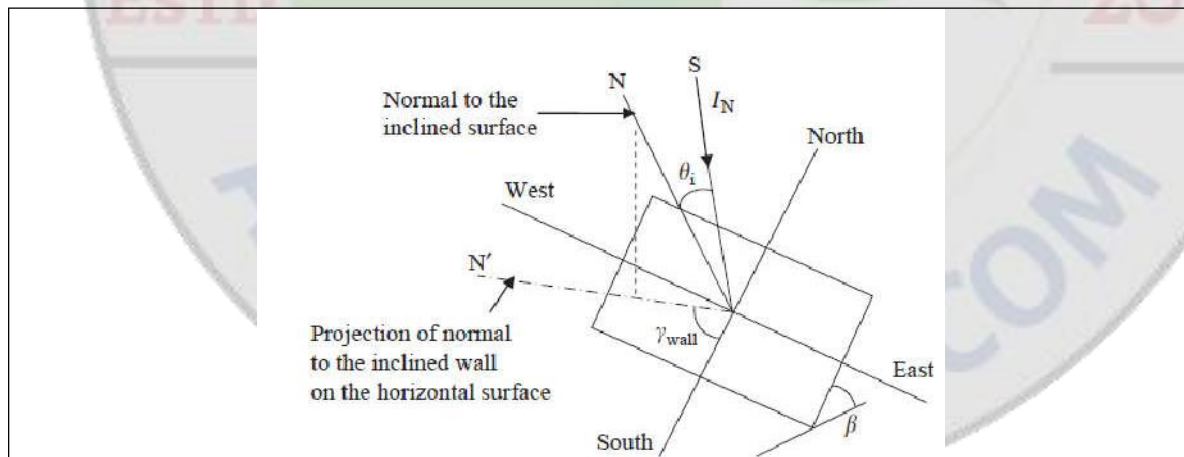
(iii) Solar Azimuth Angle (γ_{Sun})

This angle is measured with respect to the south direction (the directions pointed to by a compass are magnetic south and north). We must consider geographic south, which is different from magnetic south. A person standing vertically at noon (noon is the moment at which shadows are shortest) makes their shortest shadow on the Earth pointing towards geographic south and north. If the person is facing the Sun then that direction is geographic south, whereas the direction of the back of the person will be geographical north. Considering above Figure, the angle between the south direction and the projection of the rays of the Sun on a horizontal plane is known as the solar azimuth angle γ_{Sun} (Fig. 6.1).

(iv) Wall Azimuth Angle (γ_{wall})

‘Wall’ does not mean any vertical surface. It can also mean an inclined surface. The angle that the projection of normal at the inclined surface on the horizontal surface makes with the south direction is known as the wall azimuth angle or surface azimuth angle γ_{wall} (Fig. 9.2). The following are the main points:

- (i) γ_{wall} for the surface facing north will be $\pm 180^\circ$.
- (ii) γ_{wall} for the surface facing south will be 0° .
- (iii) If the wall or surface has $\beta = 90^\circ$, the wall is vertical.
- (iv) If $\beta = 0^\circ$, the surface is horizontal.
- (v) If N' falls on the west side of the south direction, then γ_{wall} is taken as positive.
- (vi) If N' falls on the east side of the south direction, then γ_{wall} is negative.
- (vii) The angle of incidence θ_i is the angle between the beam radiation on a surface and the normal to that surface.


Fig. 9.2 Wall azimuth angle for an inclined surface.

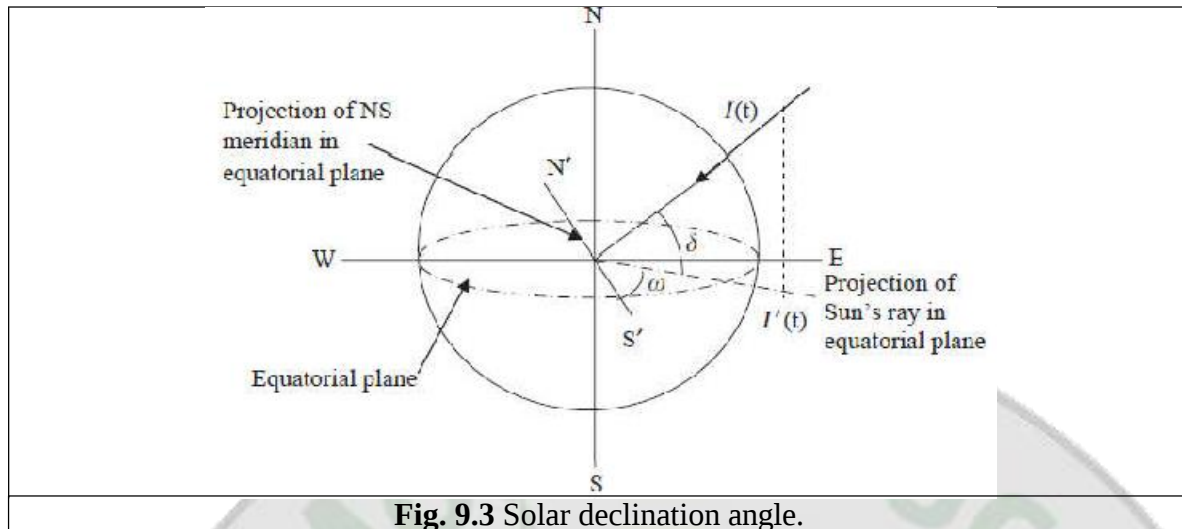


Fig. 9.3 Solar declination angle.

(v) Solar Declination (δ)

The angle that the Sun's rays make with the equatorial plane is known as the declination angle. In other words, the solar rays hit our planet at a certain angle with respect to the equator; this angle is the solar declination. On any day, δ is taken as a constant which changes on the next day. Cooper's empirical relation for calculating the solar declination angle (in degrees) is

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

where n day of the year ($1 \leq n \leq 365$).

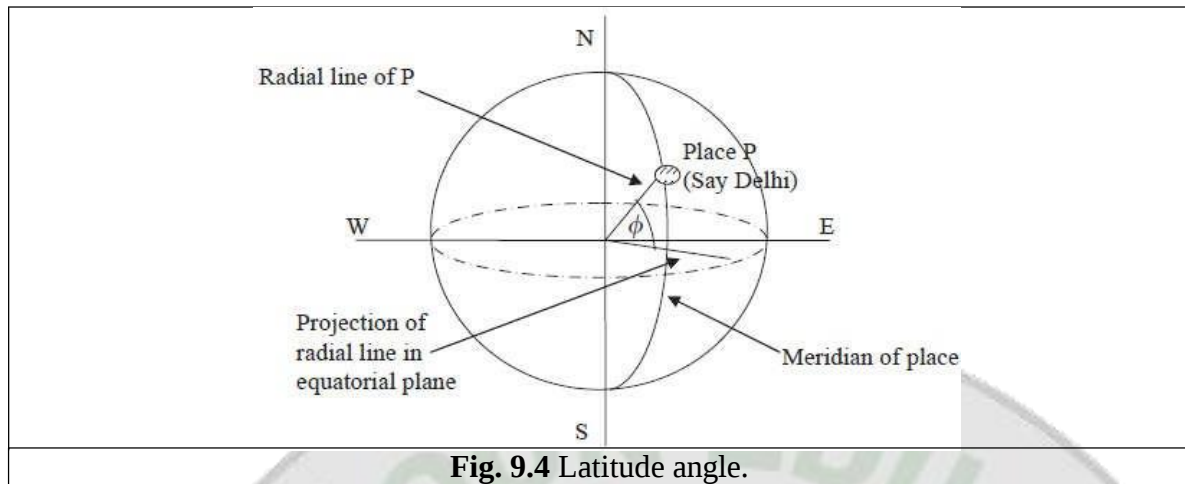
Solar declination can also be defined as the angle between the line joining the centres of the Sun and the Earth and its projection on the equatorial plane (Fig. 9.3). The solar declination changes mainly due to the rotation of Earth about an axis. Its maximum value is 23.45° on 21 December and the minimum is -23.45° on 21 June.

Key Points

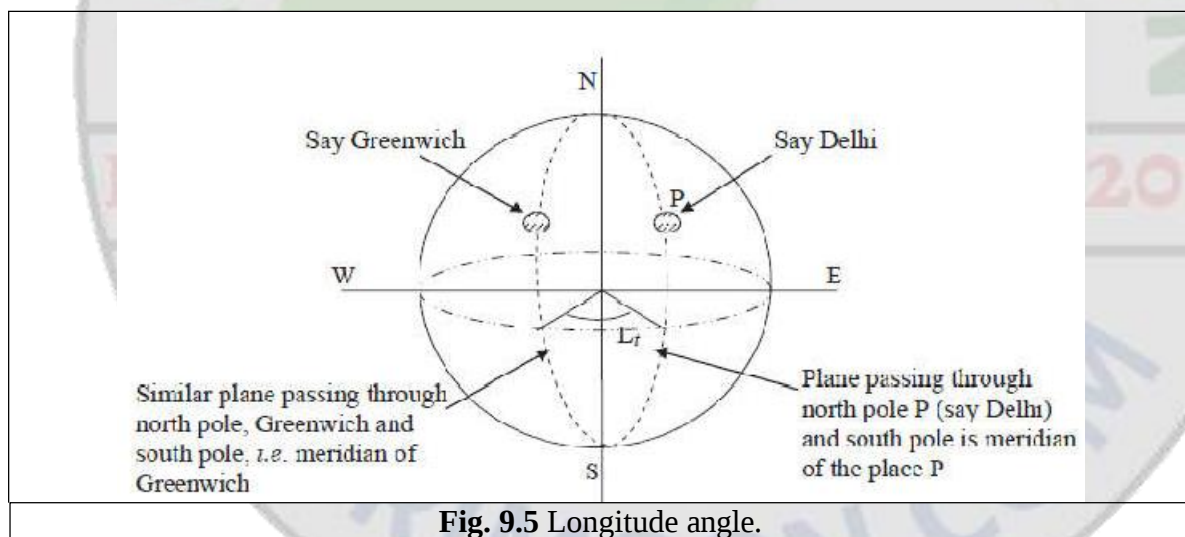
- (i) The line joining the centre of the Sun and the Earth is important for δ .
- (ii) The axis of rotation remains pointed in the same direction. It is never perpendicular to the orbital plane.
- (iii) The equinox dates when solar declination is zero are 22 March and 22 September, i.e. when night is equal to day.
- (iv) The longest day is 22 June and the shortest is 22 December.

(vi) Latitude (ϕ) and Longitude (L_t)

We can describe a location on Earth using latitude and longitude. Consider P to be a place under consideration on Earth's surface. Angle ϕ represents the latitude of the place P . Normally we need three coordinates to define any point in space (radius, 1st angle and 2nd angle). For describing any place on Earth's surface, the radius of the Earth is fixed. Now, there are only two angles, i.e. the 1st and 2nd angles, which are to be understood to describe any place. These angles are latitude and longitude.



The latitude of a location is the angle made by the radial line joining the given location to the centre of the Earth with its projection on the equatorial plane. This angle indicates how far we are from the equatorial plane. Lines of latitude run parallel to the equator (Fig. 9.4). Equator is the only line of latitude which is also a great circle. On the Earth, a circle of latitude is an imaginary east–west circle that connects all the locations with a given fixed latitude. The position of any place on the circle of latitude is given by the longitude (Fig. 9.5). Each is perpendicular to all meridians at the intersection points. Those parallels closer to the poles are smaller than those at or near the equator.



On the Earth, a meridian is an imaginary north–south line between the north pole and the south pole that connects all locations with a given longitude. The position on the meridian is given by the latitude, each being perpendicular to all circles of latitude at the intersection points.

The meridian that passes through Greenwich (England) is considered as the prime meridian, i.e. zero degrees of longitude. Any other meridian is referred to from the prime meridian, and has a fixed angular distance from the prime meridian known as the longitude of that meridian. All the places on that meridian have the same longitude. The Earth can be divided in two

parts with reference to the prime meridian, viz. eastern and western hemispheres. The maximum distant meridian on both sides can be at 0 to 180° from the principal meridian.

Key Points

- (i) The latitude is taken as positive for the northern hemisphere and negative for the southern hemisphere.
- (ii) In the case of Delhi, the longitude is 77.21 E, also known as -77.21, i.e. towards east from the Greenwich meridian and is considered as negative.

Hour Angle (ω)

The hour angle is the angle through which the Earth has to rotate to bring the meridian plane of any place or location under the Sun. This angle continuously decreases from sunrise to noon, becomes zero at noon and then starts increasing when its value becomes positive. At sunset the hour angle is maximum positive and at sunrise it is maximum negative for any place. In other words, the hour angle is the measure of the angular displacement of the Sun through which the Earth has to rotate to bring the meridian of the place directly under the Sun. Thus, it is very clear that ω will vary with the time of the day as shown in Figure below. The angle between an observer's (at a particular place on Earth) meridian and the hour circle on which some celestial body lies is known as the hour angle. This angle is conventionally expressed in units of time (hours, minutes and seconds), which gives the time elapsed since the celestial body's last transit at the observer's meridian (for a positive hour angle), or the time expected for the next transit (for a negative hour angle) (1 hour=15°).

At sunrise, the value of ω will be maximum, then it will slowly and steadily reduce and keep reducing with time until solar noon. At this point ω becomes zero. It starts increasing the moment after solar noon and will be maximum at sunset. The values at sunrise and sunset are numerically the same but have opposite signs (Fig. 9.6).

An expression for the hour angle, ω (in degrees), is given by

$$\omega = (ST-12)*15$$

where ST is local solar time.

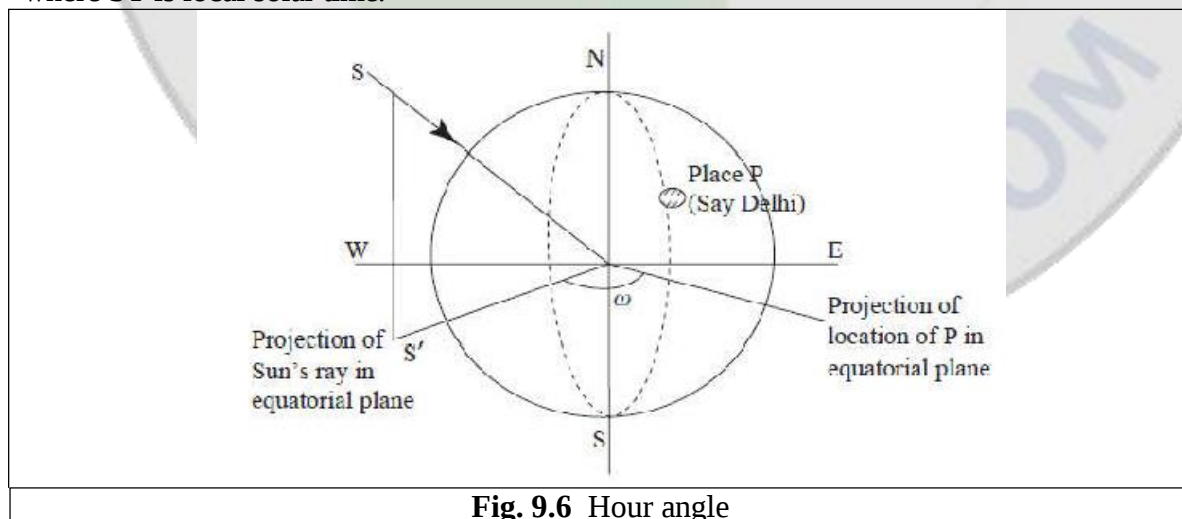


Fig. 9.6 Hour angle

9.6 Definitions:

Air Mass m The ratio of the mass of atmosphere through which beam radiation passes to the mass it would pass through if the sun were at the zenith (i.e., directly overhead). Thus at sea

level $m = 1$ when the sun is at the zenith and $m = 2$ for a zenith angle $\theta_z = 60^\circ$. For zenith angles from 0° to 70° at sea level, to a close approximation,

$$m = 1/\cos(\theta_z)$$

For higher zenith angles, the effect of the earth's curvature becomes significant and must be taken into account.

Beam Radiation The solar radiation received from the sun without having been scattered by the atmosphere. (Beam radiation is often referred to as direct solar radiation; to avoid confusion between subscripts for direct and diffuse, we use the term beam radiation.)

Diffuse Radiation The solar radiation received from the sun after its direction has been changed by scattering by the atmosphere. (Diffuse radiation is referred to in some meteorological literature as sky radiation or solar sky radiation; the definition used here will distinguish the diffuse solar radiation from infrared radiation emitted by the atmosphere.)

Total Solar Radiation The sum of the beam and the diffuse solar radiation on a surface. (The most common measurements of solar radiation are total radiation on a horizontal surface, often referred to as **global radiation** on the surface.)

Irradiance, W/m^2 The rate at which radiant energy is incident on a surface per unit area of surface. The symbol G is used for solar irradiance, with appropriate subscripts for beam, diffuse, or spectral radiation.

Irradiation or Radiant Exposure, J/m^2 The incident energy per unit area on a surface, found by integration of irradiance over a specified time, usually an hour or a day. **Insolation** is a term applying specifically to solar energy irradiation. The symbol H is used for insolation for a day. The symbol I is used for insolation for an hour (or other period if specified). The symbols H and I can represent beam, diffuse, or total and can be on surfaces of any orientation.

Radiosity or Radiant Exitance, W/m^2 The rate at which radiant energy leaves a surface per unit area by combined emission, reflection, and transmission.

Emissive Power or Radiant Self-Exitance, W/m^2 The rate at which radiant energy leaves a surface per unit area by emission only. Any of these radiation terms, except insolation, can apply to any specified wavelength range (such as the solar energy spectrum) or to monochromatic radiation. Insolation refers only to irradiation in the solar energy spectrum.

Solar Time Time based on the apparent angular motion of the sun across the sky, with solar noon the time the sun crosses the meridian of the observer. Solar time is the time used in all of the sun-angle relationships; it does not coincide with local clock time. It is necessary to convert standard time to solar time by applying two corrections. First, there is a constant correction for the difference in longitude between the observer's meridian (longitude) and the meridian on which the local standard time is based. The sun takes 4 min to transverse 1° of longitude. The second correction is from the equation of time, which takes into account the perturbations in the earth's rate of rotation which affect the time the sun crosses the observer's meridian. The difference in minutes between solar time and standard time is

$$\text{Solar time} - \text{standard time} = 4 (L_{\text{st}} - L_{\text{loc}}) + E$$

where L_{st} is the standard meridian for the local time zone, L_{loc} is the longitude of the location in question, and longitudes are in degrees west, that is, $0^\circ < L < 360^\circ$. The parameter E is the equation of time (in minutes)

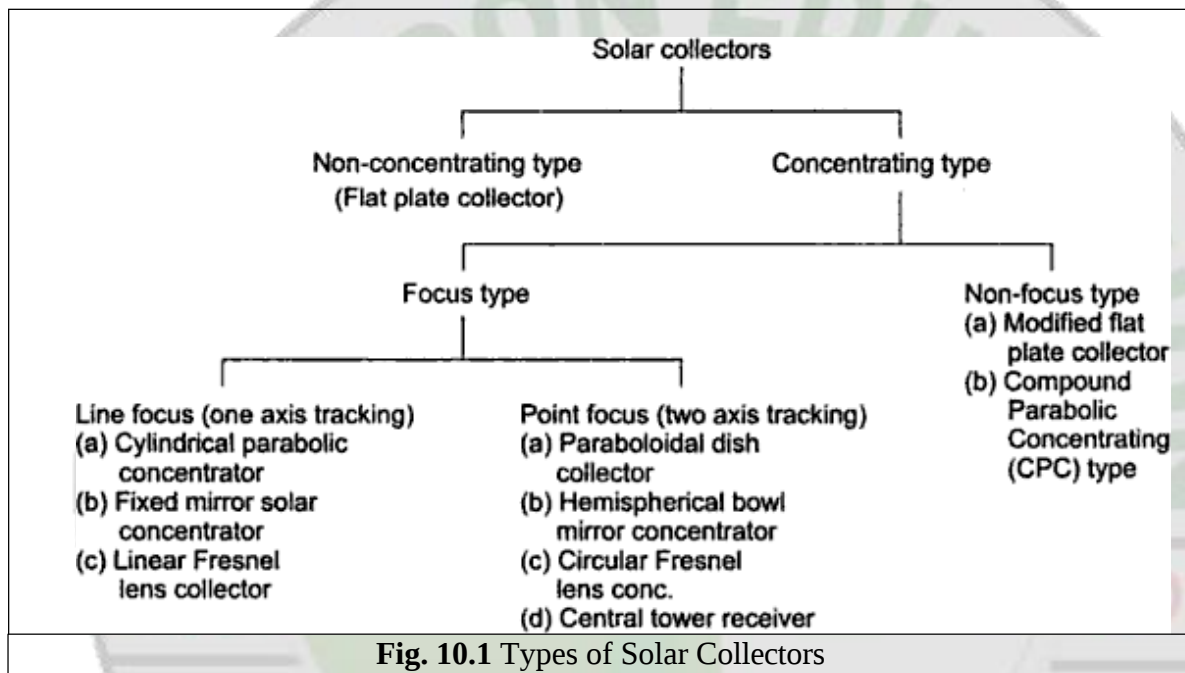
$$E = 229.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B),$$

where $B = (n-1) \times 360/365$ and n is the day of the year. Thus $1 < n < 365$

Chapter 10

Solar Collectors

10.0 Introduction: Solar power has low density per unit area (1 kW/sq-m to 0.1 kW/sq-m). hence, it is to be collected by covering large ground area by solar thermal collectors. Solar thermal collector essentially forms the first unit in a solar thermal system. It absorbs solar energy, converts it into heat and then transfers it to heat transport fluid. The heat transport fluid delivers this heat to thermal storage tank/boiler/heat exchanger, etc. to be utilized in the subsequent stages of the system. Solar collectors are classified as below (Fig. 10.1);



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

While non-focus type collectors utilize both beam and diffuse radiation, the focus type collectors make use of beam radiation only, as diffuse radiation cannot be focused. The important features of a solar collector are: (i) collector efficiency (ii) concentration ratio, and (iii) temperature range. The performance of a solar collector is evaluated on the basis of these factors.

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

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

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

In flat plate collectors, no optical system is utilized to concentrate the solar radiation, and hence, the concentration ratio is equal to one, and temperature range is less than 100°C . Line focus collectors have CR up to 100 and temperature range of the order $100\text{--}300^{\circ}\text{C}$. Concentration ratio of the order of thousands and temperature range of $300\text{--}1000^{\circ}\text{C}$ can be obtained by using point focus collectors.

10.1.1 Flat Plate Collector

The characteristic features of flat plate collector are:

- i) It absorbs both beam and diffuse radiation.
- ii) It can function without the need for sun tracking. Therefore, it can be properly secured on a rigid platform and thus, becomes mechanically stronger than those requiring flexibility for tracking purpose. As a collector is installed outdoor it should be mechanically strong enough to withstand atmospheric disturbances (rain, storm, etc.).
- iii) It is simple to construct and requires little maintenance.

The basic elements in a majority of these collectors are (Fig. 10.2):

- i) Transparent cover (one or two sheets) of glass or plastic.
- ii) Blackened absorber plate usually of copper, aluminum or steel, typically 1-2 mm thick.
- iii) Tubes (1-2 cm dia), channels or passages, in thermal contact with the absorber plate. In some designs, the tubes form integral part of absorber plate.
- iv) Thermal insulation, typically 5-10 cm in thickness.
- v) Tight container to enclose the above components.

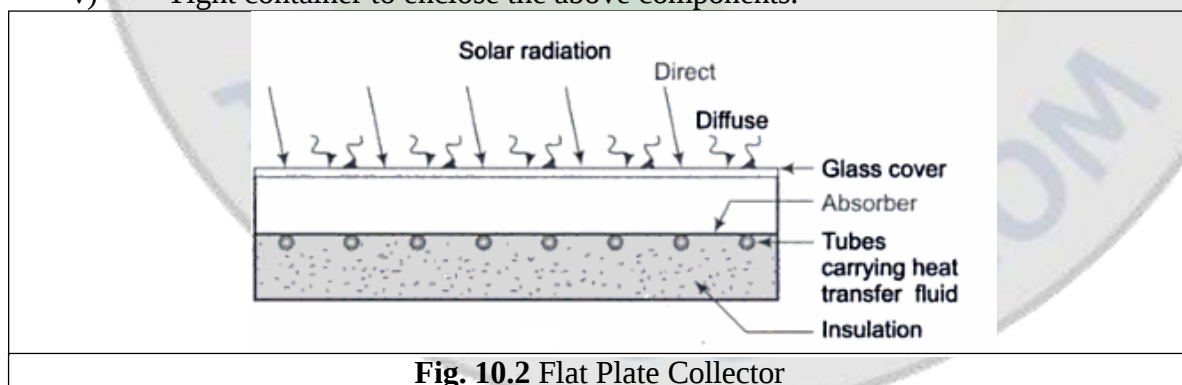


Fig. 10.2 Flat Plate Collector

Working: As solar radiation strikes on specially treated metallic absorber plate, it is absorbed and raises its temperature. The heat is transferred to heat transfer fluid circulating in the tube (channels) beneath the absorber plate and in intimate contact with it. Thermal insulation prevents heat loss from the rear surface of the collector. The glass cover permits the entry of solar radiation as it is transparent for incoming short wavelengths, but is largely opaque to the longer infrared radiation reflected from the absorber. As a result, heat remains trapped in the airspace between the absorber plate and glass cover in a manner similar to the greenhouse. The glass cover prevents heat loss due to convection by keeping the air stagnant. The glass

cover may reflect 15 % of incoming solar radiation, which can be reduced by applying anti-reflective coating on the outer surface of the glass. Transparent plastics may also be used in place of glass, but they suffer from some drawbacks. Most plastics are not opaque to infrared radiation as glass. Also their transparency for incoming solar radiation decreases with time (Fig. 10.3). The life of plastic material is short when exposed to sunrays as it breaks down, and cracks are developed over a span of time.

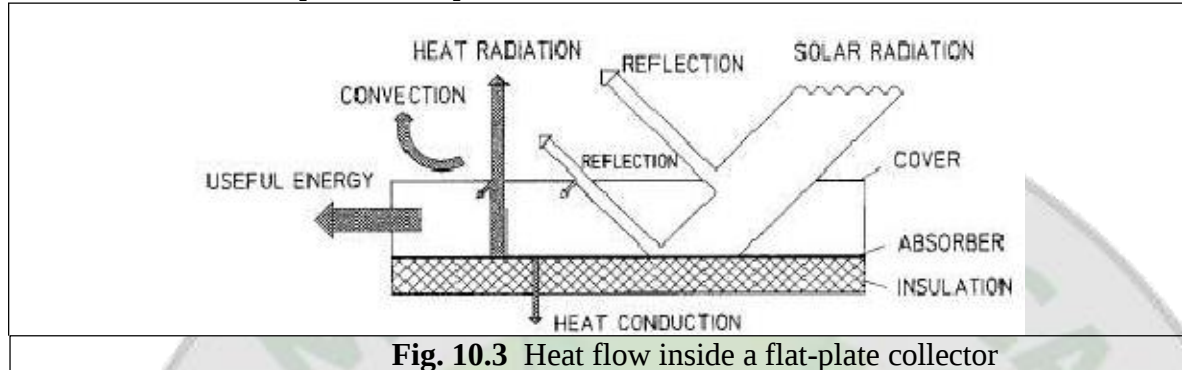


Fig. 10.3 Heat flow inside a flat-plate collector

10.1.2 Modified Flat Plate Collector

By providing plane reflectors at the edges of flat plate collector to reflect additional radiation into the receiver, the concentration of solar radiation can be increased. These mirrors are also called booster mirrors. The concentration ratio of these concentrators has a maximum value of 4. Such a design (V-trough) is aligned in East-West direction and requires periodic tilt adjustment. Different optimum depth to base width ratio and cone angles are possible depending on the frequency of seasonal tilt adjustment (Fig. 10.4).

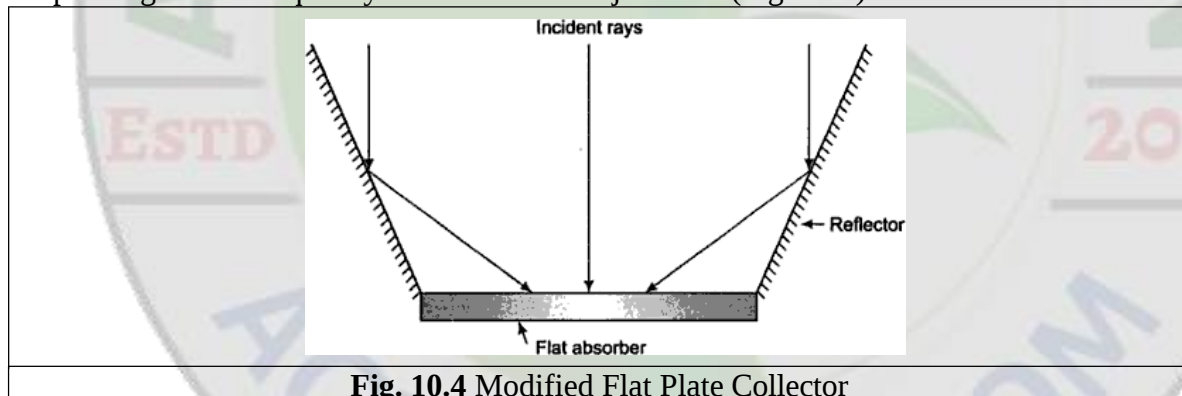


Fig. 10.4 Modified Flat Plate Collector

10.1.3 Compound Parabolic Concentrator (CPC)

Compound parabolic concentrator consists of two parabolic mirror segments, attached to a flat receiver. The segments are oriented such that the focus of one is located at the bottom end point of the other in contact with the receiver. It has a large acceptance angle and needs to be adjusted intermittently. Rays in the central region of the aperture reach the absorber directly whereas, those near the edges undergo one or more reflections before reaching the absorber. The concentration ratio achieved from this collector is in the range of 3-7 (Fig. 10.5).

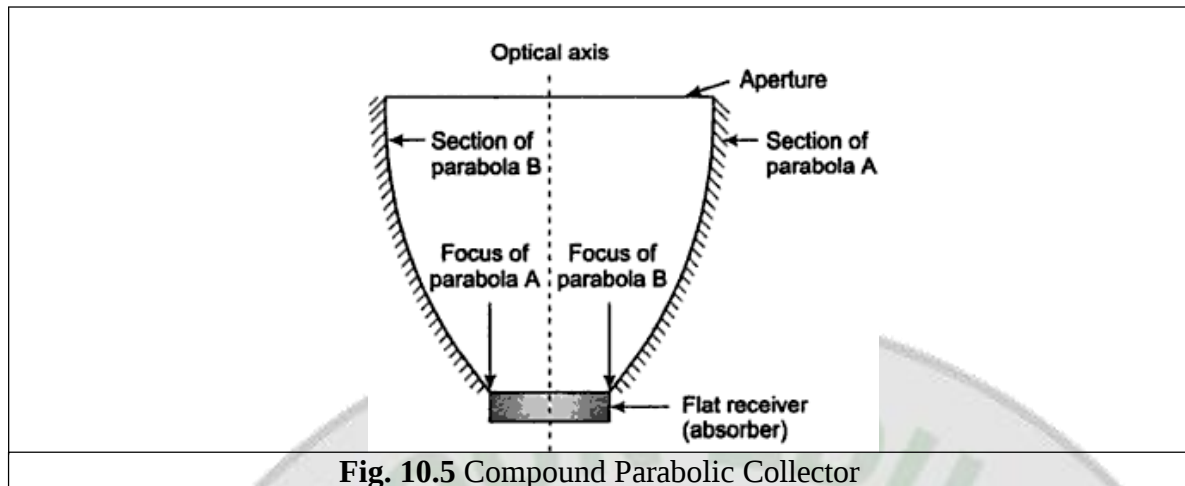


Fig. 10.5 Compound Parabolic Collector

10.1.4 Cylindrical Parabolic Concentrator

It consists of a cylindrical parabolic trough reflector and a metal tube receiver at its focal line. The receiver tube is blackened at the outside surface to increase absorption. It is rotated about own axis to track the sun. the heat transfer fluid flows through the receiver tube, carrying the thermal energy to the next stage of the system. This type of collector may be oriented in any one of the three directions: East-West, North-South or polar. The polar configuration intercepts more solar radiation per unit area as compared to other modes and thus gives best performance. The concentration ratio in the range of 5-30 may be achieved from these collectors (Fig. 10.6).

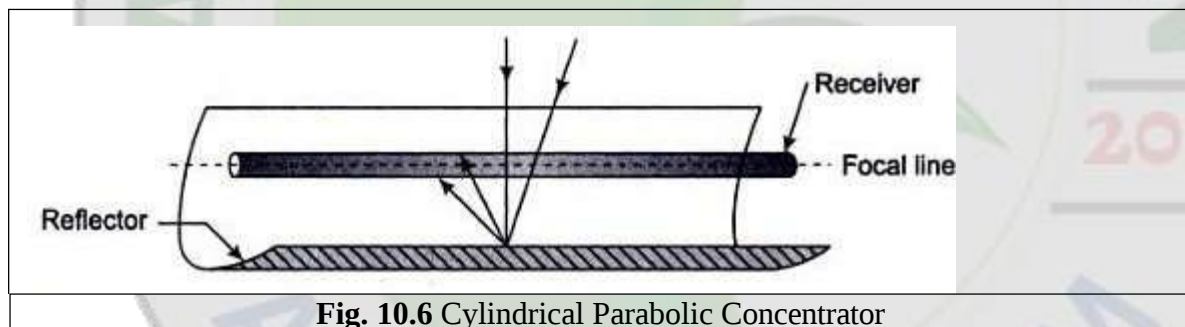


Fig. 10.6 Cylindrical Parabolic Concentrator

10.1.5 Fixed Mirror Solar Concentrator

Due to practical difficulty in manufacturing a large mirror in a single piece in cylindrical parabolic shape, long narrow mirror strips are used in this concentrator. The concentrator consists of fixed mirror strips arranged on a circular reference cylinder with a tracking receiver tube. The receiver tube is made to rotate about the center of curvature of reflector module to track the sun. the image width at the absorber is ideally the same as the projected width of a mirror element; the concentration ratio is approximately the same as the number of mirror strips (Fig. 10.7).

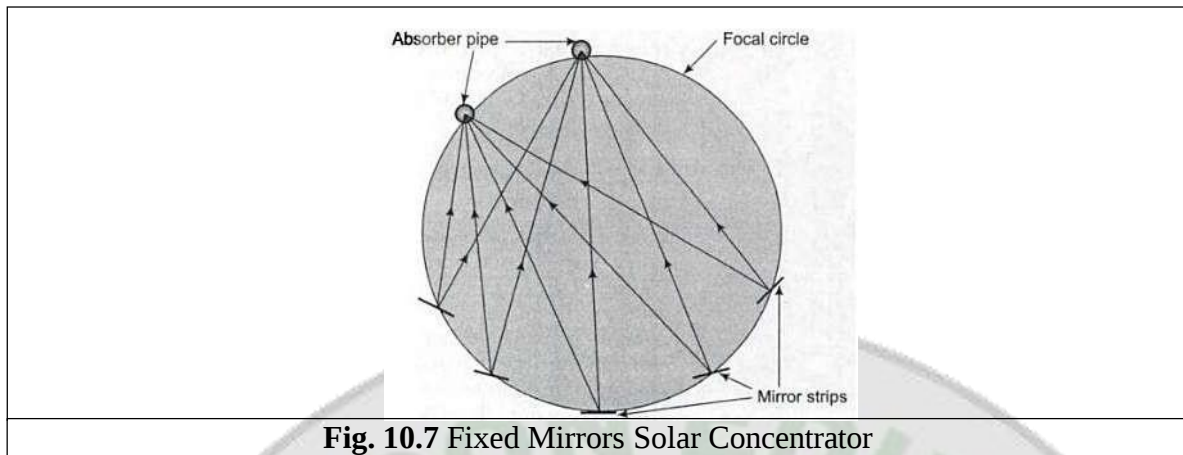


Fig. 10.7 Fixed Mirrors Solar Concentrator

10.1.6 Linear Fresnel Lens Collector

In this collector a Fresnel lens, which consists of fine, linear grooves on the surface of refracting material (generally optical quality plastic) on one side and flat on the other side, is used. The angle of each groove is designed to make the optical behavior similar to a spherical lens. The beam radiation, which is incident normally, converges on focal line, where a receiver tube is provided to absorb the radiation. A concentration ratio of 10-30 may be realized which yields temperatures between 150-300 °C (Fig. 10.8).

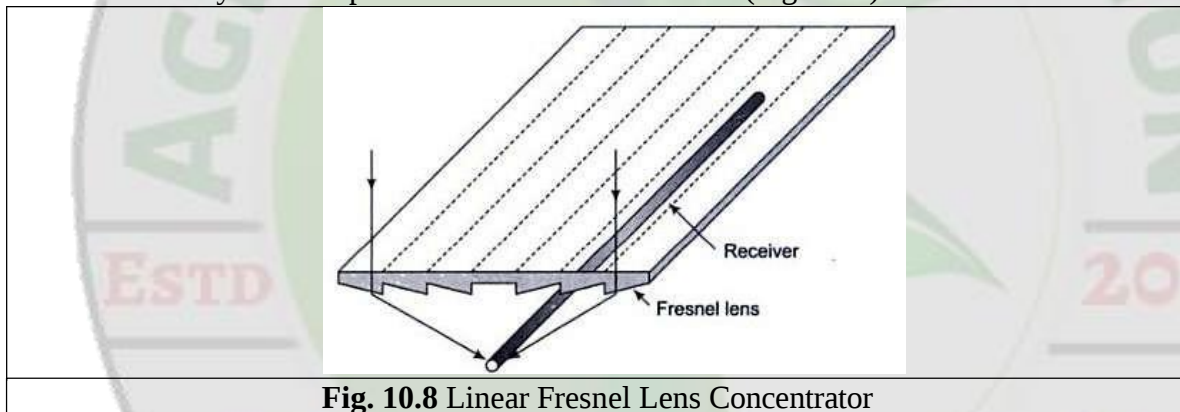


Fig. 10.8 Linear Fresnel Lens Concentrator

10.1.7 Parabolic Disc Collector

When a parabola is rotated about its optical axis a paraboloidal surface is produced. Beam radiation is focused at a point in the paraboloid. This requires two-axis tracking. It can have concentration ratio ranging from 10 to few thousands and can yield temperature up to 3000 °C. Paraboloidal dish collectors of 6-7 m in diameter are commercially manufactured (Fig. 10.9).

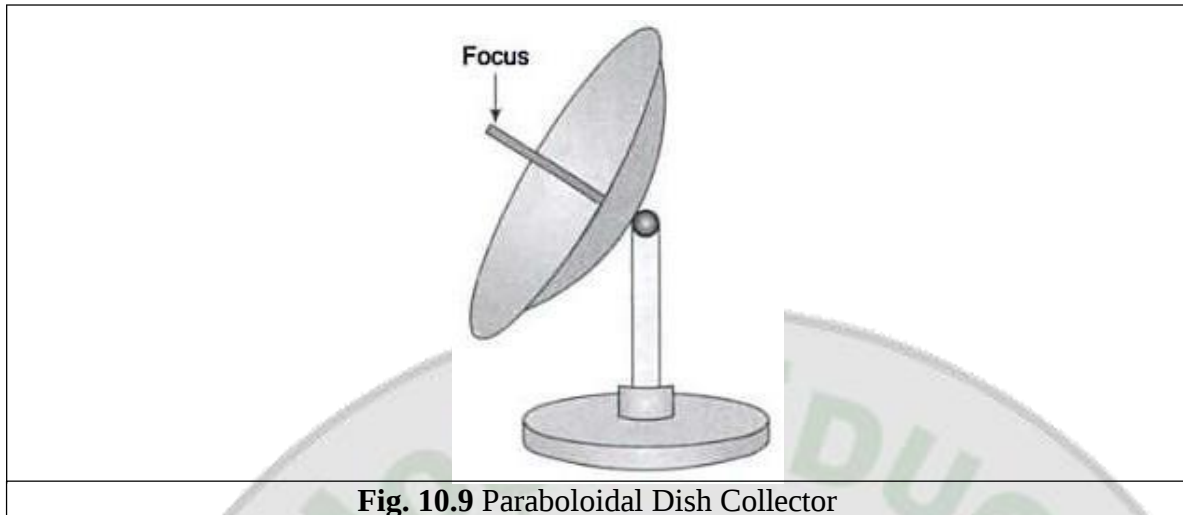


Fig. 10.9 Paraboloidal Dish Collector

10.1.8 Hemispherical Bowl Mirror Concentrator

It consists of hemispherical fixed mirror, a tracking absorber and supporting structure. All rays entering the hemisphere after reflection cross the paraxial line at some point between the focus and the mirror surface. Therefore, a linear absorber pivoted about the center of curvature of the hemisphere intercepts all reflected rays. The absorber is to be moved so that its axis is always aligned with solar rays passing through the center of the sphere. This requires two-axis tracking. The absorber is either driven around a polar axis at a constant angular speed of 15 degrees/hour or adjusted periodically during day-time. This type of concentrator gives lesser concentration, owing to spherical aberration, than that obtained in paraboloidal concentrator (Fig. 7.10).

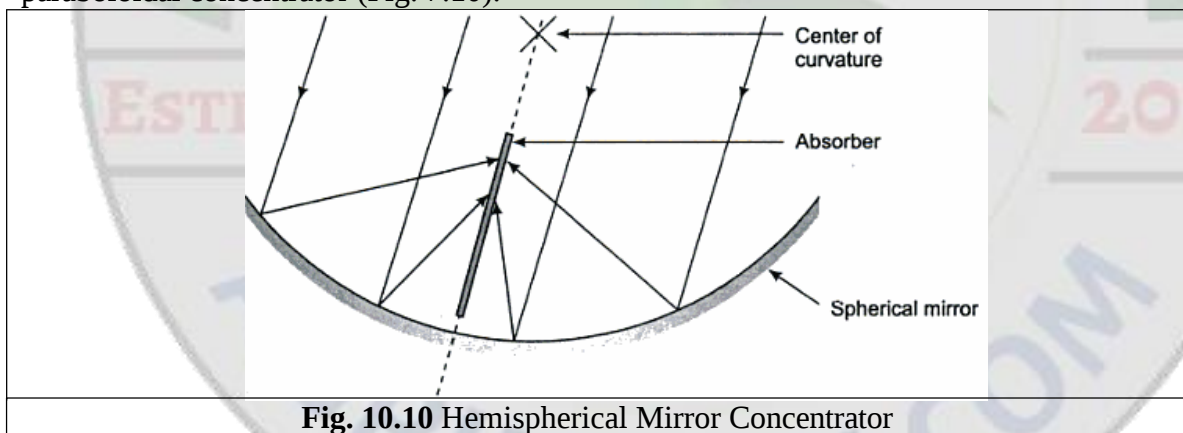


Fig. 10.10 Hemispherical Mirror Concentrator

10.1.9 Circular Fresnel Lens Concentrator

These lenses are generally used where high flux is desired, such as with silicon solar cells or with gallium arsenide solar cells as receiver. It is divided into a number of thin circular zones. The tilt of each zone is so adjusted that optically, the lens approximates a thin spherical lens. The concentration ratio may be as high as 2000, but is less than that obtained from a paraboloidal reflector. In solar cell applications, tracking is required to keep the small solar image centered on the receiver (Fig. 10.11).

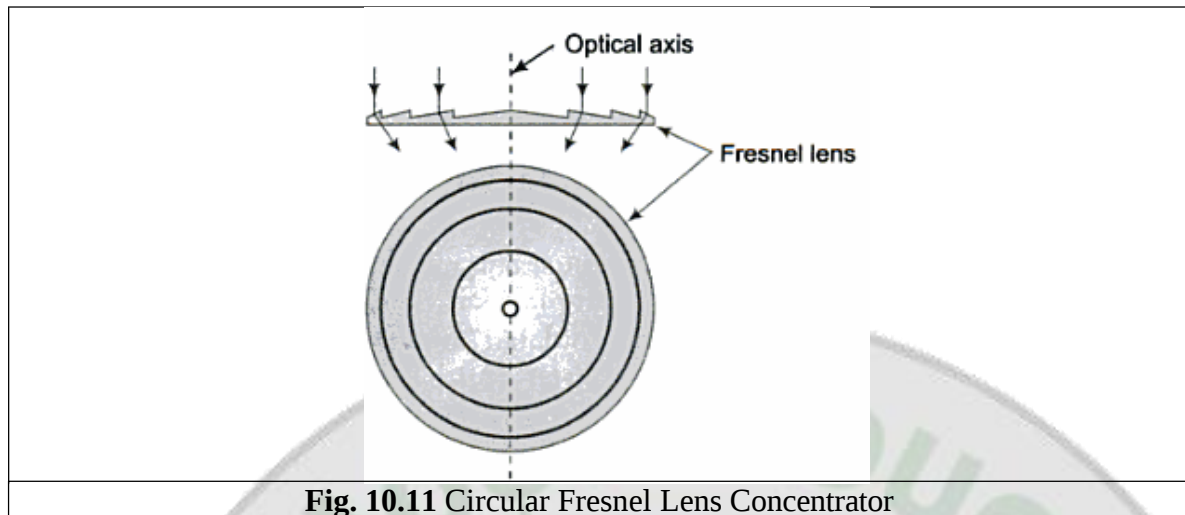


Fig. 10.11 Circular Fresnel Lens Concentrator

10.1.10 Central Tower Receiver

In central tower receiver collector, the receiver is located at the top of a tower. Beam radiation is reflected on it from a large number of independently controlled; almost flat mirrors, known as *heliostats*, spread over a large area on the ground, surrounding the tower. Thousands of such heliostats track the sun to direct the beam radiation on the receiver from all sides. The heliostats, together act like a dilute paraboloid of very big size. Concentration ratio of as high as 3000 can be obtained. The absorbed energy can be extracted from the receiver and delivered at a temperature and pressure suitable for driving turbines for power generation (Fig. 10.12).

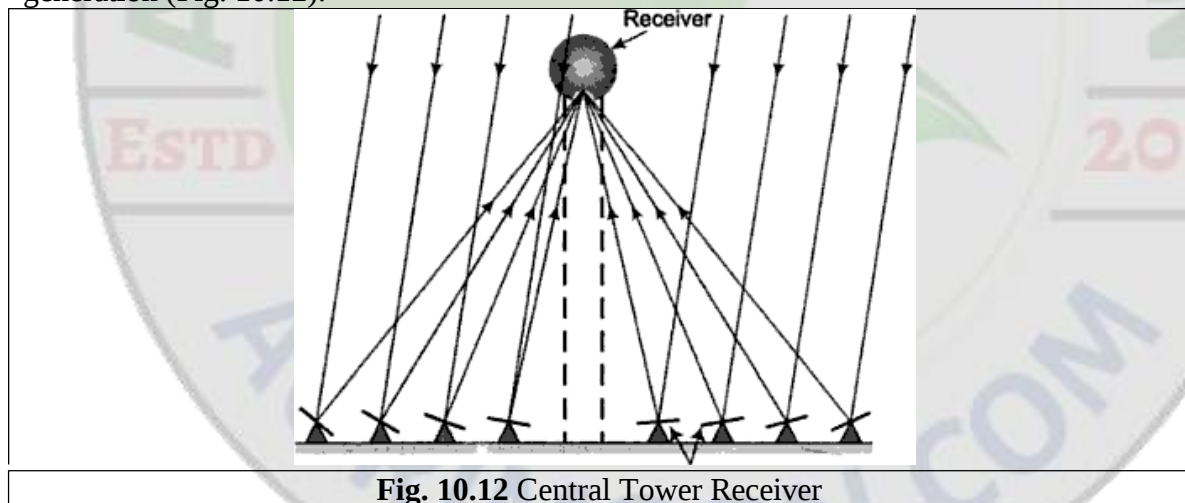


Fig. 10.12 Central Tower Receiver

Chapter 11

Applications of solar energy: solar drying, solar pond, solar distillation**11.0 Introduction:**

Solar energy reaches the earth's surface as shortwave electromagnetic radiation in the wavelength band between 0.3 and 3.0 μm ; its peak spectral sensitivity occurs at 0.48 μm . Total solar radiation intensity on a horizontal surface at sea level varies from zero at sunrise and sunset to a noon maximum which can reach 340 Btu/(ft²-h) (1,070 W/m²) on clear summer days. This inexhaustible source of energy, despite its variability in magnitude and direction, can be used in three major processes (1) **Heliothermal**, in which the sun's radiation is absorbed and converted into heat which can then be used for many purposes, such as evaporating seawater to produce salt or distilling it into potable water; heating domestic hot water supplies; house heating by warm air or hot water; cooling by absorption refrigeration; cooking; generating electricity by vapor cycles and thermoelectric processes; attaining temperatures as high as 6,500 °F (3,600 °C) in solar furnaces. (2) **Heliochemical**, in which the shorter wavelengths can cause chemical reactions, can sustain growth of plants and animals, can convert carbon dioxide to oxygen by photosynthesis, can cause degradation and fading of fabrics, plastics, and paint, can be used to detoxify toxic waste, and can increase the rate of chemical reactions. (3) **Helioelectrical**, in which part of the energy between 0.33 and 1.3 μm can be converted directly to electricity by photovoltaic cells. Silicon solar batteries have become the standard power sources for communication satellites, orbiting laboratories, and space probes.

11.1 Heat transfer for solar energy utilization

There are three heat transfer mechanisms that should be considered in any solar energy design for efficiency. For any solar radiation collector to work efficiently it is necessary to reduce the heat losses or to minimize them. As a material is heated by solar radiation, it seeks to reach equilibrium with its surroundings by conduction, convection, and radiation processes.

Conduction: This corresponds to heat transfer within a solid body where there are at least two different heat areas, *i. e.*, a temperature difference. Such a heat transfer is possible by means of vibrations of the atomic lattice which forms the body of the material. The heat is also carried away by electrons, and this contribution is much greater than that due to lattice vibration. During *conduction* there is no mass transfer. Atoms move randomly under thermal stress in liquids and gases, and they also lead to heat conduction.

Convection: This is the process by which heat from the hot surfaces is carried away by a fluid such as water. Fluid flowing across a surface is heated and then the heated volume is removed due to fluid flow with replacement by new, cold fluid. This heat transfer is referred to as *convective* cooling or heating. The rate of heat removal will depend on both the temperature difference between the surface and the bulk fluid temperature, and also on the velocity and characteristics of the fluid. Another sort of convective heat transfer can be considered for a horizontal hot plate in still air where the air adjacent to the top surface will become hotter than the bulk of the air. As a result of hot air expansion and density decrease, hot air is replaced by cooler air. In solar energy conversion both forced and natural convections may be accompanied by phase changes.

Radiation: A hot body may lose heat by radiation through emission of EM waves. The maximum power which can be radiated from a body at a given temperature is called the black body radiation corresponding to that temperature. The radiation power, P , from a black body increases as the fourth power of the absolute temperature, T , of the same body and it is given by Stefan's law as

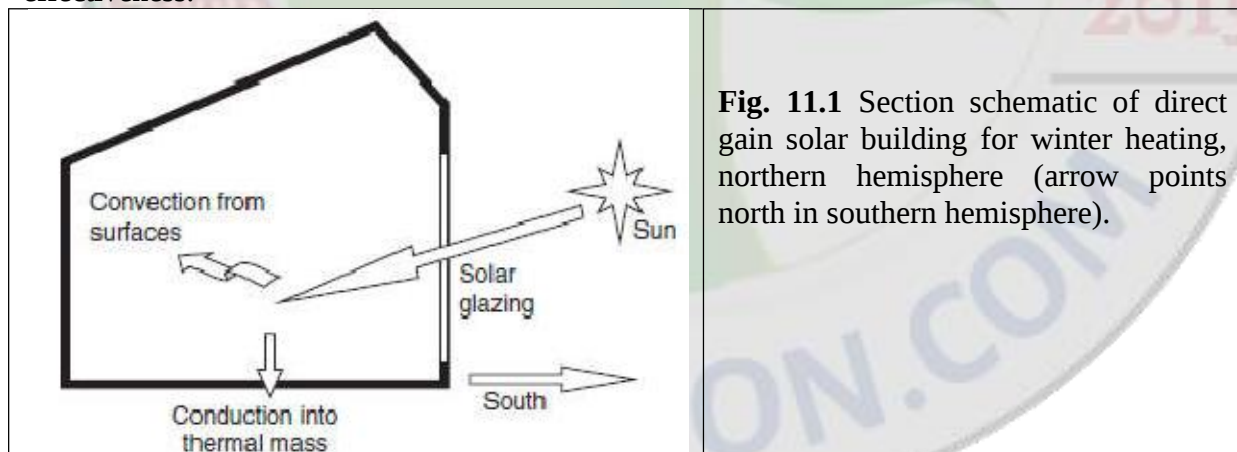
$P = \sigma T^4$, where $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ is Stefan's constant.

11.2 Types of Passive Solar Heating Systems

Passive solar space heating systems can be classified as *direct gain*, *indirect gain*, or *isolated gain*. Direct gain is based on solar radiation being absorbed within the space to be heated. Indirect gain is based on absorbing solar energy into a thermal mass for later release. Isolated gain describes situations where solar energy is absorbed to heat a separate space for later release, if desired, into the living space. Thermal mass is required to buffer large and rapid temperature swings and store heat for later, and can be water, concrete, stone, adobe, or other material with a high volumetric specific heat and high thermal conductivity.

11.2.1 Direct Gain

South-facing glass transmits insolation directly into the living space in a direct gain passive solar building, where it is absorbed. Part of the absorbed heat is released immediately to the indoor air by convection from the heated surfaces of the space. The rest moves into the thermal mass by conduction for release back to the indoors late in the day, or at night (Fig. 11.1). An advantage of a direct gain passive system is its relatively low construction cost and rapid warm-up in the morning. Disadvantages include overheating during midday, excessive light glare in the living space, and accelerated solar degradation of materials near the solar glazing (e.g., wood and fabrics). Additionally, carpets and furniture tend to prevent solar gain from reaching the thermal mass, exacerbating overheating and reducing thermal mass effectiveness.



Several practical rules are suggested when planning a direct gain solar home:

- Thermal mass elements should not be more than 15-cm (6 in) thick.
- Keep floors and the living space near the solar glazing as free of carpets and furniture as functionally and aesthetically reasonable.
- Spread thermal mass throughout the living space rather than concentrating it in one element (such as only in the floor).
- If concrete blocks are used for thermal mass (such as for walls), fill the cores with concrete.

- Use dark colors for floors and walls most directly irradiated by the sun to reduce glare.

11.2.2 Indirect Gain, Trombe Wall

The most common form of indirect gain passive solar system is the Trombe wall. Insolation is absorbed by the outer surface of the thermal mass wall. The distance between the glazing and wall is narrow (e.g., 15 cm). As the wall outer surface heats, warm air is created within the space. The heated air can move by thermal buoyancy if vent areas are provided near the floor and ceiling. Vents must be closed at night to prevent reverse siphoning of cold air into the living space, of course.

As the outer surface of the wall warms, heat conducts as a thermal wave through the mass and toward the living space side, traveling at a velocity of 2 to 3 cm h⁻¹. The wall is typically 30- to 40-cm thick so the thermal wave and, thereby, the living space surface temperature, peaks approximately 12 h after peaking at the outer surface during early afternoon. Timing is important so more heat is delivered to the living space during the night when outdoor air temperature is lowest. Heat transfers to indoor air by convection and to other surfaces within the space by thermal radiation. A warm wall, radiating to people, can compensate for an air temperature several degrees lower than normally perceived as comfortable.

Movable insulation can be deployed between the wall and glass at night (or exterior to the glass) to limit heat loss back to outdoors and keep the mass from cooling too rapidly at night. If movable insulation is installed, a system of automated control to open and close it is best to make most effective use of the system. The thermal wall, alternately, may hold water in vertical tubes with a diameter of approximately 15 cm. In such a system, if the tubes are translucent and the water is dyed, the wall can function strictly as an indirect gain system if the dye is opaque, or a combination of direct (with daylighting) and indirect passive gain when a useful portion of insolation is transmitted (e.g., 50%).

Hybrid direct gain and indirect gain passive solar systems can be integrated to create a compromise and limit the disadvantages of direct gain systems, but achieve faster warming of the living space in the morning than would be provided by an indirect gain system, as well as providing natural lighting (daylighting). Natural light is usually more acceptable for visual comfort and natural lighting uses no conventional energy. A hybrid system would have vision strips or windows placed in the Trombe wall at appropriate locations for vision and lighting. A room generally requires glazing area equal to at least 5% of its floor area for adequate vision lighting during the day. A hybrid direct/indirect gain system may require glazing to be somewhat more than 5% of the floor area to provide sufficiently rapid warm up during mornings, but not so much as to create overheating and visual glare.

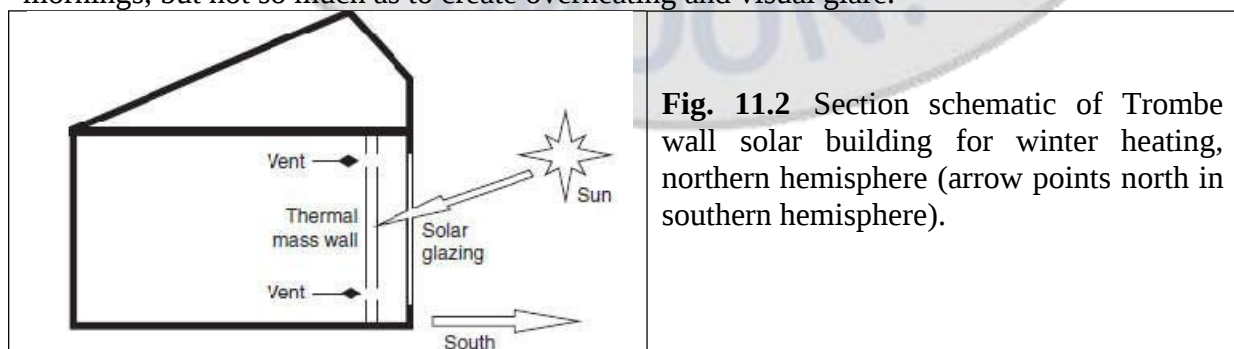


Fig. 11.2 Section schematic of Trombe wall solar building for winter heating, northern hemisphere (arrow points north in southern hemisphere).

11.2.3 Isolated Gain

A sunspace (sunroom, or solar greenhouse) combined with a convective loop to the attached house, permits isolation from solar gain when heat is not needed but gives access to solar heat during cold days. The wall between the sunspace and living space may be thermally massive to act somewhat like a Trombe wall. Although a thermally massive wall may buffer the heat from the sunspace somewhat, unless it is constructed with the thickness and volumetric heat capacity of a Trombe wall there will be less thermal wave delay than provided by a Trombe wall. If the thermal wave arrives at the living space side during the afternoon, for example, overheating and wasted energy could be the result. A sunspace can overheat on hot and sunny days and must be vented when it is used as a greenhouse as well as a means to provide solar heat. Plants are generally stressed at temperatures above 35°C. Solar greenhouses must also be heated during winter if plants are to be kept in them. Additionally, sunspaces may be sources of insects, other pests, and mildew spores that move into the living space. Plants with large leaf canopies can add a considerable amount of humidity to the air, which may be an advantage or a disadvantage. One disadvantage is that transpiration and evaporation reduce the quantity of sensible solar heat that can be collected. However, a sunspace can provide a very pleasant addition to a building for relaxation and entertainment.

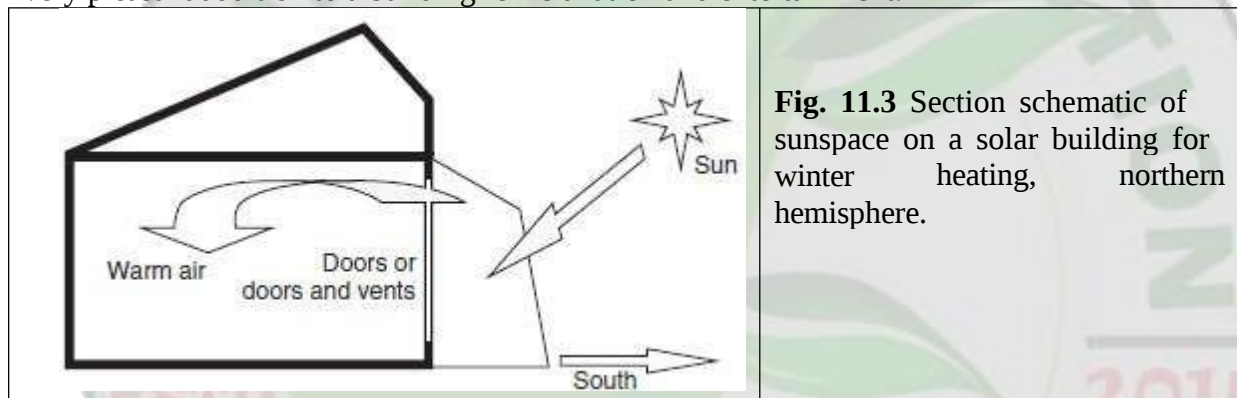


Fig. 11.3 Section schematic of sunspace on a solar building for winter heating, northern hemisphere.

Roof ponds are another isolated gain passive solar heating system. Fifteen to thirty centimeters of water is contained in a large plastic or fiberglass container on a flat roof, with the container covered with a glazing. Water within the container warms during the day and the stored heat conducts downward at night through the roof to the living space, where the major heat transfer path to occupants is thermal radiation. Movable insulation over the container is required to retain the heat at night. Conversely, operation can be reversed to permit the water to cool at night to provide a form of passive air conditioning the next day. Roof ponds require drainage systems and a structural support to support the weight of the water. Few roof ponds are in active use today. A sectional view is shown of sunspace on a solar building for winter heating, northern hemisphere in Fig. 11.3.

11.3 Solar cooking utilizes (1) a sun-following broiler-type device with a metallized parabolic reflector and a grid in the focal area where cooking pots can be placed; (2) an oven-type cooker comprising an insulated box with glass covers over an open end which is pointed toward the sun. When reflecting wings are used to increase the solar input, temperatures as high as 400 °F (204 °C) are reached at midday. Large solar cookers for community cooking in third world country villages can be floated on water and thus easily adjusted to point at the sun. For cooking when the sun does not shine, oils or other fluids can be heated to a high temperature, 800°F (around 425°C), with a solar concentrator when the sun shines, and then

stored. A range similar to an electric range but with the hot oil flowing through the coils, at adjustable rates, is then used to cook with solar energy 24 h/day.

11.4 Direct Conversion of Solar Radiation to Electricity Photovoltaic cells made from silicon, cadmium sulfide, gallium arsenide, and other semiconductors can convert solar radiation directly to electricity without the intervention of thermal cycles. Of primary importance today are the silicon solar batteries which are used in large numbers to provide power for space probes, orbiting laboratories, and communication satellites. Their extremely high cost and relatively low efficiency have thus far made them noncompetitive with conventional power sources for largescale terrestrial applications, but intensive research is currently underway to reduce their production cost and to improve their efficiency. Generation of power from solar radiation on the earth's surface encounters the inherent problems of intermittent availability and relatively low intensity. At the maximum noon intensity of 340 Btu/(ft²-h) (1,080 W/m²) and 100 percent energy conversion, 10ft² (1.1 m²) of collection area would produce 1 thermal kilowatt, but with a conversion efficiency of 10 percent, the area required for an electrical kilowatt approaches 100 ft² (9.3 m²). Thus very large collection areas are essential, regardless of what method of conversion may be employed.

11.5 Solar Crop Drying

Food is a basic need of human being along with air and water. Food holds a key position in the development of any society. The drying of food is necessary to avoid food losses between harvesting and consumption. High moisture content is one of the reasons for its spoilage during the course of storage after harvesting. Crops with high moisture content are prone to fungus infectio. Crops are attacked by insects, pests and the increased respiration of agricultural produce. To solve this problem drying of a crop with optimum moisture content is an answer. Dried crops can be used for longer periods after storage. Drying has the following advantages:

1. Facilitates early harvest
2. Permits planning the harvest season
3. Helps in long-term storage
4. Helps farmers to achieve better returns
5. Helps farmers to sell a better quality product
6. Reduces the requirement of storage space
7. Helps in handling, transport and distribution of crops, and
8. Permits maintaining viability of seeds.

Probably the largest use of solar energy over the centuries—the drying of agricultural crops, evaporation of ocean and salt lake ponds for salt production, etc.—has led more recently to more efficient dryers. The newer dryers prevent rain and dew from rewetting the materials. Simple inexpensive solar dryers—essentially transparent covers—sometimes are supplemented by air heaters providing hot air to dry crops, fish, etc., especially in tropical regions where daily rains prevent efficient natural drying

11.6 Solar Distillation

The supply of potable water is a major problem in underdeveloped as well as some developing countries due to pollution developed in underground water due to various human activities. It has caused a scarcity of fresh water in many towns and villages near lakes and

rivers. Along with food and air, good quality water is a basic necessity for man. Man has been dependent on rivers, lakes and underground water reservoirs for fresh water. Survey show that about 79 % of water available on the Earth is salty, only 1 % fresh. The remaining 20 % is brackish.

Distillation of brackish/saline water is a good method to obtain fresh water (potable water). However, the conventional distillation processes such as multieffect evaporation, multistage fresh evaporation, thin-film distillation, reverse osmosis and electrodialysis are energy intensive techniques. Therefore, solar distillation is an attractive alternative due to its simple technology and nonrequirement of highly skilled labour for maintenance work and low energy consumption. As such, it can be used at any place without much problem.

Covering swimming pools, ponds, or basins with airtight covers (glass or plastic) will condense the water vapors on the underside of the covers. The condensate produced by the solar energy can be collected in troughs as distilled water. Deep-basin stills have a water depth of several feet (between approximately 0.5 and 1.5 m) and require renewal only every few months. Shallow-basin stills have a water depth of about 0.5 to 2.0 in (approximately 1 to 5 cm) and have to be fed and flushed out frequently. The glass-covered roof-type solar still is in wide use in arid areas for the production of drinking water from salty or brackish sources. The sun's rays enter through the cover glasses, warm the water, and thus produce vapor which condenses on the inner surface of the cover. Daily yield ranges from 0.4 lb/ft² (2kg/m²) of water surface in winter to 1.0 lb/ft² (5 kg/m²) in summer.

Inflated plastic films have also been used to cover solar stills, but their greatest success has been achieved in controlled environment greenhouses where the vapor which transpires from plant leaves is condensed and reused at the plant roots. Stills made of inflatable plastic also are equipment in survival kits, on lifeboats, etc.

11.7 Solar Air Heater

The heat absorbed by the absorber plate is transmitted to the air drawn into the collector. The hot air leaves the collector to a storage tank for further use. If the size of collector is large, a blower is used to draw air into the collector and transmit the hot air to dryer. The most favorable orientation, of a collector, for heating only, is due south at an inclination angle to the horizontal equal to the latitude plus 15° (Fig. 11.4).

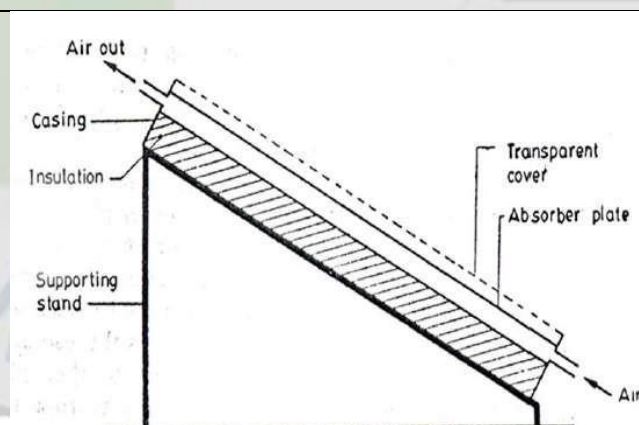


Fig. 11.4 Schematic diagram of solar air heater

11.8 Solar water heater

A tilted flat plate solar collector with water as heat transfer fluid is used. A thermally insulated hot water storage tank is mounted above the collector. The heated water of collector

risers up to the hot water tank and replaces an equal quantity of cold water, which enters the collector. The cycle repeats, resulting in all the water of the hot water tank getting heated up. When hot water is taken out from hot water outlet, the same is replaced by cold water from cold-water make up tank, fixed above the hot water tank (Fig. 11.5).

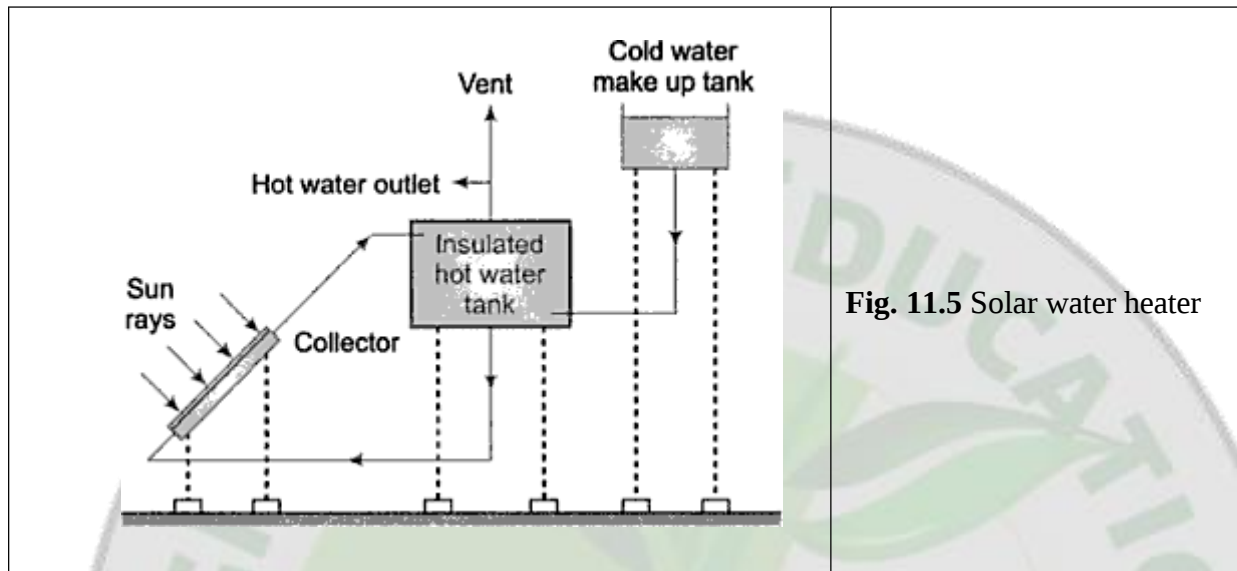


Fig. 11.5 Solar water heater

The scheme is known as passive heating scheme, as water is circulated in the loop naturally due to thermo siphon action. When the collector is fixed above the level of hot water tank, a pump is required to induce circulation of water in the loop and the scheme will be known as active (or forced) solar thermal system. An auxiliary electrical emersion heater may be used as back up for use during cloudy days. In average Indian conditions, solar water heater can be used for about 300 days in a year. A typical 100 liters per day (LPD) rooftop, solar water heater costs approximately Rs. 13,000-15,000 and delivers water at 60-80 °C. it has a life span of 10-12 years and payback period of 2-6 years.

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

These can be the pan (batch) type—a tank or basin with transparent cover—or tube collector type, described previously. Under favorable climatic conditions(abundant sunshine and moderate winter temperatures) they can produce 30 to 50 gal (110 to 190 L) of water at temperatures up to 160°F (70°C) in summer and 120°F (50°C) in winter. Auxiliary electric heaters are often used to produce higher temperatures during unfavorable winter weather.

In the United States and Europe, solar collectors are usually placed on the roof, with the hot water storage tank lower. This requires a small circulating pump. The pump is controlled by a timer, a temperature sensor in the collector, or a differential temperature controller. Ideally, the pump runs when heat can be added to the water in the tank. To protect the system from freezing, the collectors are drained, manually or automatically. The system can also be designed with a primary circuit containing antifreeze and effecting heat transfer with a heat exchanger in the tank, or by use of a double-walled tank. Another method for protection is a dual system, in which the water drains from the collectors when the pump stops. This is the

preferred method for large systems. Auxiliary heaters, usually electric, are used often in solar water heaters to handle overloads and unusually bad weather conditions.

11.9 Solar Furnaces Precise paraboloid concentrators can focus the sun's rays upon small areas, and if suitable receivers are used, temperatures up to 6,500°F (3,600°C) can be attained. The concentrator must be able to follow the sun, either through movement of the paraboloidal reflector itself or by the use of a heliostat which tracks the sun and reflects the rays along a horizontal or vertical axis into the concentrator. This pure, noncontaminating heat can be used to produce highly purified materials through zone refining, in a vacuum or controlled atmosphere. This allows us to grow crystals of high-temperature materials, crystals not existing in nature, or to do simple things such as determining the melting points of exotic materials. Other methods of heating contaminate these materials before they melt. With solar energy the materials can be sealed in a glass or plastic bulb, and the solar energy can be concentrated through the glass or plastic onto the target. The glass or plastic is not heated appreciably since the energy is not highly concentrated when it passes through it. Solar furnaces are used in high-temperature research, can simulate the effects of nuclear blasts on materials, and at the largest solar furnace in the world (France) produce considerable quantities of highly purified materials for industry.

11.10 Solar Ponds If water in ponds or reservoirs contains salts in solution, the warmer layers will have higher concentrations and, being heavier, will sink to the bottom. The hot water on the bottom is insulated against heat losses by the cooler layers above. Heat can be extracted from these ponds for power generation. Solar ponds are, effectively, large inexpensive solar collectors. Their heat can be used to power vapor engines and turbines; these, in turn, drive electric generators.

Chapter 12

Photovoltaic System and their application

12.0 Introduction: A photovoltaic (PV) cell converts sunlight into electricity, which is the physical process known as photoelectric effect. Light, which shines on a PV cell, may be reflected, absorbed, or passed through; however, only absorbed light generates electricity. The energy of absorbed light is transferred to electrons in the atoms of the PV cell. With their newfound energy, these electrons escape from their normal positions in the atoms of semiconductor PV material and become part of the electrical flow, or current, in an electrical circuit. A special electrical property of the PV cell, called “built-in electric field,” provides the force or voltage required to drive the current through an external “load” such as a light bulb. To induce the built-in electric field within a PV cell, two layers of different semiconductor materials are placed in contact with each other. One layer is an “n-type” semiconductor with an abundance of electrons, which have a negative electrical charge. The other layer is a “p-type” semiconductor with an abundance of “holes,” which have a positive electrical charge.

Although both materials are electrically neutral, n-type silicon has excess electrons and p-type silicon has excess holes. Sandwiching these together creates a p/n junction at their interface, thereby creating an electric field. Fig. 12.1 shows the p–n junction of a PV cell. When n-type and p-type silicon come into contact, excess electrons move from the n-type side to the p-type side. The result is the buildup of positive charge along the n-type side of the interface and of negative charge along the p-type side.

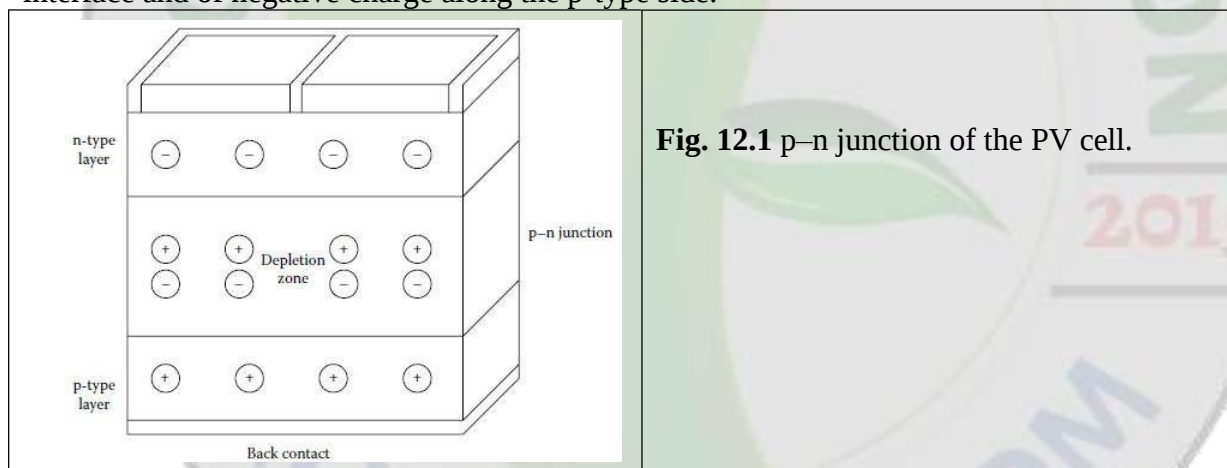


Fig. 12.1 p–n junction of the PV cell.

The two semiconductors behave like a battery, creating an electric field at the surface where they meet, called the p/n junction. This is a result of the flow of electrons and holes. The electrical field forces the electrons to move from the semiconductor toward the negative surface to carry current. At the same time, the holes move in the opposite direction, toward the positive surface, where they wait for incoming electrons [8].

Additional structures and components are required to convert the direct current (DC) to alternate current (AC). Some systems also store some electricity, usually in batteries, for future use. All these items are referred to as the “balance of system” (BOS) components. Combining modules with the BOS components creates an entire PV system. This system is usually all that is needed to meet a particular energy demand, such as powering a water pump, or the appliances and lights in a home. In Fig. 12.2, a single cell, a module consisting of cells, and an array consisting of modules are presented.

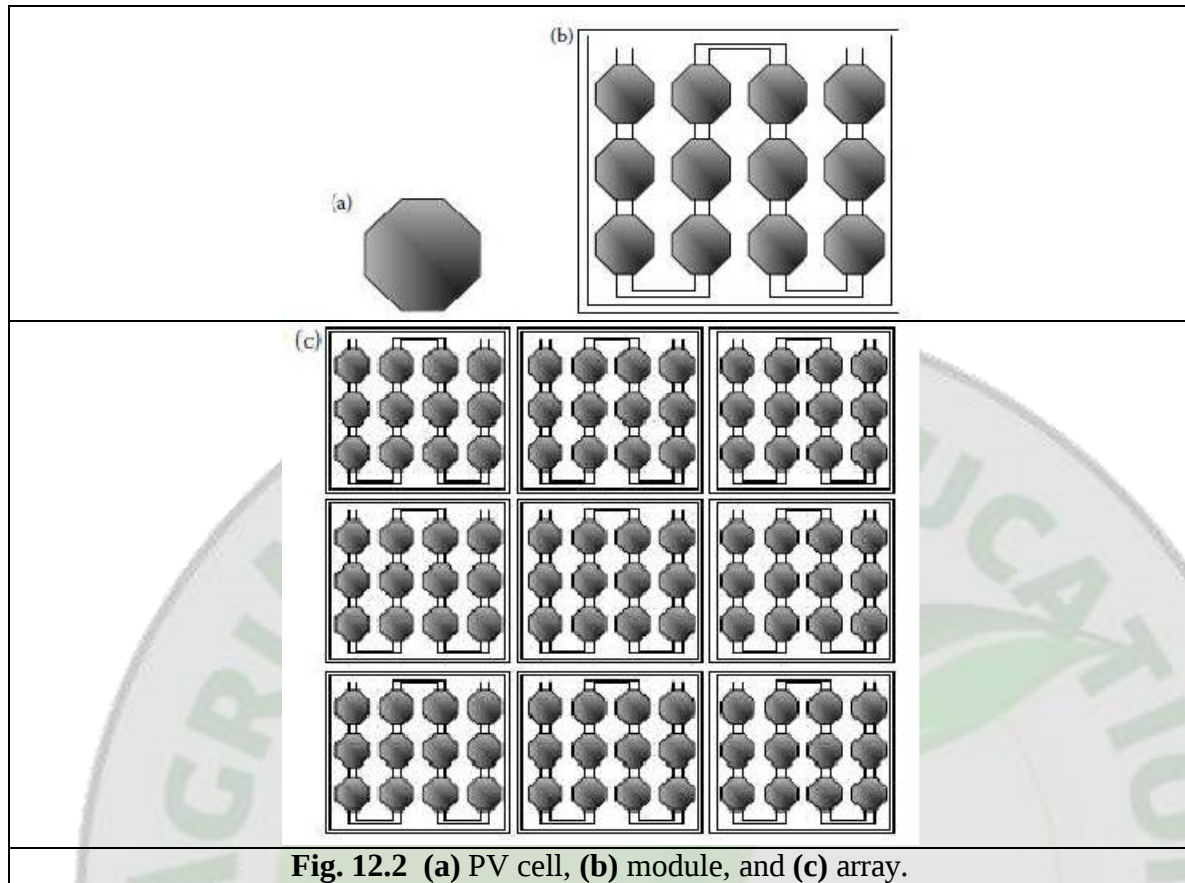


Fig. 12.2 (a) PV cell, (b) module, and (c) array.

A PV or solar cell is the basic building block of a PV(or solar electric) system. An individual PV cell is usually quite small, typically producing about 1 or 2W of power. To boost the power output of PV cells, they have to be connected together to form larger units called modules. The modules, in turn, can be connected to form larger units called arrays, which can be interconnected to produce more power. By connecting the cells or modules in series, the output voltage can be increased. On the other hand, the output current can reach higher values by connecting the cells or modules in parallel.

Based on the sunlight collection method, PV systems can be classified into two general categories: flat-plate systems and concentrator systems. Flat panel PV systems directly capture the sunlight or they use the diffused sunlight from the environment. They can be fixed or combined with sun tracking systems. On the other hand, concentrator systems collect a large amount of sunlight and concentrate and focus the sunlight to target PV panels using lenses and reflectors. These systems reduce the size and required number of cells while the power output is increased. Moreover, by concentrating the solar light, the efficiency of the PV cell is increased.

12.1 Semiconductor Materials for PV Cells

PV devices can be made from various types of semiconductor materials, deposited or arranged in various structures .

The three main types of materials used for solar cells are silicon, polycrystalline thin films, and single-crystalline thin film. The first type is silicon, which can be used in various forms, including single crystalline, multicrystalline, and amorphous. The second type is polycrystalline thin films, with a specific discussion of copper indium diselenide (CIS),

cadmium telluride (CdTe), and thin-film silicon. Finally, the third type of material is single-crystalline thin film, focusing especially on cells made from gallium arsenide (GaAs).

- *Silicon (Si)*—including single-crystalline Si, multicrystalline Si, and amorphous Si. Silicon, used to make some of the earliest PV devices, is still the most popular material for solar cells. Outranked only by oxygen, silicon is also the second-most abundant element in the earth's crust. However, to be useful as a semiconductor material in solar cells, silicon must be refined to a purity of 99.9999%. In single-crystal silicon, the molecular structure, which is the arrangement of atoms in the material, is uniform, because the entire structure is grown from the same crystal. This uniformity is ideal for transferring electrons efficiently through the material. To make an effective PV cell, silicon has to be “doped” with other elements to make it n-type or p-type. Semicrystalline silicon, in contrast, consists of several smaller crystals or grains, which introduce boundaries. These boundaries impede the flow of electrons and encourage them to recombine with holes to reduce the power output of the solar cell. Semicrystalline silicon is much less expensive to produce than singlecrystalline silicon. Hence researchers are working on other methods to minimize the effects of grain boundaries.

- *Polycrystalline thin films*—including CIS, CdTe, and thin-film silicon. Another scientific discovery of the computer semiconductor industry, which vitally impacted the PV industry, is thin-film technology. The “thin-film” term comes from the method used to deposit the film, not from the thinness of the film: thin-film cells are deposited in very thin, consecutive layers of atoms, molecules, or ions. Thin-film cells have many advantages over their “thick-film” counterparts. For example, they use much less material—the cell's active area is usually only 1–10 μm thick, whereas thick films are typically 100–300 μm thick. Thin-film cells can usually be manufactured in a large-area process, which can be an automated, continuous production process. Finally, they can be deposited on flexible substrate materials.

- *Single-crystalline thin films*—including high-efficiency material such as GaAs. GaAs is a compound semiconductor: a mixture of two elements, gallium and arsenic. Gallium is a by-product of the smelting of other metals, notably aluminum and zinc, and it is rarer than gold. Arsenic is not rare, but it is poisonous [15]. GaAs was developed for use in solar cells at about the same time that it was developed for light-emitting diodes, lasers, and other electronic devices that use light. GaAs is especially suitable for use in multijunction and high-efficiency solar cells for the following reasons:

- The GaAs band gap is 1.43V, nearly ideal for single-junction solar cells.
- GaAs has a very high absorptivity so that a cell requires only a few micrometers thickness to absorb sunlight (crystalline silicon requires a 100 μm or thicker layer).
- Unlike silicon cells, GaAs cells are relatively insensitive to heat. Cell temperatures can often be quite high, especially in concentrator applications.
- Alloys made from GaAs and aluminum, phosphorus, antimony, or indium have characteristics that are complementary to those of GaAs, allowing great flexibility in cell design.

- GaAs is highly resistant to radiation damage. This, along with its high efficiency, makes GaAs desirable for space applications.

One of the most important advantages of GaAs and its alloys as PV cell materials is that it is amenable to a wide range of designs. A cell with a GaAs base can have several layers of

slightly different compositions; this allows a cell designer to precisely control the generation and collection of electrons and holes.

This degree of control allows cell designers to push efficiencies closer and closer to theoretical levels. For example, one of the most common GaAs cell structures has a very thin window layer made of aluminum GaAs. This thin layer allows electrons and holes to be created close to the electric field at the junction.

12.2 Active and Passive Solar Energy Systems

Solar energy systems are typically classified into two systems: passive and active systems.

Passive solar energy systems do not involve panel systems or other moving mechanisms to produce energy. Passive systems utilize nonmechanical techniques to control the amount of captured sunlight and distribute this energy into useful forms such as heating, lighting, cooling, and ventilation. These techniques include selecting materials with favorable thermal properties to absorb and retain energy, designing spaces that naturally circulate air to transfer energy, and referencing the position of a building to the sun to enhance energy capture. In some cases passive solar devices can be composed of moving parts, with the distinction that this movement is automatic and directly powered by the sun. These systems can be used for heating and lighting purposes. This means that solar power is used for powering the movement of the sun tracking system as well as heating and lighting.

Active solar energy systems typically involve electrical and mechanical components such as tracking mechanisms, pumps, and fans to capture sunlight and process it into usable forms such as heating, lighting, and electricity. The panels are oriented to maximize exposure to the sun. Depending on the system, the panels will then convert sunlight into electricity, which is then transformed from DC electricity to AC electricity and stored in batteries or fed into the local utility grid. Active systems are more expensive and complex.

12.3 Components of a Solar Energy System

Fig. 12.3 demonstrates the block diagram of a solar energy system. In this system, sunlight is captured by the PV array. The sun tracking system takes the photodiode or photosensor signals and determines the sun tracking motor positions. Therefore, daily and seasonal solar position changes are followed in order to face the sun directly and capture the most available sunlight. The output of the PV panel is connected to a DC/DC converter to operate at the desired current or voltage to match the maximum available power from the PV module.

This MPPT DC/DC converter is followed by a DC/AC inverter for grid connection or to supply power to the AC loads. A battery pack can be connected to the DC bus of the system to provide extra power that might not be available from the PV module during night and cloudy periods. The battery pack can also store energy when the PV module generates more power than that demanded.

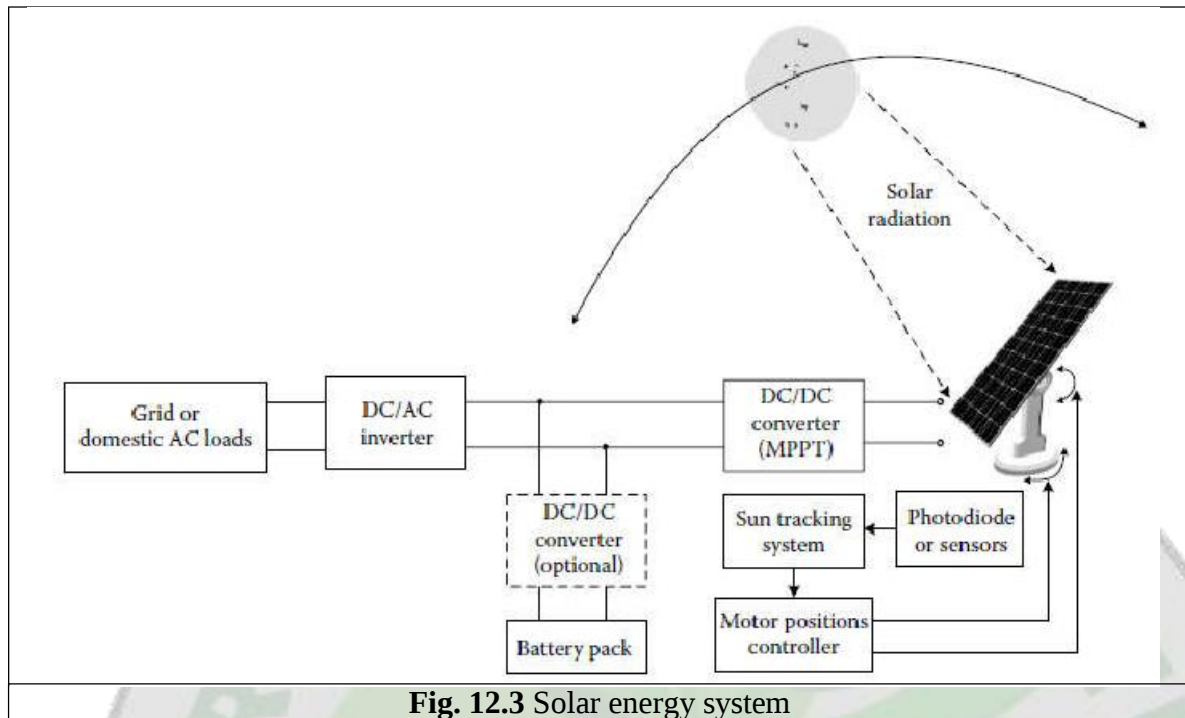


Fig. 12.3 Solar energy system

A solar energy system consists of several components, as shown in Fig. 9.3. Several PV modules are connected in series or in parallel, depending on the voltage and energy requirements of the PV array. The direction of the PV arrays toward the sun might be controlled by the position motors allowing the motion of the panels horizontally and/or vertically. The sun tracking system takes the data from sun sensors or photodiodes and processes the data to determine the motor positions for the best illumination position of the PV array directed to the sun. This position detection and adjustment is similar to a mechanical power point tracking technique. On the other hand, due to the voltage–current and current–power characteristics of the PV array, the electrical maximum power point (MPP) may vary based on operating current and voltage. Therefore, an electrical maximum power point tracking (MPPT) system is needed to operate the PV array at the MPP. This can be done through a DC/DC converter.

Due to the possible mismatches of the power generated by the PV array and the power requirements of the load, a battery pack might be used in order to compensate for these mismatches. This battery pack can be used as the energy buffer to store energy when the available power from the PV array is more than the required power. Contrarily, the battery pack can be discharged in order to satisfy the sustained load demands during periods when the solar energy is less than the required load power. The battery can be connected in various topologies. Each topology might have advantages and disadvantages in terms of number of required parts, control complexity, flexibility, battery size, and cost. Finally, the DC bus power should be converted to AC power for grid connection or for satisfying the power requirements of domestic AC loads in stand-alone applications. A grid connection is also useful to draw/inject power from/to the utility network to take advantage of the excess power or to recharge the batteries using grid power during the peak-off periods of the utility network.

12.4 Photovoltaic Effect

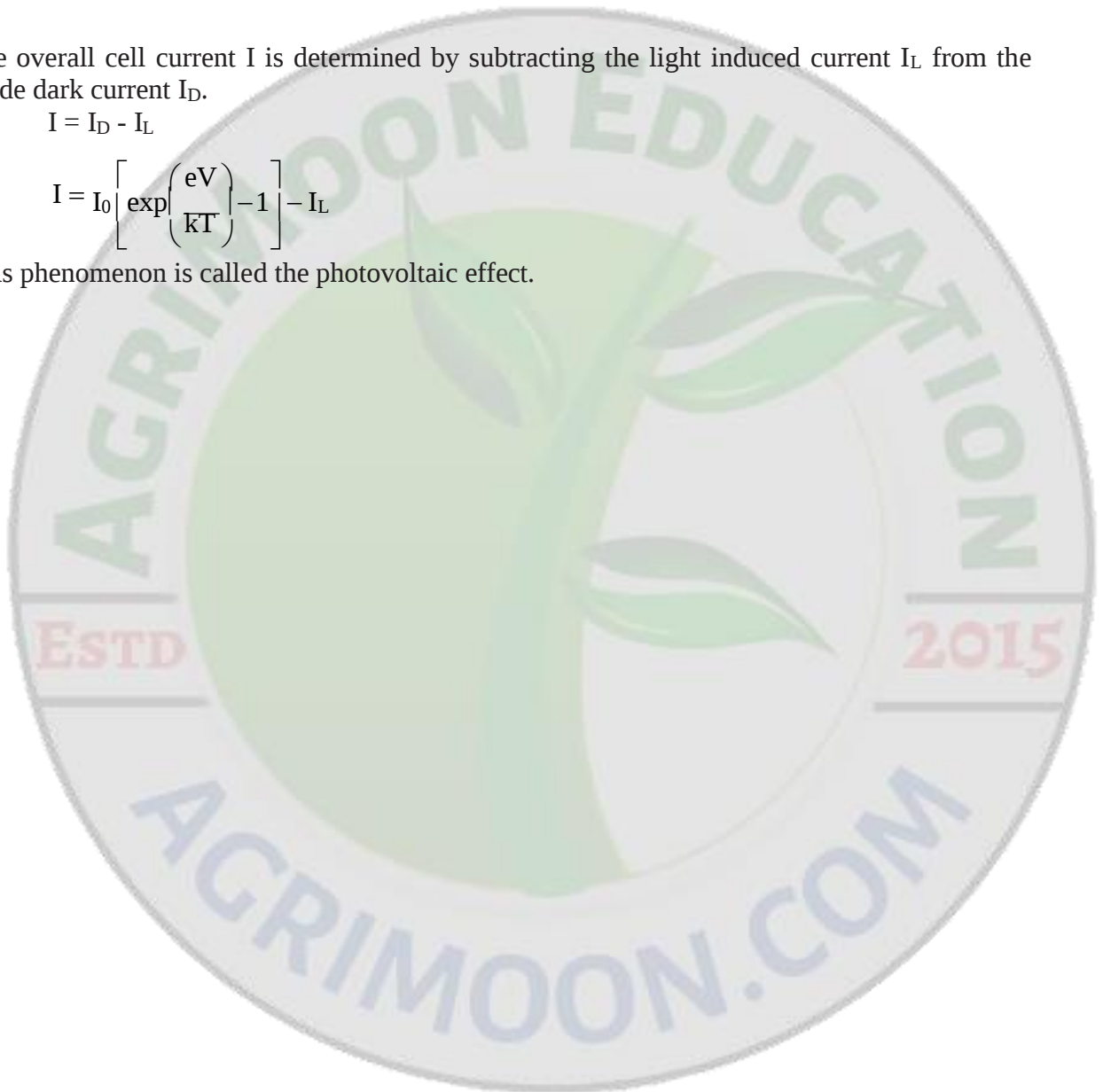
When the solar cell (p-n junction) is illuminated, electron–hole pairs are generated, and acted upon by the internal electric fields, resulting in a photocurrent (I_L). The generated photocurrent flows in a direction opposite to the forward dark current. Even in the absence of an external applied voltage, this photocurrent continues to flow, and is measured as the short-circuit current (I_{sc}). This current depends linearly on the light intensity, because absorption of more light results in additional electrons to flow in the internal electric field force.

The overall cell current I is determined by subtracting the light induced current I_L from the diode dark current I_D .

$$I = I_D - I_L$$

$$I = I_0 \left[\exp \left(\frac{eV}{kT} \right) - 1 \right] - I_L$$

This phenomenon is called the photovoltaic effect.



Chapter 13 Application of Solar Photovoltaic System

With the ever-increasing demand for energy, the search for alternative energy sources has increased. The worldwide use of fossil fuels has led to the critical situation of global warming, significantly affecting our health, environment and climate. Extensive emphasis has been put on the implementation of renewable energy sources. Solar energy is by far the most abundant form of renewable energy and has the potential to partially replace fossil fuels. The amount of solar radiation striking our earth's surface is about ten thousand times higher than the current global electrical energy consumption. Photovoltaic (PV) cells is one of the way to harness solar energy. PV cells convert sunlight directly to electricity and can be influential in meeting the world's energy demand. PV systems are being used in a variety of applications. These applications may be grouped into two categories: “**utility interactive systems**” and “**stand-alone systems**”.

Utility Interactive Applications:

In utility interactive (or grid-connected) PV systems, PV modules are connected to inverters that convert the DC produced by the PV modules to AC. This electricity can then power household appliances or can be sold directly to the grid. As a building receives this energy, it is distributed to appliances and lighting, or other devices where needed. Since PV systems are restricted to function only exposed to the sun, a backup system is frequently required to ensure continuous supply of electricity irrespective of the weather conditions. These systems are most commonly used in houses or commercial buildings to offset electricity cost. A well designed PV system with a proper storage facility can be an attractive prospect for displacing power during the peak hours (Fig. 13.1).

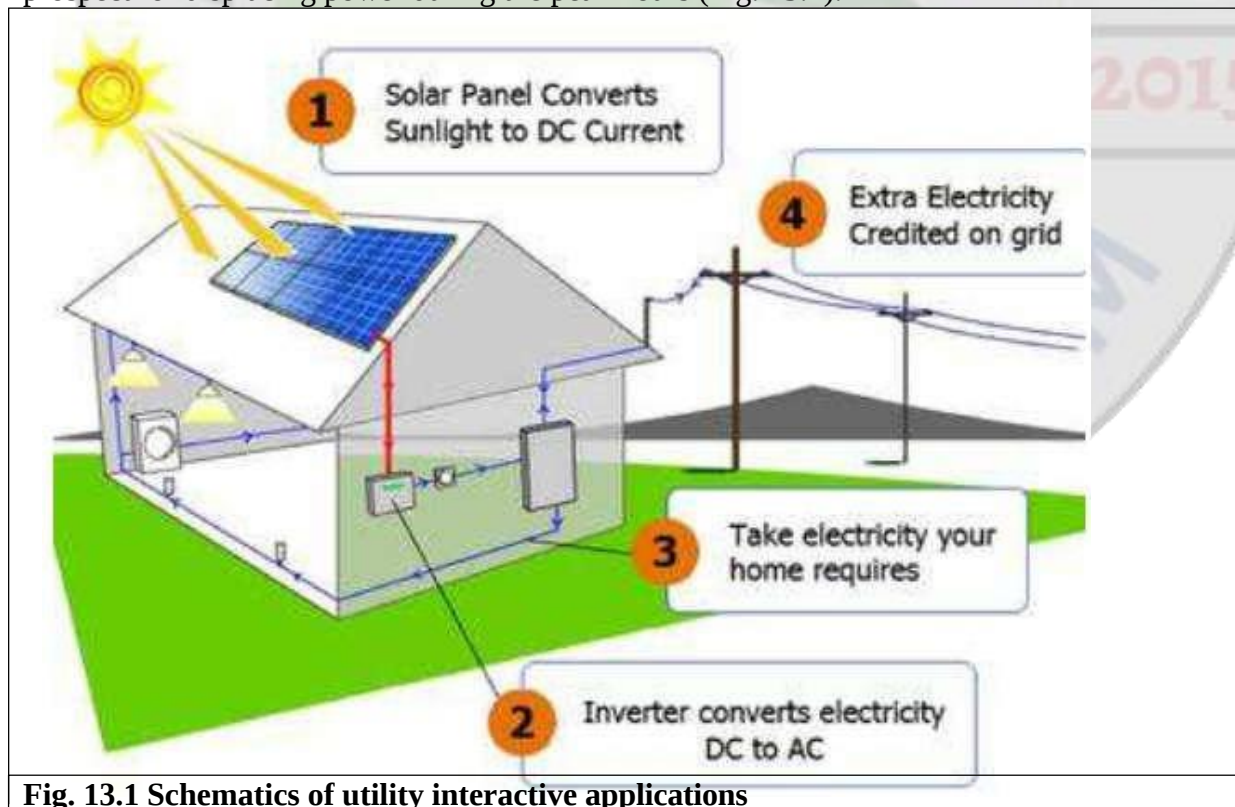


Fig. 13.1 Schematics of utility interactive applications

The schematic above shows a typical photovoltaic panel system, on the roof of a house. This system allows the owner to sell generated electricity to the National Grid, effectively lowering the house owners' electricity bills.

Stand-Alone Systems

Stand-alone systems directly use the generated produced electricity. Stand-alone systems do not rely on utility/grid connections. When the requirement arises during night time or poor sunlight, a battery storage system is used. In some situations, stand-alone systems use conventional generators as backup systems. There are numerous applications of stand-alone PV systems, some of which are mentioned below.

13.1 Lighting:

With the invention of LED (light emitting diode) technology as low power lighting sources, PV systems find an ideal application in remote or mobile lighting systems. PV systems combined with battery storage facilities are mostly used to provide lighting for billboards, highway in formation signs, public-use facilities, parking lots, vacation cabins, lighting for trains.

13.2 Communications:

Signals required by communication systems need amplification after particular distance intervals. Various relay towers are stationed to boost radio, television, and phone signals. High grounds are mostly favoured as the sites for repeater stations. These sites are generally far from power lines. To reduce the difficulty and cost associated with generators, PV systems are being installed as a viable alternative.

13.3 Electricity for remote areas:

Some areas are quite far from the distribution network to establish connection with the grid. Areas under construction also need power supply before they are connected. PV systems are an attractive option for these cases. Furthermore, PV systems can be backed up by conventional generators to provide uninterrupted supply.

13.4 Disaster Relief:

Natural calamities often bring about an electricity crisis. As the disasters such as hurricanes, floods, tornadoes, and earthquakes destroy electricity generation and distribution systems. In situations like these, where power will be out for an extended period, portable PV systems can provide temporary solutions for light, communication, food and water systems. Emergency health clinics opt for PV based electricity over conventional systems in lieu to problems of fuel transport and pollution.

13.5 Scientific experiments:

In various cases, scientific experiments are set up in areas far from power supply. PV systems can be effectively used to carry out scientific activities in remote areas. Systems monitoring seismic activities, highway conditions, meteorological information and other research activities can be powered by PV systems.

13.6 Signal Systems:

Navigational systems, such as light houses, highway and aircraft warning signals can be far from the electric grid. PV systems can be a reliable power source for these important applications. Even portable traffic lights can be powered by PV systems.

13.7 Water Pumping:

PV is a perfect candidate for agricultural and livestock purposes due to the need for water during the periods with bright sunshine. These pumping systems can supply water directly to fields, or can store water for the time of need. These systems can even be used to provide water to remote areas and villages (Fig. 13.2-3).

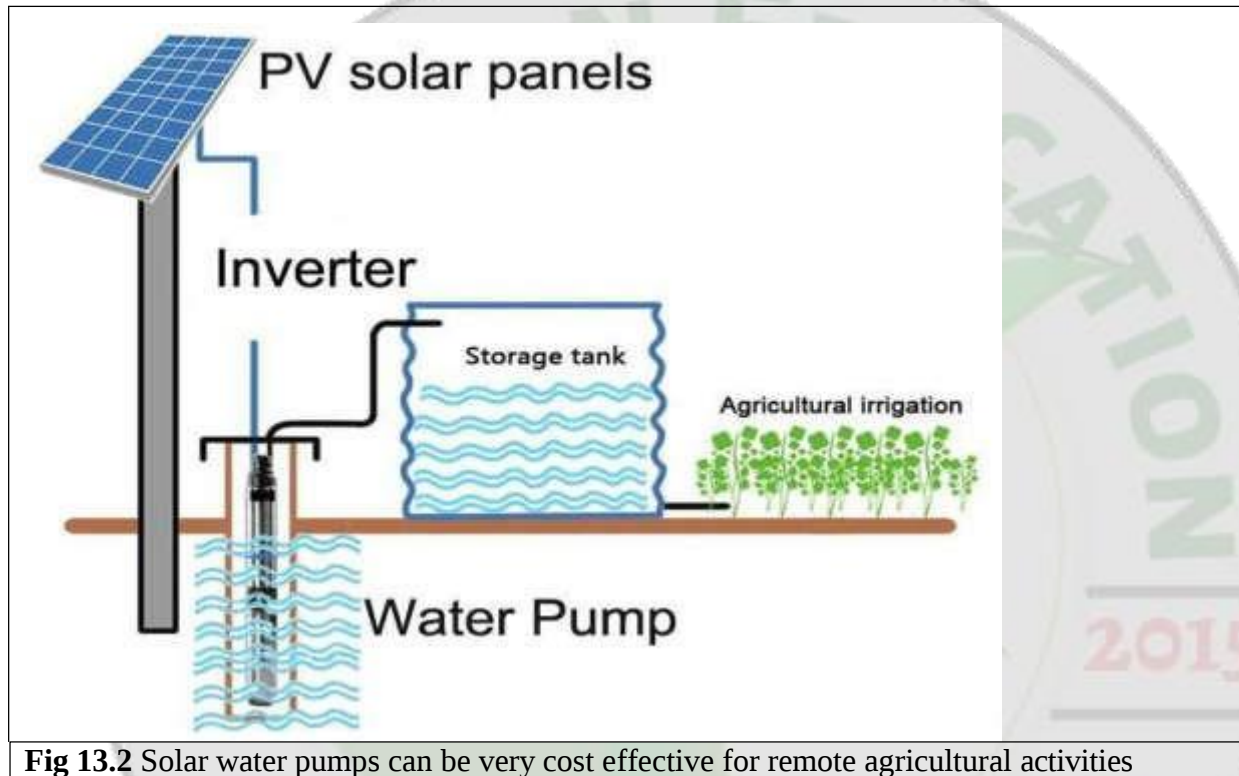


Fig 13.2 Solar water pumps can be very cost effective for remote agricultural activities

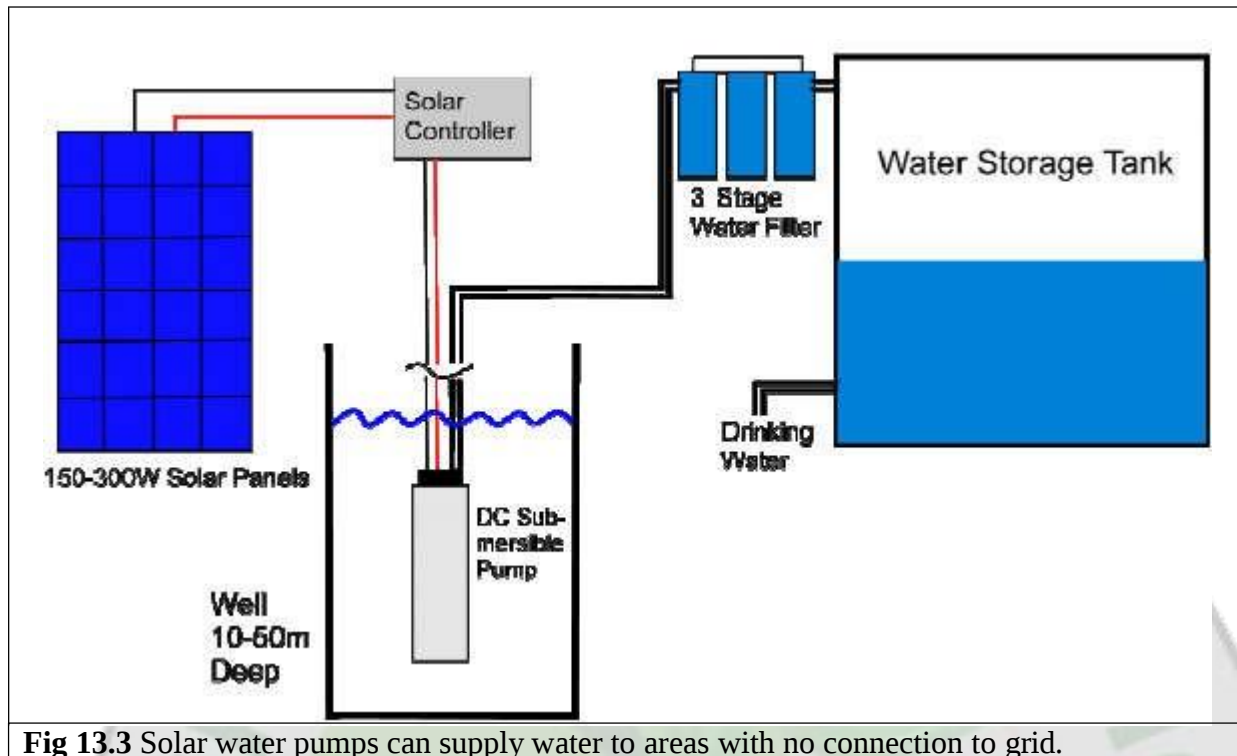
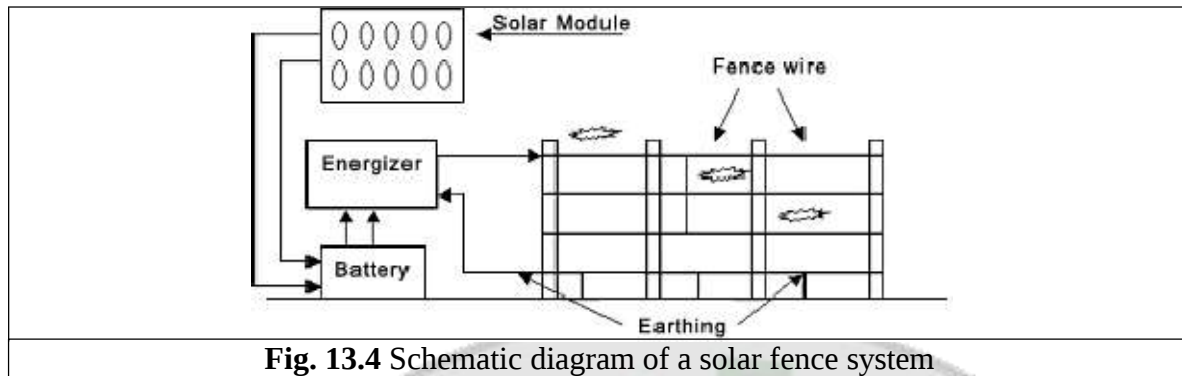


Fig 13.3 Solar water pumps can supply water to areas with no connection to grid.

13.8 Solar Fencing System: Solar Fencing is the modern day alternative to the conventional type of perimeter protection. These are active fences and punish the unwelcome intruder the moment they touches the fence or try to tamper the fence. The conventional types of fences are only passive fences and cannot resist the intruder if they try to forcibly intrude into the protected area. The Solar Fence gives a sharp, short but a safe shock and creates psychological fear. Against any tampering the alarm incorporated in the system gets activated and alerts the inmates of the protected area, which facilitates them to counter the unwelcome intruders. The solar fence is scientific fence and works on Solar Energy with backup facility to run uninterruptedly during the nights as well as cloudy days.

13.8.1 Working principle

The Solar module generates the DC energy and charges the Battery. The output of the battery is connected to Energizer or Controller or Charger or Fencer. The energizer will produce a short, high voltage pulse at regular rate of one pulse per second. The live wire of the energizer is connected to the fence wire and the earth terminal to the Earth system. Animal / Intruder touching the live wire creates a path for the current through its body to the ground and back to the energizer via the earth system and completes the circuit. Thus the intruder will receive a shock, the greater the shock the intruder receives the more lasting the memory will be avoided in future (Fig. 13.4).



The Energizer has to be set up with its earth terminal coupled to an adequate earthing or grounding system. The live terminal is coupled to the live insulated wires of the fence. Energizer will send an electric current along an insulated steel wire. An animal or intruder touching the live wire creates a path for the electrical current through its body to the ground and back to the Energizer via the earth or ground system, thus completing the circuit. The greater the shock the animal receives the more lasting the memory will be and the more the fence will be avoided in the future. The shock felt is a combination of fence voltage and pulses time or energy. The higher the joule rating of the energizer the greater the shock and the greater the fence performance.

13.8.2 Features of solar fencing system

- a) Easy Construction.
- b) Power fence can be erected to target species only.
- c) Low maintenance.
- d) Long lasting because of minimal physical pressure.
- e) All domestic and wild animals can be controlled economically.
- f) Makes strip grazing and back fencing easy.
- g) Encourages additional subdivision, giving increased production.
- h) Modification of system to control a variety of animals is very easy.
- i) Aesthetically pleasing.
- j) Discourages trespassers and predators.
- k) Not harmful. It gives a short, sharp but safe shock to the intruder.
- l) Perimeter protection

13.8.3 The basic building blocks of a power fence are:

1. Energizer 2. Earthing (Grounding System) and 3. Fence system

13.8.3.1 Energizer The heart of the power fence is the Energizer. The energizer is selected depending on the animals to be controls, length of the fence and number of strands.

Main function of the energizer is to produce short and sharp pulses of about 8000 volts at regular intervals. The power input is from the DC energy from battery. The energizer should be protected from children, should be enclosed, free from mechanical damage and away from inflammable.

13.8.3.2 Earthing system The earth or ground system of the Energizer is like the antenna or aerial of a radio. A large radio requires a large antenna to effectively collect sound waves and a high powered Energizer requires a large number of electrons from the soil. The earth or ground system must be perfect to enable the pulse to complete its circuit and give the animal an effective shock. Soil is not a good conductor so the electrons spread out and travel over a wide area, inclining towards moist mineral soils. If possible, select an area for the energizer earth site which is damp all the year.

13.8.4 Fence wire systems They are of two types: (i) All live wire system and (ii) Earth or ground wire return system.

- (i) **All Live Wire System** The all live wire system should be used where there is relatively even rainfall and where there is some green vegetation most of the year, or in areas with highly conductive soils. The all live wire system should be used as much as possible.
- (ii) **Earth or ground wire return system** The earth or ground wires return system should be used where there is low rainfall stony and dry soil condition most of the year. The system overcomes the problem of dry, non-conductive, or frozen soils not allowing sufficient current to flow through the animal's feet back to the energizer. The fence should have both live and ground wires. By touching the live and ground wires on the fence, the animal gets the full shock.

13.9 Space cooling and refrigeration system

Space cooling is one of the promising applications of solar energy to provide comfortable living conditions (air-conditioning) or of keeping a food product at low temperature to increase its shelf life. Since the energy of the sun is being received as heat, the obvious choice is absorption refrigeration system, which requires most of its energy input as heat.

A diagram of a simple solar operated absorption refrigeration system is shown in Fig.13.5. The water heated in a flat plate collector array, is passed through a heat exchanger called the generator where transfer of heat takes place to a solution (absorbent + Refrigerant), which is rich in refrigerant. Refrigerant vapour boiled off at a high pressure and goes to the condenser where it is condensed into a high pressure liquid. The high pressure liquid is throttled to a low pressure and temperature in an expansion valve and passes through an evaporator coil. Hence, the refrigerant vapour absorbs heat and cooling is obtained in the space surrounding this coil. The refrigerant vapour is now absorbed back into a solution mixture withdrawn from the generator. The refrigerant concentration is weak in this solution and pumped back into the generator, thereby completing the cycle. The common refrigerant absorbent liquids are ammonia-water, water-lithium bromide. The later is used in air conditioning.

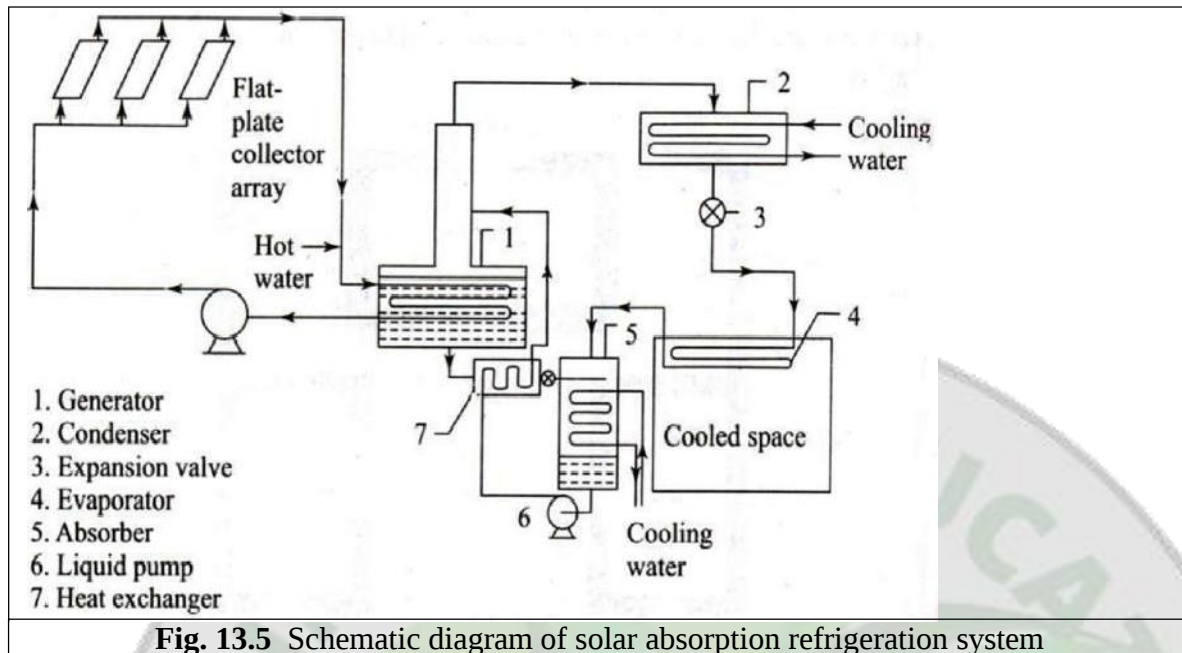


Fig. 13.5 Schematic diagram of solar absorption refrigeration system

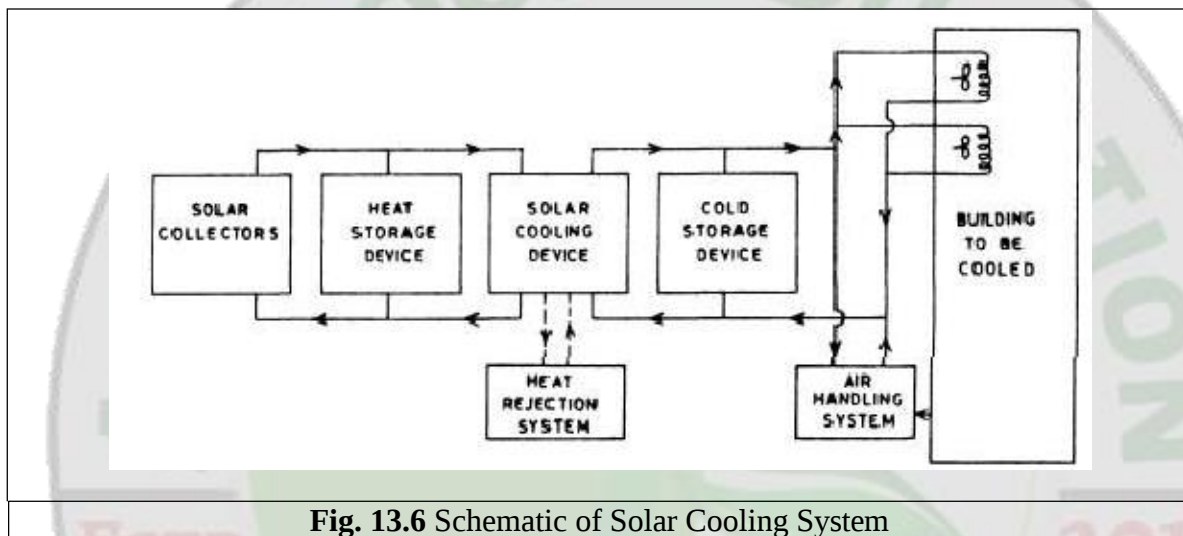
Solar Energy can be used for producing cold either for cooling of buildings (generally known as air-conditioning) or for refrigeration required for preserving food. Solar cooling appears to be an attractive proposition due to the fact that when the cooling demand is more the sunshine is strongest. This, alongwith the necessity for providing thermal comfort for people in hot areas of the world, and for providing food preservation, may be the motivating factors in continuing research and development in the field of solar cooling systems. Although considerable work on solar cooling system has been done for the last three decades, due to its complexity, both in concept and in construction, the utilization and commercialisation of solar cooling is not as widespread as other solar energy applications like solar water heating and solar space heating. However, if solar cooling of buildings is combined with the solar heating then the combined solar cooling and heating systems can become economical. Similarly solar refrigerators or cooled space (cold storage) can be provided economically for preserving essential drugs and food in isolated localities.

There are several ways of providing cold using solar energy such as:

- Using the absorption cycle with liquid absorbents such as $\text{LiBr} - \text{H}_2\text{O}$, $\text{H}_2\text{O} - \text{NH}_3$, $\text{LiCl} - \text{H}_2\text{O}$, $\text{NH}_3 - \text{LiNO}_3$, $\text{R22} - \text{DMF}$, $\text{NH}_3 - \text{NaSCN}$.
- Using the absorption cycle with solid absorbents such as: $\text{CaCl}_2 - \text{NH}_3$ * Using adsorption cycle with solid absorbents such as: Silicagel - H_2O , Zeolites - H_2O
- Using the vapor compression cycle employing a solar powered Rankine engine.
- Using the vapor compression cycle with the compressor driven by electricity from photovoltaic panels
- Nocturnal passive cooling

The choice of a particular system not only depends on its economics but will depend on local factors such as climate, availability of cooling water, auxiliary energy source, and the type of collector available. The temperature limitation of solar energy collectors alongwith the need of a suitable heat storage device makes the solar cooling system more costly and bulky.

A solar air conditioning system is complicated and will consist of many components, the major ones being the field of solar collectors, a heat storage device, a solar cooling device (based on absorption or Rankine cycle), a cold storage device, a heat rejection device, air handling system, etc as shown in Fig. 13.6. A simple flat plate collector or evacuated tube collector or concentrating collector, depending on the temperature requirement, can be employed to heat the heat transfer fluid which is used to operate the cooling device. A part of the heat can be stored in the storage unit. The heat collected from the building is rejected to the atmosphere using a cooling tower or any other suitable heat rejecting device. If air is cooled by the cooling device then it is directly supplied to the building to be cooled or if chilled water is produced then it is circulated through fan coil units and a part of a chilled water is stored for use when the cooling device is not in operation.



The performance of a cooling process is judged from its COP (coefficient of performance), which is the ratio of the amount of cooling to the energy input. The overall COP for a Rankine cycle operated solar cooling system is of about 0.3 to 0.4 which very much depends on the solar collector efficiency. The main advantage of the solar Rankine vapor compression cooling process is that it can be used in the heat pump mode also, and for electricity generation as well when cooling is not required. Moreover, the system may be designed for any operating range of temperatures with minimum pumping operations. The main problems with the system is with the controls during variable solar insolation. Many solar Rankine vapour compression cooling systems have been designed and made with different capacities, and tested for performance, but more research and development is required to improve performance and reliability.

The vapour compression cooling process operated by photovoltaic panels gives a COP in the range of 0.25 to 0.35 due to lower solar cell efficiency. This system can also be used in the heat pump mode, and the electricity can be used for other applications when cooling is not required. Here no auxiliary pumps are required. The main problem with the system is of its very high cost due to low cell efficiency and high cost of photovoltaic panels and also due to need of a costly electrical storage system. The cooling system is quiet, reliable and technically feasible.

The cooling system based on absorption closed cycle gives a COP of about 0.10 to 0.20 depending on the collector efficiency. The advantage of this system is that it can be used with low grade heat (even waste heat can be used) and is very quiet in operation. In the absorption cooling system some auxiliary power is required to drive fans and pumps. The system is uneconomical for places where heating is not required. Commercial systems based on the absorption principle are available, but more research and development is required to improve their performance, reliability and economics.

13.10 Charging Vehicle Batteries:

Vehicles running on electric power can be charged at PV powered stations. Such vehicles can also maintain their critical battery states using PV powered sources. Boats and other leisure vehicles can be charged directly using PV systems.

13.11 Solar Power Cathodic Protection:

Pipelines, well heads and other metallic structures are prone to corrosion due to exposure to water. Corrosion occurs due to the electrolytic activity of metals as they lose ions in contact with water. This electrolytic process leading to corrosion can be reduced by applying an external voltage. This external voltage will prevent the ion loss from the metal. To that end, only a small DC voltage will be enough. PV are a suitable candidate for this purpose as they produce low voltage DC power that can be used directly.

13.12 Consumer Products:

PV technology is being used for variety of commercially available consumer based products. Small DC appliances such as toys, watches, calculators, radios, televisions, flashlights, fans etc. can operate with PV based energy systems.

13.13 Public utilities:

Various public utility systems such as teller machines and telephone booths can also be powered by PV systems.

13.14 Conclusion

The huge amount of research that has been carried over the past decade has led to an increased interest in implementing PV systems to satisfy energy needs. PV systems can be mounted directly to the building structure instead of putting on separate support structures, thus reducing space requirements. PV systems are available on flexible modules and can be mounted on almost every surface to harness solar energy. Finally, we should mention that, with the advance of technology, transparent and wearable PV systems are not far.

Chapter 14

Introduction to Wind Energy

14.0 Introduction: Wind is the airflow that consists of many gases in the atmosphere of the earth. Rotation of the earth, uneven heating of the atmosphere, and the irregularities of the ground surface are the main factors that create winds. Motion energy of the wind flow is used by humans for many purposes such as water pumping, grain milling, and generating electricity. Windmills that are used for electricity generation are called wind turbines in order to distinguish them from the traditional mechanical wind power applications. Wind is a sustainable energy source since it is renewable, widely distributed, and plentiful. In addition, it contributes to reducing the greenhouse gas emissions since it can be used as an alternative to fossil-fuel-based power generation. Wind turbines capture the kinetic energy of winds and convert it into a usable form of energy. The kinetic energy of winds rotates the blades of a wind turbine. The blades are connected to a shaft. The shaft is coupled to an electric generator. The generator converts the mechanical power into electrical power.

Even though wind turbines currently provide only 1% of the worldwide power supply, wind energy is one of the fastest growing renewable energy technologies all over the world. In countries such as Denmark, Spain, Portugal, and Germany, wind power accounts for approximately 19%, 9%, 9%, and 6% of the required electric power, respectively.

The wind is the phenomenon of air moving from the equatorial regions toward the poles, as light warm air rises toward the atmosphere, while heavier cool air descends toward the earth's surface. Therefore, cooler air moves from the North Pole toward the Equator and warms up on its way, while already warm air rises toward the North Pole and gets cooler and heavier, until it starts sinking back down toward the poles. Another phenomenon that is affecting global winds is caused by the "Coriolis force," which makes all winds on the northern hemisphere divert to the right and all winds from the southern hemisphere divert to the left.

Both of the above-mentioned phenomena affect global winds that exist on the earth's surface. Hence, as the wind rises from the Equator, there will be a low-pressure area close to ground level attracting winds from the North and South. At the poles, there will be high pressure due to the cooling of the air. In order to find the most suitable sites for wind turbines, it is crucial to study the geological data of the area since the wind's speed and direction are highly influenced by the local topology. Surface roughness and obstacles not only will affect the speed of the wind, but also affect its direction and overall power.

During the daytime, land masses are heated by the sun faster than water bodies due to their higher specific densities, which allows them to have better heat transfer capabilities. Thus, during the day, air rises from the land, flows out to the sea, and creates a low-pressure area at ground level, which attracts the cool air from the sea. At nightfall, there is often a calm period when the land and sea temperatures are equal. During the night, the high pressure is inland, and the wind blows in the opposite direction. In order to efficiently capture wind energy, several key parameters need to be considered: air density, area of the blades, wind speed, and rotor area. The force of the wind is stronger at higher air densities. Wind force generates torque, which causes the blades of the wind turbine to rotate. Therefore, the kinetic energy of the wind depends on air density; therefore heavier (denser) winds carry more kinetic energy.

At normal atmospheric pressure and at 15°C (59°F), the weight of the air is 1.225 kg/m³, but if the humidity increases, the density decreases slightly. Air density is also influenced by

temperature; therefore warmer winds are less dense than cold ones, so at high altitudes the air is less dense.

In addition, the area of the blades (air-swept area), that is, the diameter of the blade, plays an important role in the captured wind energy. The longer the blade, the bigger the rotor area of the wind turbine, and therefore, more wind can be captured under the same conditions. The other parameter is the wind speed. It is expected that wind kinetic energy rises as wind speed increases. The kinetic energy of the wind can be expressed as

$$E = \frac{1}{2}mv^2 = \frac{1}{2}\rho Vv^2 = \frac{1}{2}\rho Adv^2 = \frac{1}{2}\rho\pi R^2dv^2$$

where E is the wind kinetic energy, m is the wind mass, v is the wind speed, ρ is the air density, A is the rotor area, R is the blade length, and d is the thickness of the “air disc” shown in Fig. 14.1. Hence, the overall power of wind (P) is

$$P = \frac{E}{t} = \frac{1}{2}\frac{m}{t}v^2 = \frac{1}{2}\rho\frac{V}{t}v^2 = \frac{1}{2}\rho A\frac{d}{t}v^2 = \frac{1}{2}\rho\pi R^2v^3$$

The power content of the wind varies with the cube (the third power) of the average wind speed.

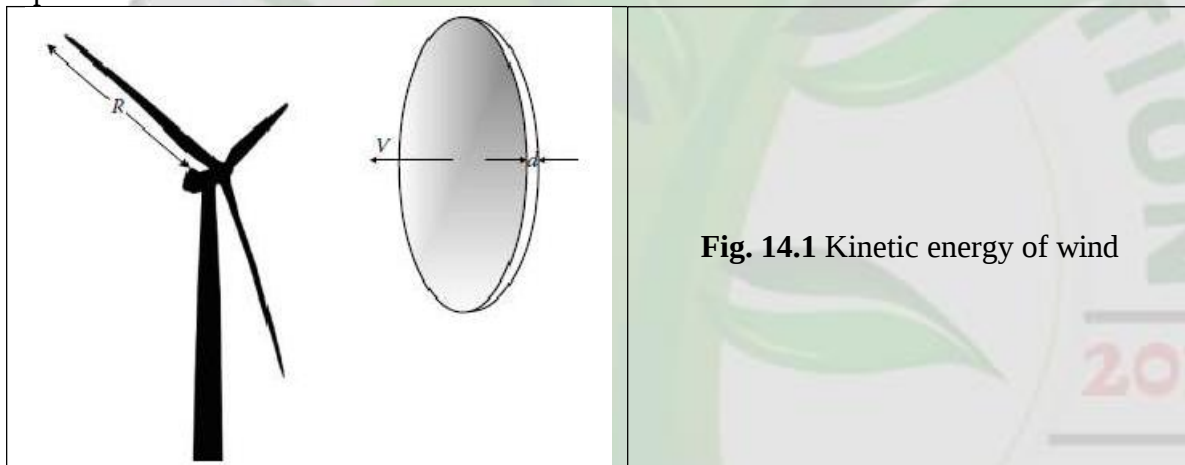


Fig. 14.1 Kinetic energy of wind

Wind turbines can be grid connected or independently operated from isolated locations. The two critical factors in finding the most suitable locations for wind turbines are wind speed and the quality of wind. This information is provided by wind roses. The most suitable sites for wind turbines are turbulence-free locations since turbulence makes wind turbines less efficient and affects overall stability of the turbine. Wind turbulence is influenced by the surface of the earth. Depending on the roughness of the terrain, the wind can be more or less turbulent. It is only at 3000 ft and above ground level that the wind speed is not affected by friction against the earth’s surface and therefore there is no turbulence.

Wind power can be categorized into seven classes according to the wind speed (m/s) and wind power density (W/m^2). These wind power classes are shown in Table 14.1. It should be noted that in this table each wind power class corresponds to two power densities. For example, wind power class 4 represents the wind power density range between 200 and $250W/m^2$.

Table 14.1 Wind Power Classes		
Wind Power	At a Height of 10 m (33 ft)	At a Height of 50 m (164 ft)

Class	Wind Power Density (W/m ²)	Wind Speed (m/s)	Wind Power Density (W/m ²)	Wind Speed (m/s)
1	0	0	0	0
1-2	100	4.4	200	5.6
2-3	150	5.1	300	6.4
3-4	200	5.6	400	7.0
4-5	250	6.0	500	7.5
5-6	300	6.4	600	8.0
6-7	400	7.0	800	8.8
7	1000	9.4	2000	11.9

Most utility-size designs have now settled on three blades as the optimal number (enough blades to take sufficient energy out of the wind and to function in a stable way in changing wind directions, but not so many that the turbine would become excessively heavy or costly). In terms of function, the blades and hub of a turbine are similar to an airplane propeller or helicopter rotor operating in reverse, that is, the device takes energy out of the air instead of putting energy into it like those of aircraft. Hence, the process of designing the shape of the turbine blade resembles the design of a propeller.

14.1 Rated Capacity and Capacity Factor

Worldwide installed capacity of wind energy reached approximately 59 GW in 2005. This figure is calculated using the maximum output of the turbines installed, also known as the *rated capacity*. Average wind speeds are significantly lower than the rated wind speed in virtually all locations, so actual output from the wind system is likely to be substantially lower than what you would get at the rated wind speed. For example, suppose the 59 GW of capacity had a single rated wind speed of 13 m/s. If the wind blew constantly at 13 m/s for an entire year, the output would be (59 GW) @ (8760 h/year) @516,840 GWh/year, or approximately 517 TWh/year of electricity, ignoring conversion losses in electricity generation.

The *capacity factor* for a wind turbine is the actual annual output divided by the annual output that would be obtained if the devices functioned at rated capacity for the entire year. For the world wind power example, if the capacity factor were on average 33%, all the wind turbines around the world would produce 171 TWh/year, and not 517 TWh. Given that capacity factors for wind turbines typically are in the range of 20 to 40%, comparisons of the value of wind installations to other energy alternatives must be undertaken carefully. For example, returning to the example of fossil-fuel-powered plants in the United States, the 602 GW of capacity produced 5724 TWh of electricity in 2000, for a capacity factor of 72%. Thus fossil-fuel-powered plants on average produce a larger electric output per GW of installed capacity than do wind plants.

14.2 Advantages of Wind Power

The wind blows day and night, which allows windmills to produce electricity throughout the day. (Faster during the day) Energy output from a wind turbine will vary as the wind varies, although the most rapid variations will to some extent be compensated for by the inertia of the wind turbine rotor. Wind energy is a domestic, renewable source of energy that generates

no pollution and has little environmental impact. Up to 95 percent of land used for wind farms can also be used for other profitable activities including ranching, farming and forestry. The decreasing cost of wind power and the growing interest in renewable energy sources should ensure that wind power will become a viable energy source in the United States and worldwide.

Disadvantages of wind power

1. Wind energy available is dilute and fluctuating in nature.
2. Noisy in operation
3. Large area is required
4. Wind velocity in India are relatively low (5 km/hr to 20 km/hr)

14.3 Site Selection Considerations:

Following things to be considered when selecting sites for installing wind monitoring devices and wind generators. Site selection depends on a number of factors including the general terrain and wind flow characteristics of an area and the proximity to the location of intended use.

Wind Characteristics: Ideal sites are generally located in areas with good exposure to the prevailing wind, away from structures, terrain or vegetation that might alter the wind or introduce excessive turbulence. For wind measurement, sites that represent a wide area are ideal in order to estimate the wind resource over as wide an area as possible. Vegetation will often show signs of "flagging" if wind is present in sufficient amounts.

Proximity to End Use: The costs associated with wind energy grow with increased distance to where the energy might be used. A windy site close to transmission lines or close to a pumping location might be most appropriate.

Terrain and Land Use: Consider the amount of land available, how this land is currently used, its proximity to other uses such as roads, houses, towns or parks. Avoid potential problems by considering your neighbors and the public in this process.

Site Accessibility: To install a monitoring tower or a wind turbine and to provide routine maintenance it will be necessary to get equipment to the site. Accessibility may be important. It may also be useful to have cell phone coverage at the site to obtain help with maintenance issues that might arise. The following characteristics are important in considering a wind turbine site, and are examined in this

- A. Predicted Wind Resource
- B. Noise
- C. Environmental Issues and Permitting
- D. Proximity to Airports
- E. Wind Turbine Component Transportation & Access
- F. Distance to Transmission/Distribution Lines for Power Distribution
- G. Net-metering
- H. Production Estimates for Selected Turbines

14.4 Internal Components of a Wind Turbine

Anemometer: This device is used for measurement of speed. The wind speed is also fed to the controller as it is one of the variables for controlling pitch angle and yaw

Blades: These are aerodynamically designed structures such that when wind flows over them they are lifted as in airplane wings. The blades are also slightly turned for greater aerodynamic efficiency

Brake: This is either a mechanical, electrical or hydraulic brake used for stopping the turbine in high wind conditions

Controller: This is the most important part of the turbine as it controls everything from power output to pitch angle. The controller senses wind speed, wind direction, shaft speed and torque at one or more

Gear box: This steps-up or steps down the speed of turbine and with suitable coupling transmits rotating mechanical energy at a suitable speed to the generator. Typically a gear box system steps up rotation speed from 50 to 60 rpm to 1200 to 1500 rpm

Generator: This can be a synchronous or asynchronous Ac machine producing power at 50Hz High-speed shaft: Its function is to drive the generator. Low-speed shaft: The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.

Nacelle: The nacelle is the housing structure for high speed shaft, low speed shaft, gear box, generator, converter equipment etc. It is located atop the tower structure mostly in the shadow of the blades

Pitch: This is basically the angle the blades make with the wind. Changing the pitch angle changes whether the blades turn in or turn out of the wind stream.

Rotor: The hub and the blades together compose the rotor.

Tower: Towers are basically made up of tubular steel or steel lattice. Taller the towers greater is the amount of power generated as the wind speed generally goes on increasing with height. Also the temp of generator and power output produced is sensed

Wind direction: Generally erratic in nature, hence the rotor is made to face into the wind by means of control systems.

Wind vane: Basically the job of a wind sensor, measuring the wind speed and communicating the same to the yaw drive, so as to turn the turbine into the wind flow direction.

Yaw drive: This drive controls the orientation of the blades towards the wind. In case the turbine is out of the wind, then the yaw drive rotates the turbine in the wind direction

Yaw motor: Powers the yaw drive.

Chapter 15

Types of Wind Mills and application of wind energy

15.1 Alternative Turbine Designs: Horizontal versus Vertical Axis

In the best known large or small turbine designs currently in use, the blades rotate in a vertical plane around a horizontal axis, so the design is given the name horizontal axis wind turbine (HAWT). However, it is not the only design option available. Wind engineers continue to be interested in the possibility of a turbine operating on a vertical axis, also known as a VAWT (vertical axis wind turbine) (Fig. 15.1).

The most prominent airfoil design for the VAWT is the *Darrieus* VAWT, patented by Georges Darrieus in France in 1931. The VAWT has a number of potential advantages over the HAWT, for example, that it receives wind equally well from any direction, and therefore does not need any mechanism to change orientation with changing wind direction. At the present time, there are no large-scale VAWT designs that are competing in the large-scale wind turbine market with the large HAWT designs. However, the VAWT technology remains an active area of research, and some conceptual and prototype designs are currently emerging that may lower the cost per kWh for this technology in the future, so it is entirely possible that new designs will successfully capture some market share from HAWTs as the wind energy industry evolves over the coming decades. Small-scale VAWTs are commercially available at the present time in rated capacities from 500 watts to 20 kW.

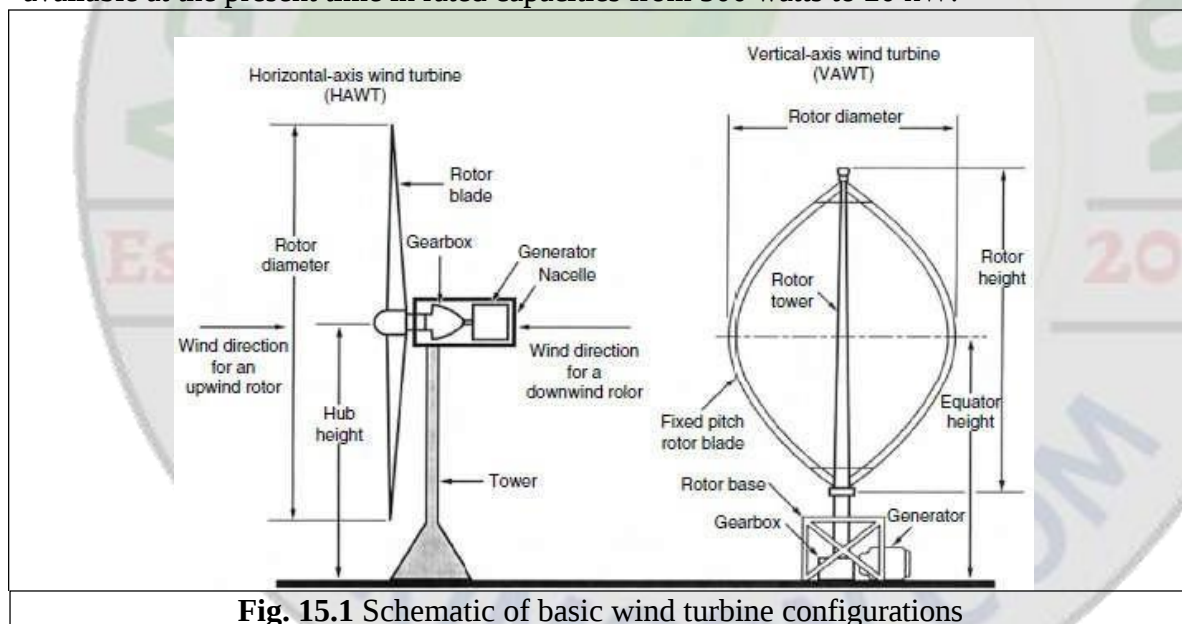


Fig. 15.1 Schematic of basic wind turbine configurations

15.1.1 Horizontal Axis Wind Turbines (HAWTs)

Horizontal-axis wind turbines (HAWT) get their name from the fact that their axis of rotation is horizontal. The blades of horizontal-axis wind turbines spin in a vertical plane. During rotation, blades move more rapidly over one side, creating a low pressure area behind the blades and a high pressure area in front of it. The difference between these two pressures creates a force which causes blades to spin. The HAWTs have the main rotor shaft and electrical generator at the top of a tower, and are pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable for generating electricity.

One-blade and two-blade wind turbines generate 15% and 5% less power than three blade wind turbines, respectively. However, the main issue for using one-blade or two-blade systems is the stability of the turbine. More sophisticated and costly control mechanisms are necessary to make one-blade or two-blade turbines stable during rotation. Wind turbines with more than three blades (multi-blade) have also been explored, but no significant gain in costs or stability of multi-blade systems over three-blade turbines have been achieved.

HAWT advantages

- As wind energy increases with height, the tall tower in the HAWT gives access to higher wind speed. In some cases increase of even 10m height leads to increase in wind speed by 20 %
- In HAWTs' the blades move horizontally that is perpendicular to the wind and hence have minimum drag and they receive power throughout the rotation.
- The design and location of blades provide a better stability of the structure.
- The ability to pitch the rotor blades in a storm minimizes the damage.
- The use of a tall tower allows access to stronger wind in sites with wind sheer and placement on uneven land.
- The manufacturing cost can be less because of higher production volume, larger sizes and, in general, higher capacity factors and efficiencies.

HAWT disadvantages

- Due to inherent large structures, construction costs are very high and so are transportation costs.
- Civil construction is costly due to erection of large towers.
- Wind turbine operation often leads to production of electronic noise which affects radar sites.
- In case of downwind HAWTs' the regular turbulence produced leads to structural failure.
- HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

Types of HAWTs:

(i) Mono-Blade Horizontal Axis Wind Turbine (HAWT)

Features:

1. They have lighter rotor and are cheaper.
2. Blade are 15-25 m long and are made up of metal, glass reinforced plastics, laminated wood, composite carbon fiber/ fiberglass etc.
3. Power generation is within the range 15 kW to 50 kW and service life of plant is 30 years.

Advantages:

1. Simple and lighter construction.
2. Favorable price
3. Easy to install and maintain.

Disadvantages:

1. Tethering control necessary for higher loads.
2. Not suitable for higher power ratings.

Applications:

1. Field irrigation
2. Sea-Water desalination Plants
3. Electric power supply for farms and remote loads.

(ii) Twin-Blade HAWT

1. They have large sizes and power output in range of 1 MW, 2 MW and 3MW.

2. These high power units feed directly to the distribution network.

(iii) Three-Blade HAWT

1. The rotor has three blades assembled on a hub. The blade tips have a pitch control of 0 to 30° for controlling shaft speed.
2. The shaft is mounted on bearings.
3. The gear chain changes the speed from turbine shaft to generator shaft.

15.1.2 Vertical Axis Wind Turbines (VAWTs)

The blades of vertical-axis wind turbines spin in a horizontal plane. VAWTs have the main rotor shaft running vertically. An advantage of this arrangement is that the generator and/or gearbox can be placed at the bottom, near the ground; therefore, a tower is not needed to support the turbine. This turbine does not need to be pointed into the wind.

The disadvantages are usually the pulsating torque that is produced during each revolution and the drag created when the blade rotates into the wind. The vertical axis turbines on towers need lower and more turbulent air flow near the ground. This type of condition is difficult to sustain resulting in lower energy extraction efficiency. These are useful in sites where wind direction is random or there is presence of large obstacles like trees, houses etc. Also VAWTs' don't require a tower structure and can be placed nearby a ground enabling access to electrical components. Some drawbacks are the low efficiency of wind production and the fact that large drag is created for rotating the blades in a vertical axis (Fig. 15.2).

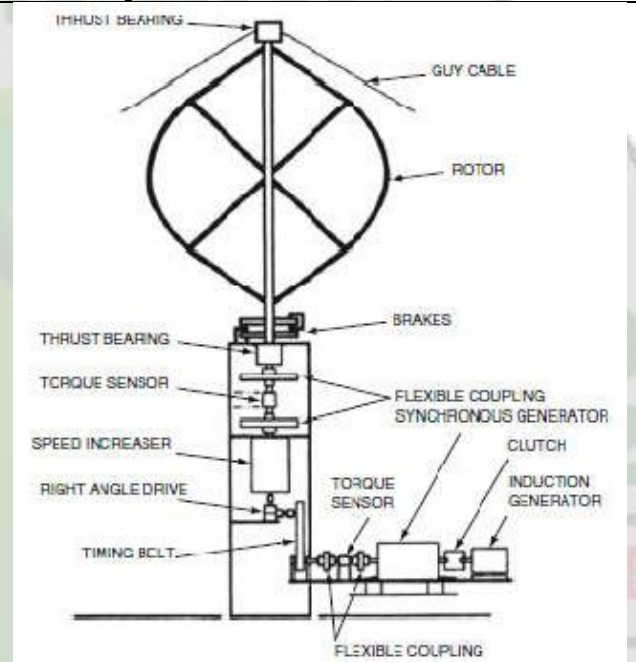


Fig. 15.2 Components of a vertical axis wind turbine

VAWT advantages

- A massive tower structure is not required, as VAWTs' are mounted closer to the ground
- They don't require yaw mechanisms.
- These are located closer to the ground and hence easier to maintain.
- These have lower startup speeds than their horizontal counterparts. These can start at speeds as low as 10Kmph.
- These have a lower noise signature.

VAWT disadvantages

- VAWTs' have lower efficiency as compared to HAWTs' because of the additional drag produced due to rotation of blades.
- Even though VAWTs' are located closer to the ground, the equipment now resides at the bottom of the turbines structure thus making it inaccessible.

- Because of their low height they cannot capture the wind energy stored in higher altitudes.

Types of VAWTs

15.1.2.1 Savonius Rotor VAWT:

The Savonius turbine consists of two half-cylinders mounted on a vertical shaft that has an S-shape appearance when viewed from the top (Fig. 15.3). This drag-type VAWT turns relatively slowly, but yields a high torque. Because of the curvature, the scoops experience less drag when moving against the wind. The differential drag causes the Savonius turbine to spin. Most of the swept area of a Savonius turbine is near the ground, therefore, the overall energy extraction efficiency is lower. However, Savonius turbines are cheap and reliable.

1. Patented by S.J. Savonius in 1929.
2. It is used to measure wind current.
3. Efficiency is 31%.
4. It is Omni-directional and is therefore useful for places where wind changes direction frequently.

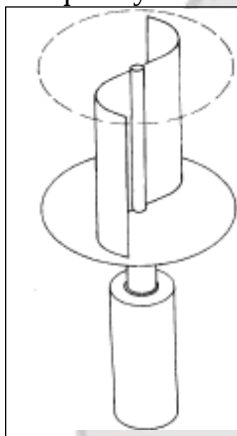


Fig. 15.3 Savonius rotor for wind turbine

15.1.2.2 Darrieus Rotor VAWT:

The most common type of VAWT is the Darrieus wind turbine. The design of these types of turbines looks like an eggbeater. Generally, an external power source is required to start the rotation. The starting torque is very low. In the newer design, three or more blades are used which results in a higher solidity for the rotor. Solidity is measured by blade area over the rotor area. New Darrieus type turbines are not held up by guy wires, but have an external structure connected to the top bearing (Fig. 15.4).

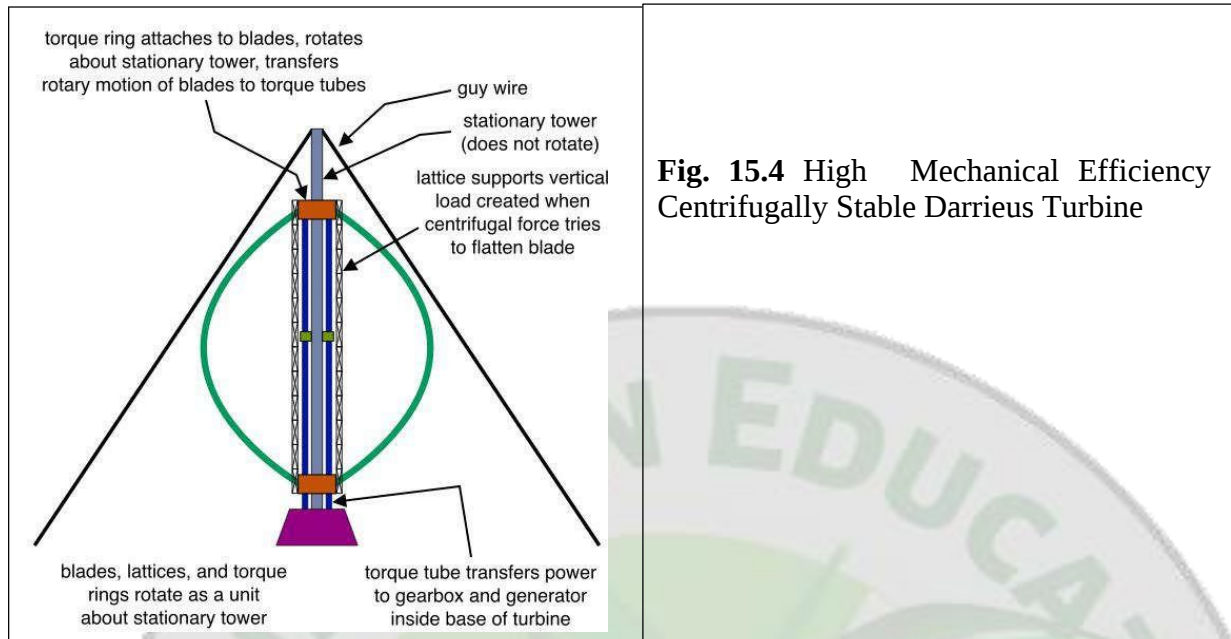


Fig. 15.4 High Mechanical Efficiency Centrifugally Stable Darrieus Turbine

15.2 Applications

There are perhaps four distinct categories of wind power which should be discussed. These are:

- **Small, non-grid connected**
- **Small, grid connected**
- **Large, non-grid connected**
- **Large, grid connected**

By small, we mean a size appropriate for an individual to own, up to a few tens of kilowatts. Large refers to utility scale.

15.2.1 Small, Non-Grid Connected

If one wants electricity in a location not serviced by a utility, one of the options is a wind turbine, with batteries to level out supply and demand. This might be a vacation home, a remote antenna and transmitter site, or a Third-World village. The costs will be high, on the order of \$0.50/kWh, but if the total energy usage is small, this might be acceptable. The alternatives, photovoltaics, microhydro, and diesel generators, are not cheap either, so a careful economic study needs to be done for each situation.

15.2.2 Small, Grid Connected

The small, grid connected turbine is usually not economically feasible. The cost of wind-generated electricity is less because the utility is used for storage rather than a battery bank, but is still not competitive. In order for the small, grid connected turbine to have any hope of

financial breakeven, the turbine owner needs to get something close to the retail price for the wind-generated electricity. One way this is done is for the owner to have an arrangement with the utility called net metering. With this system, the meter runs backward when the turbine is generating more than the owner is consuming at the moment. The owner pays a monthly charge for the wires to his home, but it is conceivable that the utility will sometimes write a check to the owner at the end of the month, rather than the other way around. The utilities do not like this arrangement. They want to buy at wholesale and sell at retail. They feel it is unfair to be used as a storage system without remuneration. For most of the twentieth century, utilities simply refused to connect the grid to wind turbines.

The utility had the right to generate electricity in a given service territory, and they would not tolerate competition. Then a law was passed that utilities had to hook up wind turbines and pay them the avoided cost for energy. Unless the state mandated net metering, the utility typically required the installation of a second meter, one measuring energy consumption by the home and the other energy production by the turbine. The owner would pay the regular retail rate, and the utility would pay their estimate of avoided cost, usually the fuel cost of some base load generator. The owner might pay \$0.08 to \$0.15 per kWh, and receive \$0.02 per kWh for the wind-generated electricity. This was far from enough to economically justify a wind turbine, and had the effect of killing the small wind turbine business.

15.2.3 Large, Non-Grid Connected

These machines would be installed on islands or in native villages in the far north where it is virtually impossible to connect to a large grid. Such places are typically supplied by diesel generators, and have a substantial cost just for the imported fuel. One or more wind turbines would be installed in parallel with the diesel generators, and act as fuel savers when the wind was blowing.

This concept has been studied carefully and appears to be quite feasible technically. One would expect the market to develop after a few turbines have been shown to work for an extended period in hostile environments. It would be helpful if the diesel maintenance companies would also carry a line of wind turbines so the people in remote locations would not need to teach another group of maintenance people about the realities of life at places far away from the nearest hardware store.

15.2.4 Large, Grid Connected

We might ask if the utilities should be forced to buy wind-generated electricity from these small machines at a premium price which reflects their environmental value. Many have argued this over the years. A better question might be whether the small or the large turbines will result in a lower net cost to society. Given that we want the environmental benefits of wind generation, should we get the electricity from the wind with many thousands of individually owned small turbines, or should we use a much smaller number of utility-scale machines?

If we could make the argument that a dollar spent on wind turbines is a dollar not spent on hospitals, schools, and the like, then it follows that wind turbines should be as efficient as possible. Economies of scale and costs of operation and maintenance are such that the small, grid connected turbine will always need to receive substantially more per kilowatt hour than the utility-scale turbines in order to break even. There is obviously a niche market for turbines that are not connected to the grid, but small, grid connected turbines will probably not develop a thriving market. Most of the action will be from the utility-scale machines.

Sizes of these turbines have been increasing rapidly. Turbines with ratings near 1 MW are now common, with prototypes of 2 MW and more being tested. This is still small compared to the needs of a utility, so clusters of turbines are placed together to form wind power plants with total ratings of 10 to 100 MW.





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