SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
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SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

GREEN ENERGY SYSTEMS – SEEA3010

SEEA3010	Green Energy Systems (For EEE)	L	T	P	Credits	Total Marks
		3	0	0	3	100

COURSE OBJECTIVES

To understand the need and advantages of renewable energy.

To study the performance, efficiency and the relevancy to the future energy needs.

UNIT 1 INTRODUCTION 9 Hrs.

Overview of conventional & renewable energy sources, need, potential & development of renewable energy sources, types of renewable energy systems, Future of Energy Use, Present Indian and international energy scenario of conventional and RE sources, Energy for sustainable development, Environmental Aspects of Energy, Limitations of RE sources.

UNIT 2 SOLAR ENERGY 9 Hrs

Theory of solar cells - VI and PV curves - Equivalent circuit. Concept of solar PV module, Panel, Array, Maximum Power Point tracking - Solar PV systems - Solar Collectors Classifications– Solar PV Applications- Solar Refrigeration - Solar Pond Power Plant - Solar Thermal Power Plant.

UNIT 3 WIND ENERGY 9 Hrs.

Wind Power and its Sources-Energy from Wind - Horizontal axis Wind Turbine - Vertical Axis Wind Turbine - Wind Energy Conversion Systems - Cp Vs Speed Curve.

UNIT 4 HYDROGEN PRODUCTION AND HYDROGEN STORAGE 9 Hrs.

Chemical Production of Hydrogen- Electrolytic Hydrogen- Thermolytic Hydrogen- Photolytic Hydrogen- Photobiologic Hydrogen Production- Compressed Gas- Cryogenic Hydrogen- Storage of Hydrogen - Adsorption- Chemical Compounds- Hydride Hydrogen Compressors- Hydride Heat Pumps.

UNIT 5 HYBRID RENEWABLE ENERGY SYSTEMS 9 Hrs.

Need for Hybrid Systems- Range and type of Hybrid systems - Configuration and Coordination, Electrical interface: wind-PV, Wind-PV-Fuel cell.

Max. 45 Hours

Course objective

To

CO1 - Gain knowledge on the various classification of energy sources and their environmental issues
CO2 - Analyse the limitless availability of green energy sources
CO3 - Acquire the knowledge of the principles of solar energy conversion and their benefits
CO4 - Enable for building a small range of wind energy conversion system
CO5 - learn hydrogen production method and storage methods
CO6 - understand the challenges in renewable hybrid system

TEXT / REFERENCE BOOKS

1. Aldo Vieira da Rosa , Juan Carlos Ordonez,"Fundamentals of Renewable Energy Processes" -Elsevier academic press 4th Edition 2021
2. Janaka Ekanayake and Nicholas Jenkins "Renewable Energy Engineering"- Cambridge university press-2017
3. B Khan ,"Non conventional Energy resources", Tata McGrawHill, 2 nd Edition 2009.
4. Mukund R. Patel ,Wind & Solar Power Systems- Design, Analysis and Operation, , Taylor and Francis, 2nd Edition2005.
5. James Larminie & Andrew Dicks, "Fuel Cell Systems Explained", John Wiely & Sons, 2nd Edition.
6. John Twideu and Tony Weir, "Renewal Energy Resources" BSP Publications, 2006.
7. C.S. Solanki, "Renewal Energy Technologies: A Practical Guide for Beginners" PHI Learning.

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UNIT – I - INTRODUCTION – SEEA3010

Unit-I

INTRODUCTION

1.0 INTRODUCTION

Energy affects every part and every field of our life. We need energy to do all sorts of physical and physiological activities like moving writing, running, cooking, thinking or doing any work. We need energy for transportation, communication, lighting, industries and agriculture. We also need energy to extract minerals from ores and to manufacture fertilizers, pesticides and all other products. We need energy for space travel and all scientific activities. Thus, we see there is hardly any aspect of life which we can think of that does not require energy. In fact, energy use is an indication of the degree of development. Some 99 percent of the energy used to heat our earth and all our buildings comes directly from sun. Without this direct input of solar energy our earth's temperature would have been 240°C and life would just not have been possible. The 99% of the energy coming from sun to the earth is natural and not sold in the market. The remaining one percent is the commercial energy used by people in different forms like fuel wood, coal, oil, dung, electricity etc.

The energy sources can be broadly categorized into renewable and nonrenewable resources. While renewable resources like biomass energy, solar energy, tidal energy, wind energy, hydel power energy etc. can be regenerated, the non-renewable energy resources like coal, petroleum and natural gas are fossil fuels which took millions of years to be formed and cannot be renewed during our life span.

1.1 CONVENTIONAL ENERGY

1.1.1 Energy Demands and Supply

The commercial sources of energy include petroleum, coal, natural gas and nuclear energy. Out of all these oil is the most widely used energy resource.

Oil (Petroleum)

Oil is the life line of global economy. The identified deposits from which oil can be extracted profitably at present prices with current technology are known as oil resources. Thirteen countries of the world make up the **Organisation of Petroleum Exporting Countries** (OPEC), which have 67% of these reserves. About one fourth of the oil reserves are located in Saudi Arabia. It is further estimated that the undiscovered oil will also be just located in Middle East Thus, the world oil supplies and prices are likely to be controlled by OPEC over a long period of time.

United States of America is the world's largest consumer of oil using 30% of global total, whereas it has only 4% of the world's oil reserves. Maximum use of oil is in transportation (63%), followed by industry (24%), residential and commercial buildings (8%) and electric utilities (8%). At the present rate of consumption, the world's crude oil reserves are estimated to be depleted in 40 years and there may be enough undiscovered oil lasting for another 40 years: Some analysts argue that rising oil prices will stimulate exploration and that the earth's crust may contain more oil than is generally thought. Such oil even if it exists, lies about 10 kilometers or still more below the surface (twice the depth of wells known today).

Some analysts strongly believe that at the current rate of use of crude oil, the following are expected:

- Saudi Arabia, with the largest known crude oil reserves, could supply all the world's needs for another 10 years.
- The estimated reserves under Alaskas North slope (the largest reserve of North America) would meet U.S. demand for just 3 years.
- All undiscovered deposits could-meet world demand for 30-40 years.

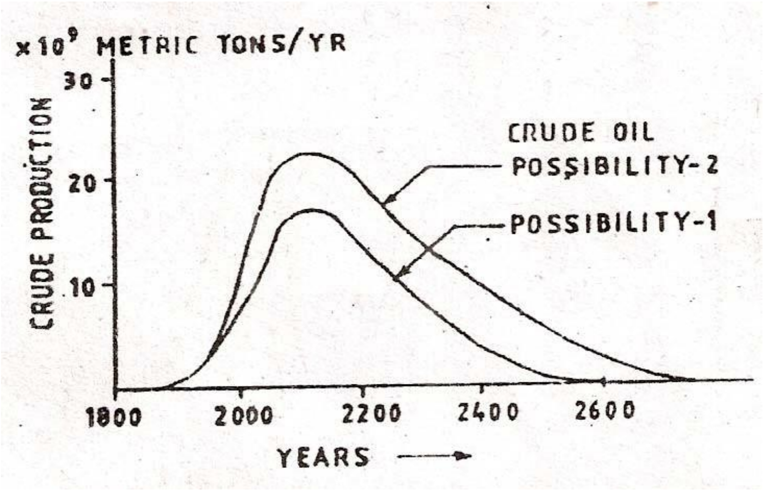

Fig. 1 Likely availability to Crude Oil and Natural Gas

Figure-l shows the end of petroleum age in near future. The two curves show that the world's known petroleum reserves will be 80% depleted between 2025 and 2035.

Coal

About 68% of world's proven coal reserves and 85% of the estimated undiscovered coal deposits are located in U.S.A., C.I.S. and China. About 55% of U.S. coal reserves are found west of Mississippi River.

Coal is the most abundant conventional fossil fuel in the world. Identified world reserves of coal should last about 210 years at the current rate of usage and just 65 years, if the rate, of usage increases by 2% per year.

The world unidentified coal reserves are however, projected to last about 900 years at current rate and 150 years, if usage rate increases by 2%.

Natural Gas

About 40% of the world's natural gas reserves are in CIS countries. Other countries with proven natural gas reserves are Iran (14%), United States (5%), Qatar (4%), Saudi Arabia (3%) and Nigeria (3%). Geologists expect to find more natural gas, especially in unexplored LDCs (less developed countries). Most of the natural gas reserves are located in same area as crude oil.

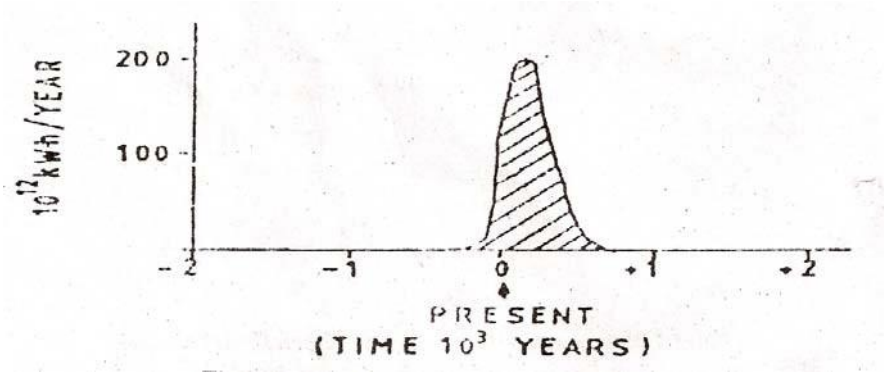

Fig. 2 Fossil Fuel Age (Year 1850-2850)

Presently we are passing through the peak period of fossil age. The fossil age may last for a few more decades, as the reserves are getting depleted very fast. Fig. 2 shows that the· fossil fuel age is likely to last from 1850 to 2850 and then all the reserves will be exhausted.

Probably, the next generation would witness a sharp depletion of oil and natural gas in their lifetime and alternate fuels will have to be developed The estimated fuel reserves of the world are tabulated below :

Fuel	Type	Reserves
Fossil Fuel	Coal Oil & Natural Gas	32Q* 6 Q
Nuclear Fossil Fuel	Uranium & Thorium	600 Q
Nuclear Fossil Fuel	Deuterium	1010 Q

*Q = Quad.

lQuad = 180 million barrels of petroleum

= 42 million tons of bituminous coal

= 0.98 trillion cubic feet of natural gas

= 293 billion kilowatt hours of electricity.

The world trends of fossil fuel combustion are shown in Figures-3 and Fig-4. The corresponding trends in different nations vary depending upon the type of natural resources and available technology.

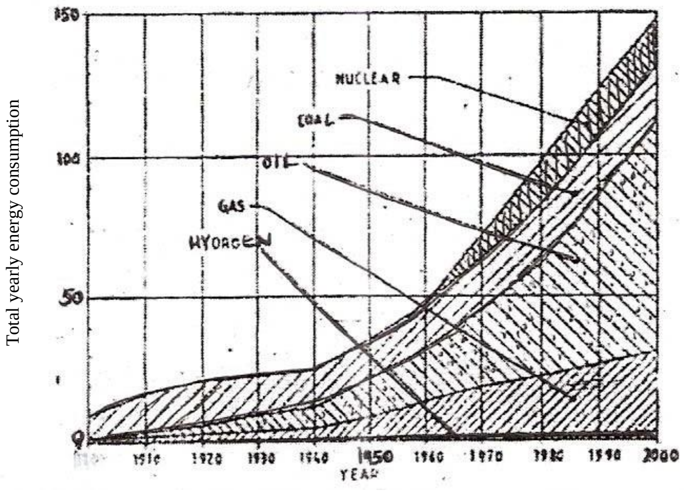

Fig. 3 Trends in World Energy Demand

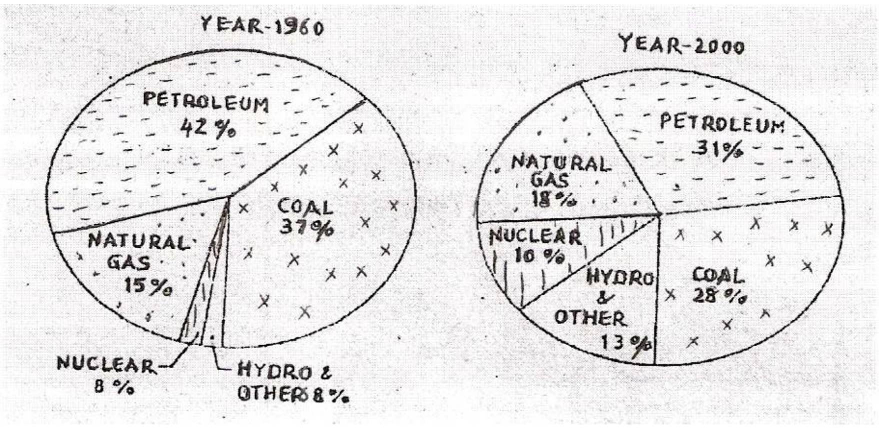

Fig.-4 Trends in World Energy Supply

Before 1850, the fuels in use were fire wood, agricultural wastes etc. During the 20th century, the use of fossil fuels increased rapidly. 'From Figure-3 it, is clear that hydropower has remained a minor source of energy since 1900. Coal was in much more use during 1900 to 1940 than oil, but after 1940-45, there was a sharp increase in petroleum use surpassing coal. Nuclear energy became an important source of energy after 1960. Figure-4 compares the change in trends of energy use in the last 40 years.

1.1.2 ENERGY RESOURCES OF INDIA

The major commercial (non-renewable) sources of energy are coal, oil, natural gas and nuclear power. The share of commercial and non- commercial sources of energy in our country in 1980's was in a ratio of 1: 1. However, following rapid industrial growth, the ratio changed to 4: 1 in 2000. Let us see what are our non-renewable energy resource reserves:

1.1.2.1 Coal

India has about 5% of world's coal production. Coal, besides a prime source of industrial energy is also a raw material. Coal including lignite even today accounts for 60% of country's commercial requirements.

Major coal fields in India are Raniganj, Jharia, East Bokaro and West Bokaro, Panch-Konkan (Tawa Valley), Singrauli, Takhar, Chanda-Wardha and Godavari Valley. The major states known for coal reserves are Bihar, Orissa, West Bengal, Madhya Pradesh, Andhra Pradesh and Maharashtra.

By and large, the quality of Indian coal is rather poor in terms of heat capacity. This poor heat capacity can be converted into electricity and gas and even oil. That is the reason why many of out thermal power stations are located on the coal fields to produce electric power to feed regional grid. Coal production in India which was just 35 million tons in 1951 went to over 180 million tons in 1988-89. Per capita consumption of coal has increased from 135 kg to nearly 225 kg. Lignite (brown coal) is generally a low quality coal. But Indian lignite has less ash than coal. The deposits at Neyveli (Tamil Nadu) are about 3,300 million tons, which is about 90% of India's lignite reserves. It produces 600 MW of thermal power.

1.1.2.2 Oil and Natural gas

Mineral oil is very unevenly distributed over space like any other mineral. India has a large proportion of tertiary rocks and alluvial deposits particularly in the extra peninsular India. Such potential oil bearing area is estimated to be over a million square kilometers. It covers the northern plains in the Ganga-Brahmaputra Valley, the coastal strips together with their off-shore continental shelf (Bombay High), the plains of Gujarat, the Thar desert and the area around Andaman and Nicobar Islands.

In India oil was first found at Makum (North East Assam) but drilling of oil was started at Digboi in Lakhimpur district. After independence, at Gujarat plains and Bombay High, major oil reserves were found. Lately, oil deposits were found in offshore areas off the deltaic coasts of Godavari, Krishna, Kaveri and Mahanadi.

Natural gas reserves are generally found in association with oil fields. However, exclusive gas reserves are also located in Tripura, Rajasthan and almost all the offshore oil fields of Gujarat, Maharashtra,Tamil Nadu, Andhra Pradesh and Orissa .

In 1951, our total petroleum production was 269,000 tons while in 1990 it was 40 million tons. Natural gas production was 2,500 million, m^3 in 1980-81 which rose to 9,810 million m^3 in 1987 and 15,000 million m^3 in 2000. Total gas reserves of India are estimated to be 5,41,000 million m^3.

Through pipe-lines, the gas from Bombay and Gujarat gas fields is now taken to M.P., Rajasthan and U.P. Hazira-Bijaipur-Jagdishpur (HBJ) gas pipe line is 1,730 km long which carries 18 million m^3 in gas daily. It feeds 6 fertilizer plants and three power plants. There are 15 refineries in India. The liquefied petroleum gas (LPG) or cooking gas is now a domestic fuel.

1.1.2.3 Nuclear Power

A small quantity of radioactive material can produce an enormous amount of energy. For instance one ton of Uranium-235 would provide as much energy as produced by 3 million tons of coal or 12 million barrels of oil.

India is rich in certain radioactive materials. Uranium mines are located in Singhbhum in Bihar and parts of Rajasthan. Most abundant Monazite sands are present on the shores of' Kerala.

Thorium is derived from the monazite sands. The major nuclear power plants in our country are located in Tarapur (Maharashtra), Kota (Rajasthan), Kalpakkam (Tamilnadu), Kakarpara (Gujarat), Kaswar (Karnataka) and Narora (Uttar Pradesh).

1.1.3 ENERGY SCENARIO OF INDIA

About 75% of population of India lives in rural areas and uses about 40% of total energy of the country. Consumption pattern of rural areas is

Sector	Energy use (%)
Domestic	64%
Agriculture	22%
Industrial/Commercial	7%
Lighting	4%
Transportation	3.%

Biomass fuels and animal energy are the two main non-commercial energy sources used in rural India; Biomass fuels include fuel wood, crop residues, animal wastes and Gobar gas. The percentage contribution of each of these biomass fuels is 65,30 and 15% respectively, on an average.

The fuel wood consumption ranges from 146-300 MT/year and the demand is increasing with rise in population growth.

Out of the total power generated in the country, the potential of the animal energy is close to 50%. This is mainly for farming operations and transportation. There are about 84 million of draught animals which is equivalent to 30,000 MW of power. Emphasis has been to improve the efficiency of equipments, devices and transport vehicles which are animal driven.

Amongst the conventional sources of commercial energy used in India, coal is the prime resource. In present day context; 60% of coal produced is utilized in generation of electricity, which in fact, is more than 95% of the thermal power or about 70% of total installed capacity of electricity generated in India.

Petroleum products are mainly used in transport and industrial sector.

About 40% of petroleum products are used for providing raw material in fertilizer, plastics, synthetic fibres, rubber, pesticides, various pharmaceutical and, organic chemical industries.

The consumption of petroleum products has increased at a much faster rate in the last few years and at present 66 million tones of petroleum products (1994-95) are being used out of which 50% is imported.

Natural gas consumption has shown an increase in the recent years. The annual gas supply has increased from 10 billion m^3 in 1990 to 16 billion m^3 in 1990.

The hydropower electricity is not yet fully harnessed. At present we are using only 25% of the total hydropower potential of our country.

Nuclear power in Indian context is yet to take off. Four nuclear power stations with installed capacity of 2005 MW are working efficiently. However, nuclear hazards resulting from any careless handling can be disastrous. Table-1 gives a summarized view of conventional sources of commercial energy in our country.

Table-l A summarized view of present conventional sources of commercial energy and their relative contribution in generation of electricity :

Conventional sources	Sectors of utility	Type	Installed capacity (MW)
Coal	- 60% used for electricity generation. - 18% used for steel and cement industries. - 22% miscellaneous	Thermal power	58,100
Petroleum & its products (petroleum, diesel, kerosene, naphtha, fuel oil etc.)	- 40% used for transport - Rest used in industries including electricity generation, domestic & other miscellaneous purposes.	Thermal power	
Natural Gas	Mainly in industries for electricity generation	Thermal power	
Surface water	Electricity generation	Hydro power	20,829
Nuclear material	Electricity generation	Nuclear power	2,005
		Total	**80,934**

Non-conventional sources of energy are still at a low ebb in our country. However in the 8th Five Year Plan we have set the targets as shown in Table-2.

Table-2 : Targets of eighth plan of various major non-conventional energy resources.

Sr. No.	Major non-conventional energy	Targets of VIIIth Plan (MW) resources
1.	Wind energy	500 MW
2.	Small hydro electric power plants (upto 15 MW)	600 MW
3.	Portable mini hydel sets (upto 15 MW)	To provide 50 portable sets particularly in hilly region
4.	Biomass based co-generation in sugar mills	300 MW
5.	Solar energy :	
	i) Solar photo voltaics (SPV) systems	SPV systems with total capacity of 25 MW proposed to be installed during VIIIth plan. These include one lakh solar lanterns, one thousand SPV water pumps and several SPV power projects.
	ii) Solar thermal programme	To increase the collector area of solar water heating system which are at present in 2.54 lakh sqm.
6.	Tidal energy	900 MW (proposal under consideration at a cost of Rs. 4,000 crores in Gulf of Kutch).
7.	Ocean thermal energy	900 MW (proposal under consideration at cost of Rs. 750 crores in Tamil Nadu).
8.	Wave-energy	To set up 100 KW to 1 MW plants.
9.	Geothermal energy	To set up power plants of 5 KW or more.

Future prospects of energy management needs a careful assessment. Our increasing population is going to cause a many time increase in energy demands. We have to increase our energy resource utilization by 12-15% in the next 5 years.

India requires an investment of $200 billion in power sector over the next 15 years if the country's GDP is to be sustained. The following two changes may be suggested in future for our country.

(i) Instead of major power projects, captive power plants (upto 25 MW) may be installed which may prove to be more economic and environment friendly.

(ii) For thermal power generation, focus is being shifted slowly from coal based to gas based plants. The conversion efficiency of gas- based power plants is not only higher but also the pollution caused in very low.

1.2 SUMMARY

Energy resources are very important as they are required in every field of our life. All development activities depend on energy. Energy consumption of a nation is an index of its development. Energy resources that can not be regenerated during our life span are called non-renewable energy resources. Fossil fuels like coal, oil and natural gas are non- renewable energy resources. About 67% of oil (petroleum) is present in 13 countries known as OPEC. Reserves of these fossil fuels are limited and at the present rate of their consumption these are not going to last long. It is estimated that oil reserves would last for another 30-40 years and coal for another 210 years. Nuclear energy is projected as one of the important energy resource of future. Uranium (U_{235}) which exists inside the earth can be mined and used as a source of nuclear energy. Thorium, a radioactive substance can be obtained from monazite sands.

In India, Thermal power using coal, gas or petroleum as source of energy is responsible for maximum generation of electricity (75%), followed by hydro power (24%) and 1% by others.

1.3 KEY WORDS

- **Fuel**: Substance containing energy which can be released by combustion or by chemical reaction or electromagnetic reaction or nuclear reaction etc.

- **Nuclear Fuel** : Fissile material used to produce energy in a nuclear reactor.

- **Benzene C_6H_6** : Colourless liquid hydrocarbon, made from coal tar by catalytic reforming of naphthalene. It is used in the manufacture of phenol, styrene, nylon, detergents, aniline, and other compounds: as a solvent; and as a component of high octane gasoline.

- **Bitumen** : General name for various solid and semisolid hydrocarbons, a native substance of dark colour, comparatively hardened non-volatile, composed principally by hydrocarbon.

- **Bituminous Coal** : Soft coal; coal that has high content of carbonaceous and volatile matter. When Volatile matter is removed from bituminous coal by heating in absence of air, the coal becomes coke.
- **Blended Fuel Oil** : Mixture of residual and distillate fuel oils.
- **Bunker-C Fuel Oil** : Heavy residual fuel oil used by ships, industry.

- **Caking Coal** : The coal which softens and agglomerates when heated, and after driving off volatile matter at high temperature, produces hard, gray cellular mass of coke.

- **Calorie** : Unit of thermal energy (heat). The amount of heat required to raise temperature of one gram of water by I degree Celsius.

  1 calorie = 3.97 X 10 ... Btu= 4.18 J = 1.13 X 10 ... Wh

- **Calorific value (Heating Value)** : Heat liberated by combustion of unit quantity of a fuel. (J/kg)

- **Coal** : A general term for a number of solid organic fossil minerals with widely differing compositions and properties. Coal is essentially rich in amorphous carbon (carbon without regular structure).

- **Metallurgical coal** : Coal as mined or after cleaning having strong or moderate cooking properties. It should not contain more than 1.25% sulphur and 8% ash.

- **Carbonization of Coal** : Heating of coal without contact with oxygen at high temperature, to produce a fuel of higher carbon Content than original. Carbonization gives coke and Cole Gas.

- **Cracking** : Processing which breaks down and arranges the molecular structures of the hydrocarbon chains. In thermal cracking, high temperature and pressure is applied in presence of a catalyst.

- **Crude oil (Crude)** : Petroleum oil in natural state before refining or processing.

- **Diesel Fuel** : Fraction obtained from distillation of crude oil, after kerosene. Diesel is an important fuel for Diesel-Engine used in transportation.

- **Fuel** : Any substance that can be burned to produce heat.
- **Fuel Oils** : Petroleum fractions of higher boiling point than kerosene. They are generally classified as distillates of residues. They are used for industrial heating, district heating and power generation.

- **Gasification** : Process of converting solid or liquid fuel to gaseous fuel.
- **Graphite** : Pure carbon.
- **Hydrocarbon Fuels** : Fuels that contain an organic chemical compound hydrogen and carbon (e.g. Methane CH_4). The hydrocarbon contains chains of molecules formed by carbon-hydrogen atoms arranged in systematic and symmetrical form.

- **Kerosene**. A petroleum fraction containing hydrocarbons; slightly heavier than gasoline (petrol) and naptha; Boiling point of kerosene is in the range of 180°C and 300°C. Used as fuel.

- **Lignite** : Low grade coal in between Bituminous Coal and Peat.

- **Liquefied Natural Gas (LNG)** : Natural gas which is cooled to about 160°C for liquefying for the purpose of easy storing and transportation. Liquefaction of NG greatly reduces the storage and transportation costs.

- **Liquefied Petroleum Gas (LPG)** : Consists of Propane and Butane recovered from natural gas and in petroleum refining. It is 'also called, Bottled Gas. Used as a fuel for IC Engines and domestic use in area where pipe-lines of natural gas are not laid.

- **Methane (CH_4)**. A lightest hydrocarbon in paraffin series. Colourless odorless, flammable. It forms a major portion of marsh gas and natural gas.

- **Natural gas**. A natural fossil gaseous fuel usually associated with petroleum oil. **Composition**: Methane 60 to 80%; Ethane 5 to 8%; propane 3 to 18%; heavier hydrocarbons 2 to 14%; Also non- hydrocarbons present sometimes in natural gas are : nitrogen, hydrogen sulfide; nitrogen; carbon dioxide. Propane, butane, pentane are the heavy hydrocarbons present in natural gas. They are removed from natural gas and sold as LPG. Pipeline Natural gas has energy density 52 MJ/kg-

- **Natural Gas Liquids** : Propane; Butane, Pentane are recovered from natural gas by processing in field separators; scrubbers, gas processing and reprocessing plants.

- **Natural Gas Products** : Liquids including natural gasoline, which are recovered from natural gas by processes of adsorption; absorption, compression or refrigeration of natural gas.
- **Natural Gasoline** : A mixture of liquid hydrocarbons extracted from natural gas and stabilized to obtain liquid products suitable for blending with refinery gasoline (petrol).

- **OAPEC** : Organisation of Arab Petroleum Exporting Countries **Members** (1968) : Saudi Arabia, Kuwait, Libya; and later (1970) : Abu Dhabi, Algeria, Bahrain, Dubai, Quatar.

- **OPEC** : Organization of Petroleum Producing Countries, Founded in 1960. Head Quarters in Vienna. **Members**: Abu Dhabi, Algeria, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Quarter, Southi Arabia, Venezuela.

- **Oil Shale**. Range of material containing organic matter (kerogen) which can be converted to crude shale oil, gas and organic carbonaceous residue by heating.

- **Petroleum** : An oily, bituminous flammable liquid of several colours ranging from colourless to black. Petroleum contains a complex mixture of hydrocarbons with little of other substances. Prepared for use as gasoline (petrol for car engine; naptha, other products by various refining processes.

- **Petroleum Naptha** a generic term applied to refined, semi-refined, unrefined petroleum products and liquid products of natural gas. Napthas used for cleaning, manufacture of rubber, paints, varnishes etc. have high volatility.

- **Petroleum spirits** : A refined petroleum distillate with high volatility and used for thinners and solvents of paints and varnishes and similar products.

- **Petroleum Tar** : Viscous black/brown substance obtained as residue while refining petroleum. Tar yields substantial solid residue when evaporated or fractionally distilled.

- **Photosynthesis** : Conversion of carbon dioxide and water to glucose and other complex organic materials by green plants exposed to sunlight.

- **Raw gas** : Natural gas in its naturally occurring state.
- **Refining** : A process of distilling crude oil in several stages to obtain various usable substances from each successive stage. Components of low molecular weight vaporise first. Typical crude fractions are ether, methane, ethane, propane, butane kerosene, fuel oil, lubricants, jelly paraffin, asphalt and tar.
- **Surface Mining** : Open cast mining, strip mining. Mining of coal from outcropping i.e. removal of upper surface layers of coals (as opposed to underground mining).
- **Syncrude** : Synthetic crude removed from oil shale or coal.
- **Synthetic Natural Gas (SNG)** : Gaseous fuel manufactured from coal or Naptha. Contains about 95 to 98% of Methane.
- **Tar Sands** : Deposits bearing hydrocarbons of high viscosity.
- **Ton** : Unit equal to 2000 pounds in USA, 2240 pounds in UK.
- **Metric Ton** : Is equal to 1000 kg = 2204.6 pounds.
- **Water Gas** : A mixture of gases produced by injecting steam through coke or coal.

1.4 SUGGESTED READINGS

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FOSSIL FUELS

2.0.1. COAL

Coal began to form 225 to 350 million years ago in the hot, muggy regions of the earth. Ancient plants flourished in and along the banks of lakes, streams and coastal swamps; leaves fell into water and got accumulated on the bottom. Their rate of accumulation was much faster than their rate of decomposition. Eventually, this rich organic material was covered by mud or sediment eroded from the land, and over time, heat and pressure converted the organic material into peat and then coal.

Coal seams can be 100 meters thick and can extend over tens of thousands of square kilometers in areas that were once vast swamp forests in the pre-historic times.The value of coal as a fuel was first discovered in 12th or 13th century by the inhabitants of the north east coast of England.

Coal is the organic fossil material which is solid and black in colour with varying properties and composition. It is essentially rich in amorphous carbon and contains several liquid and gaseous hydrocarbons.

2.0.1.1 Types of Coal

On the basis of characteristics, heating value, carbon and volatile matter, coal is divided into mainly the following types:

a) Anthracite (hard coal)

- It is hard, black, lusturous, shiny and dense.
- This is the highest grade coal with calorific value of 8,250 to 8,700 kcal/kg.
- It contains 86-98% of carbon.
- Volatile matter is low being just 2-14%.
- It is not found in India. It mainly occurs in UK & USA.
- It is used in industrial furnaces, graphite electrodes and in metallurgical processes.

b) Bituminous (Soft coal) :

- It is also high grade coal next to anthracite.
- It has a calorific value in the range of 7,500 to 8,700 kcal/kg. It contains about 46-86% carbon.
- Volatile matter is low and can be removed by heating in the absence of air, when it gets converted into coke. More the volatility, lower is the heating value.
- It is used for combustion, hydrogenation, gasification, blending, domestic use and metallurgy.

C) Lignite (Brown coal)

- It is inferior quality, low grade coal.
- It has laminar (banded) structure with woody, fibrous, brownish black appearance, resembling wood, hence the name. In Latin, Lignum means wood.
- Its calorific value is 6,150 to 7,300 kcal/kg.
- It has a moisture content of about 30-50% before exposure to air.
- Its volatile matter is about 30%.
- Lignite when exposed to air gets oxidised.
- Due to high moisture, rapid oxidation and low heating value, it is not economical to transport it to distant places.
- It is burned in pit head power plants.

d) Peat

- Peat is a solid fuel with highest moisture content.
- It is not fully matured form as it is partially decomposed, so it is not true coal.
- Its heating value is much less and is lower than that of wood.
- It has about 90% moisture.
- It is used as a low grade fuel.

2.0.1.2 IMPORTANT PROPERTIES OF COAL

The most important properties of coal for energy evaluation are follows:

- Calorific value (Heating Value)
- Volatile matter
- Fixed carbon
- Chemical composition (C, H, S, N, 0, ash minerals, H_2O).

The chemical composition is rather more important from the environmental point of view. If it is having more sulphur content, it would release more SOx and cause more pollution.

Various characteristics of coal arc calculated and expressed as d.m.f. which is the Gross Value for pure coal.

(1) Calorific value (CV)

$$\text{CV (d.m.f.)} = \text{C.V. (measured)}\ \frac{\text{X } 100}{\underset{\text{percent}}{100 - (\text{moisture}} - \underset{\text{percent}}{1.1\ \text{ash})}}$$

d.m.f. = Heating value of pure coal without minerals.

(2) Volatile matter d.m.f. 100 - Carbon percent

$$\text{Fixed carbon (d.m.f.)} = \frac{\text{Fixed carbon determined} \times 100}{100 - (\text{moisture\%} + 1.1\ \text{ash\%})} \quad (3)$$

2.1.1.3 Coal Production and Processing

Various production technologies involve exploration, mining, preparation, sorting, cleaning, storage and transportation.

The coal conversion technologies include coal gasification, liquefaction, coal slurry, coal carbonisation for coke and coal gas production.

Coal mining is done in two distinct ways:

- Surface mining, in which the coal beds are near the ground surface with little over-burden of soil (depth < 30 m).
- Underground mining - here the coal beds are located at depths.

After mining, the coal is prepared to make it suitable for a particular use. The coal is purified by removing dirt, mud etc. and sulphur is also removed because sulphur present in coal is responsible for high SO_2 emissions on burning.

Coal is converted from solid form to liquid or gaseous form also. Yarious solid, and gaseous fuels have their specific application. Direct burning of coal results - emission of particulates, smoke, SOx - NOx, CO and CO_2, The gaseous or liquified fuels cause lesser pollution. Some important coal conversion technologies are discussed below :

Coal Gasification

It involves chemical reaction of coal, steam and air at high temperature. A coal water mixture called a Slurry is injected with oxygen into a heated chamber, producing three combustible gases: Carbon monoxide, hydrogen and some methane. The heated gas is then cooled and purified. The resultant gas bums as cleanly as natural gas.

This gas can be used for domestic purposes. Fig.-l shows a schematic diagram of the gasification technology.

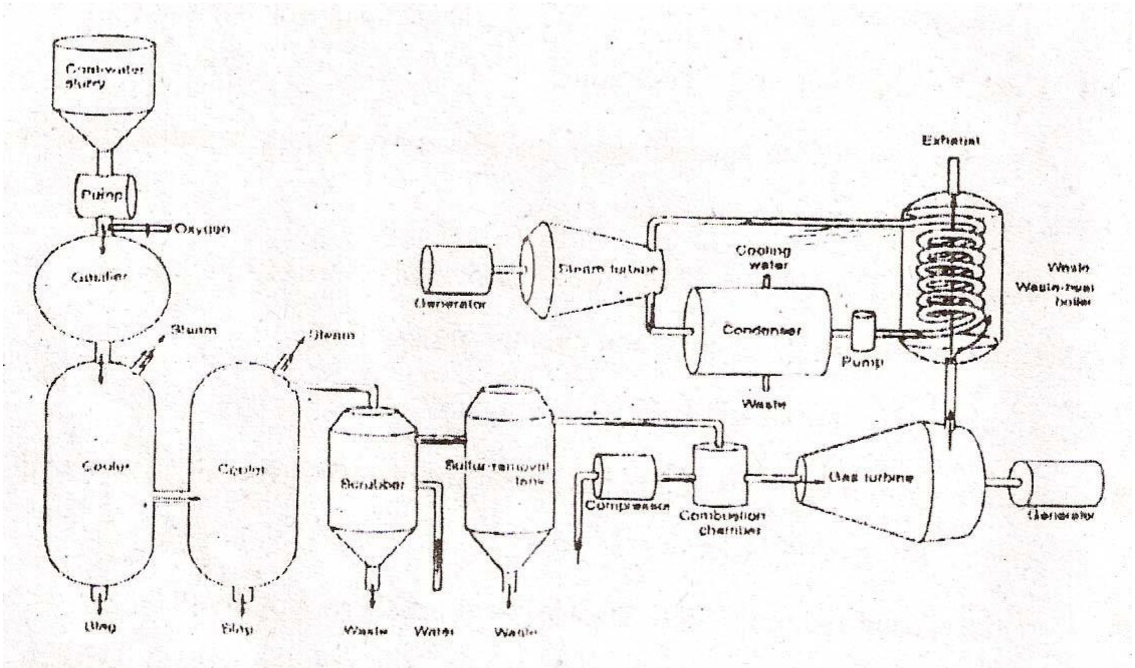

Fig.-l An efficient coal gasification process. In this process coal particles mixed with water are sprayed into a heated furnace (gasifier) where steam and combustible gases are produced. The gases are then cleaned by passing them through water. The gases of next *burned and the exhaust gas is used to spin one of two electrical generators. The heat is also captured to generate steam, which operates another generator.*

Fluidized Bed Combustion

While burning coal, a lot of pollution occurs. So there is a need to burn coal in cleaner way. Fluidized Bed combustion is one such important technology, in while coal is crushed and mixed with bits of limestone and propelled into a furnace in strong current of air (Fig.-2). The particles mix turbulently in the combustion chamber ensuring very efficient combustion and therefore, low levels of carbon monoxide are produced. The furnace also operates at a much lower temperature than a conventional coal boiler, thus reducing nitrogen oxide emissions. The limestone reacts with sulphur oxides producing calcium sulphite or sulphate, thus reducing SOx emissions from the stacks.

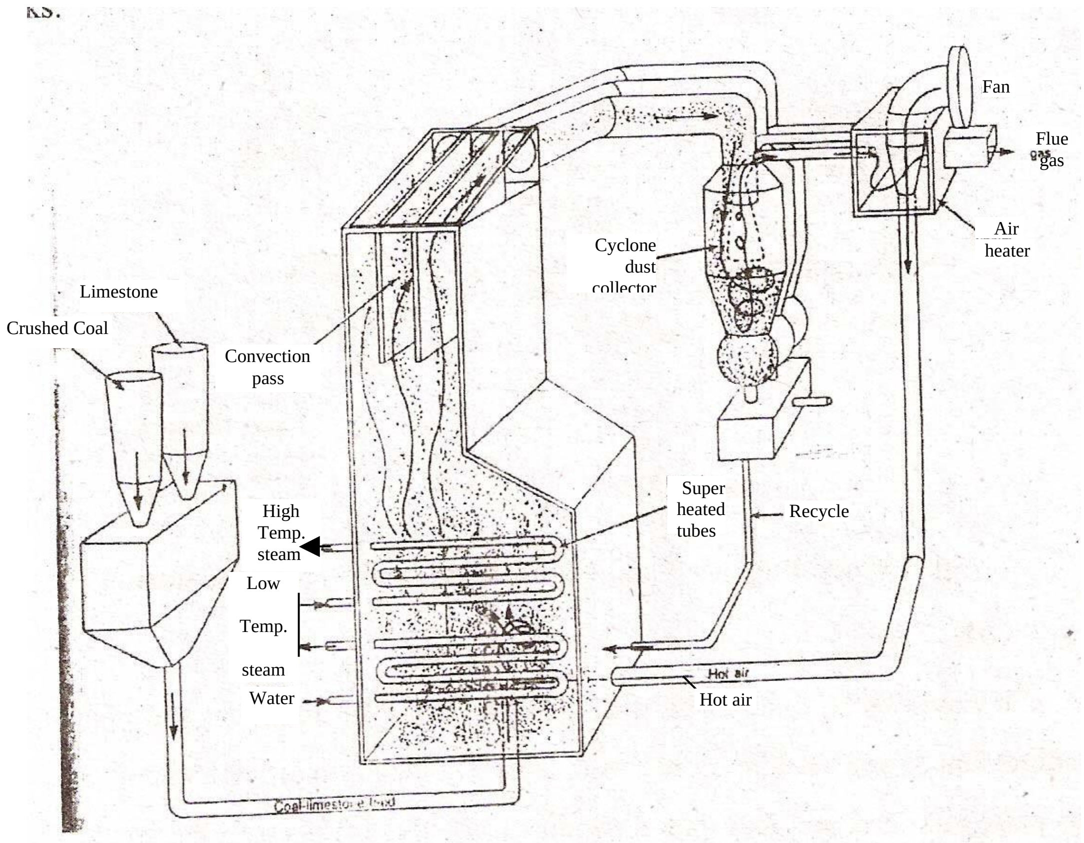

Fig. 2 Fluidized bed combustion. This process burns crushed coal blown into a furnace mixed with tiny limestone particles. The air turbulence in the furnace ensure thorough combustion, thus increasing efficiency. The limestone reacts with sulfur oxide gases moving most of them from the smokestack. Steam pipes in the furnace help maximize heat efficiency.

Coal Liquefaction

Coal can also be treated to produce a thick, oily substance by liquefaction. At least 4 major processes now exist which add hydrogen to coal to produce oil. The oil can then be refined like crude oil to produce a variety of products like jet fuel, gasoline, kerosene, many chemicals, drugs and plastics.

Coal liquefaction is a costly process and it generates pollutants like phenols. It also does not help in CO_2 emission reduction.

Flow diagram of coal liquefaction is given in Fig.-3.

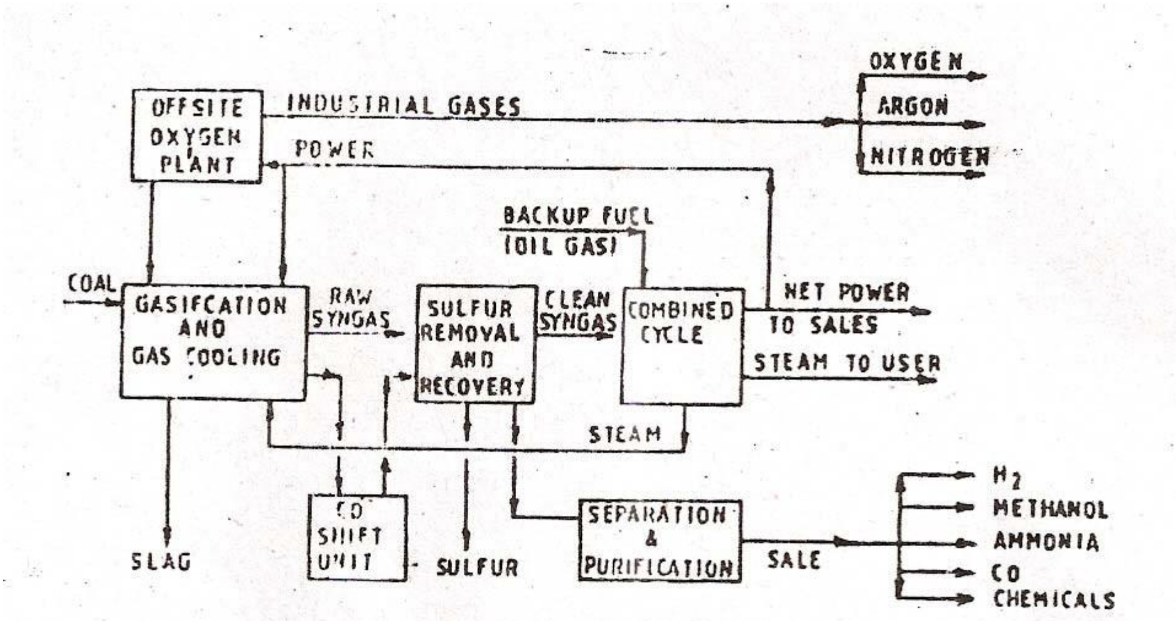

Fig. 3 Flow diagram Coal Liquefaction and Coal Dissolution

2.0.2. OIL

It was in 1859, when a steel drill in Pennsylvania hit 20 meters and a black, foul smelling liquid came gushing from a well. This was the dawn of a new energy era. This was petroleum and just less than a century later, this oil became the world's most important energy resource.

Being liquid and relatively easy-to transport long distances, either by ship or by pipeline, oil has been accepted as an ideal fuel. It burns cleaner than coal, but less cleaner than natural gas.

Oil is also obtained from oil shales and sand tars. Oil Shale is a grayish brown sedimentary rock that was formed millions of years ago from the mud at the bottom of lakes. Within the rock is contained a solid organic material called as, kerogen. When heated to high temperatures, the rock gives off its oily residue called Shale oil. High grade oil shale can produce upto 120 litres of shale oil per ton of rock. Like petroleum, shale oil can also be refined to produce gasoline, jet fuel, kerosene and a variety of feed stocks used by chemical industry to produce fabrics, drugs and plastics.

Tar sands are found in some parts of the world where oil is found to have migrated into neighbouring layers of sandstone, creating tar sands. The thick oily residue, called bitumen can be extracted from the rock and refined to produce a variety of fuels and chemicals in much the same way that shale oil is processed.

2.2.3 NATURAL GAS

Natural gas is primarily methane (CH_4). Like coal and oil, it is a fossil fuel. It was given off by decomposing plant and animal remains that were buried in the earth by sedimentary deposits for millions of years. That is why, natural gas deposits often accompany coal and oil deposits.

Natural gas is the cleanest fossil fuel. It can be easily transported within the country by pipeline. It is used primarily for heating buildings, home cooking, industrial processes and generating electricity.

Natural gas is one of the most important fuel resources in the world. The transportation of natural gas to multiple consumers started as early as in 1880 itself. Since the second world war the expansion of the natural gas industry was spectacular throughout the world. Currently; the amount of natural gas depositions in the world are of the order of 80, 450 Gm^3. The best endowed country is the erstwhile Soviet Union with 40.0% of world reserves while the second is Iran with 14% of world's reserves, followed by USA (7%).

Composition of Natural Gas

At normal temperature and pressure, the contents of commercial natural gas are mainly methane (CH_4, ethane (C_2H_6) and varying amounts of propane (C_2H_8) and butane (C_4H_{10}). An average composition of natural gas indicates methane-83.0%, ethane 7.2%, propane-2.3%, butane-1.0%, N_2-5.8%, CO_2- 0.2% etc. There may be traces of helium, oxygen, hydrogen and other substances. The main impurities are N_2, CO_2 and H_2S. If H_2S is more than 10 grains/m^3, it is removed commercially and converted to elemental sulphur by Clauss process. If concentration of H_2S is less, it is removed by the process called 'sweetening'. Natural gas containing H_2S is called 'SOUR GAS'. It has an unpleasant odour and H_2S dissolved in water follows a mild acid which is corrosive to pipes and valves. Some sources of natural gas contain helium upto 8% also. As such, natural gas is the main source of helium.

Origin of Natural Gas

According to one theory, when, earth was born, it was surrounded by methane, water, ammonia and hydrogen. Energy radiation from the sun and lightening discharges broke these simple compounds to a large number of organic compounds like 'amino acids' which form proteins, the 'stuff of life', In 1953, Nobel prize winner Harold C. Urey and Stanley Miller showed that electric discharge converts a mixture of methane, water, ammonia and hydrogen into complicated organic compounds that are responsible for making up living organisms. Thus methane generated in the final decay of dead organisms may well be the same substance from which the organism was derived. After the escape of hydrogen, oxidation of methane and breaking up of water, O_2 and N_2 remained in the earth's atmosphere. The methane is found most often, with or near the oil deposits, which indicates a major method of its formation. The gas could be considered to be the product of the microbial decomposition of organic matter in the absence of oxygen. The methane gas also escapes from decaying vegetation in swamp lakes mixed with little H_2S and CO_2, The gas also occurs in fire damps in coal mines creating explosion hazards. Methane is present in some gold and uranium mines of South Africa mixed with helium gas. Methane is also produced by the biological treatment of sewage or solid organic wastes under anaerobic conditions. These areas could be important sources of methane based on renewable resources.

Properties of Natural Gas

Since most of the natural gases contain methane over 90%, natural gas become synonymous to methane: It is the simplest form of hydrocarbon alkanes'. The melting point of methane is -183°C and its boiling point is
-161.8°C. Natural gas can also be liquefied and Liquefied Natural Gas (LNG) is ideally transported across the sea in specially designed tankers. Density of LNG is 425.0 kg/m^3. The critical point of LNG is 82.1°C at
48.0 kg/cm^2. The atmospheric boiling point of LNG is -161.5°C. Comparative analysis of properties of methane and natural gas are discussed as follows:
The gross calorific value of natural gas is 1000 (k.cal/cu.m.), for methane it is 995 kcal/m^3. The net calorific value for natural gas is 902 kcal m^3 whereas for methane it is 859 kcal/m^3. The specific gravity of natural gas is 0.59 whereas for methane it is around 0.555. The stoichiometric air requirement (vol air/ vol gas) is. 9.6 for natural gas, whereas for methane it is 9.52. The inflammability limits for both the gases are 5-15% gas. The spontaneous ignition temperature for natural gas is 700°C. Methane is a colourless gas and less dense than water. Methane is a gas at ordinary

temperature, slightly soluble in water, but highly soluble in organic liquids like gasoline under ultraviolet rays or at 250-400°C, methane and chlorine combine to yield HCI and CH_3Cl called chloromethane or methyl chloride. This is called chlorination which may lead to the formation of CH_2Cl_2 (dichloromethane or methylene chloride), $CHCl_3$ (trichloromethane or chloroform) and CCl_4 (tetra chloromethane or carbon tetrachloride). Methane reacts with fluorine even in the dark at room temperatures. Methane affects skin, throat and lungs. Being malodorous it presents an unpleasant atmosphere. It retards the growth of vegetation.

Sources of Natural Gas

There are mainly two sources of natural gas. It occurs in gas fields i.e. underground reservoirs similar to oil reserves and is recovered by drilling gas wells. In addition, large quantities of gas are produced in association with the production of crude oil. Oil normally contains alkanes from methane upwards. In the reservoir the lower gases are in solution from under considerable pressure. When the oil is brought to the surface, the pressure is released forming associated gas. In some oil fields, particularly those in inaccessible regions, this gas is burnt. In other fields it is collected and used. Composition of a typical associated gas is 76% CH_4; 11.4% C_2H_6; 5.3% C_3H_8; 2.2% C_4H_{10}; 1.3% C_5H_{12}; 2.3% CO_2 and
0.3% H_2S.

Synthetic natural gas, a mixture of carbon monoxide and hydrogen is an ideal connecting link between a source of fossil fuel and substituted natural gas. The low grade coal is initially transformed into synthetic gas ($CO+H_2$) by gasification process followed by catalytic conversion to methane. The substituted natural gas can be used as a fuel or as a feed back stock for chemical and allied industry.

Uses of Natural Gas

Natural gas is used in many ways. The global consumption of energy in the form of natural gas is presently equal to one half of the consumption of energy in the form of petroleum. Natural gas is used in energy sector, in gas turbines and in diesel engines. Natural gas is also used in the compressed form for road transport. It is the main energy resource in chemical and fertilizer industries. Natural gas is used extensively in petrochemical, metallurgical and sponge iron manufacturing units.

2.2.4 ENVIRONMENTAL IMPACTS OF FOSSIL FUEL PRODUCTION AND CONSUMPTION

There are several important environmental impacts of fossil fuel extraction as well as consumption.

2.2.4..1 Impacts of mining and burning of coal

Coal is mined by strip mining on flat terrains and by underground mining.

In strip mining, the top soil is first removed by bulldozers and set aside and thus the top fertile layer is lost. Surface mining is a fast and efficient way of removing coal but it creates on ugly eyesore that can erode away the soil. If proper precautions are not taken it results in spilling sediments into streams and lakes and destroys fish habitats, recreation sites and reservoirs that supply water for human populations. Surface mining creates dust and noise and destroys wildlife habitat, at least temporarily. Surface mines can also cause groundwater levels to fall considerably, drying up municipal and agricultural wells in the neighbouring areas.

Underground mining also result in disturbance of as much land. Underground mines can also collapse, killing workers. They can cause sinking of the surface, a process called **subsidence**. Subsidence causes the sinking of buildings and roadways, splitting apart of buildings, tilting of poles and railway tracts etc. and hence cause a lot of problem. Cracks in the earth's surface can also swallow streams, sending water into coal seams.

Water which seeps into mines, either naturally or as a result of subsidence cracks and combines with naturally occurring iron pyrites and oxygen and produces sulphuric acid. This acid mine drainage pollutes the groundwater as well as the nearby streams.

Mixed areas being devoid of vegetation are also prone to large scale erosion of soil and land degradation.

Combustion of coal is another important environmental problem. Four major pollutants that are emitted by coal combustion are carbon dioxide, sulphur dioxide, nitrogen dioxide and particulate matter.

Burning of coal has resulted in massive build-up of carbon dioxide in the atmosphere which is a greenhouse gas responsible for global warming.

Oxides of sulphur and nitrogen are acid precursors which combine with water (rain or dew drops) to form sulphuric acid and nitric acid, respectively and cause acid rains. The acid falls to the earth along with rain or snow, acidifying lakes, streams etc. and killing the fishes. They also kill trees and crops, damage the buildings and statues on which they fall.

2.2.4.2 Impacts of oil production and consumption

Oil comes from wells on land and at sea. The impacts of oil on the sea are very important. During handling and transportation lot of pollution is known to occur. Crude petroleum contains hydrocarbons; sulphur, nitrogen, oxygen and several heavy metals.

During handling, oil pollution occurs at the following stages:

- **Cargo tanker washings**: Oil wastes are discharged into the sea. As the tankers reach their destination they are emptied and filled with water to avoid floating too high. Before re-filling the dirty water is pumped out into the sea, thus polluting it. About 3 million tonnes of oil are discharged annually in this manner.

- **Bilge pumping at sea**: The dirty water which accumulates in the bilge (basal flat part of the ship) transporting oil also add substantial amounts of oil in the water reaching upto a tune of 5 lakh tons per year.

- Oil tanker collisions often cause oil spills in the oceans. The famous Torrey Canyon Accident was responsible for 1,17,000 tons of Oil spilling in the British Channel.

- During loading and unloading millions of tons of oil are lost at the sites of port into the water annually.

2.2.4.3 Impacts of oil spills

Since oil spills are immiscible with water, therefore, the spills keep on floating. The oil spreads very quickly over the water surface. One cubic meter of oil spill would spread to 48 meter diameter circular area in just
10 minutes. Some of the oil gets volatilized and some gets emulsified. Some oil gets degraded, but the degradation is slow. Due to the oil spill the following impacts occur:-

(i) As a result of oil spill over the water surface, there is reduced light transmission to lower layers: About 90 percent of light is cut off by the oil layer and due to inadequate light penetration, photosynthesis in marine flora is adversely affected and that affects the whole of the food chain.

(ii) Marine life is badly affected due to oil spills. Swimming and diving birds are covered with oil - the feathers of birds get matted with oil and the birds are unable to fly or swim. Many birds die due to such oil spills.

(iii) Even the shoreline plants get smothered by the oil and the stomata on the leaves are clogged. The flowers and fruits get smothered and the plant ultimately dies.

(iv) The oil contains many saturated hydrocarbons which adversely affect lower marine animals. Benzene, toluene, xylene etc. are even poisonous to human beings. Hydrocarbons like Naphthalene and phenanthrene present in the oil are highly toxic to fish.

(v) Aromatic compounds are more soluble in water and they kill aquatic life.

(vi) Many of the organic compounds present in the oil spills get biomagnified along with the food chain and accumulate in high concentrations in the animals occupying a high trophic level in the aquatic food chain.

(vii) The aromatic compounds with high boiling point which are constituents of the oil spills are often carcinogenic (cancer causing) in nature.

2.2.4.4 Impacts of oil refining

Petroleum refining is a combination of processes and operations designed to the crude oil into several fractions like motor gasoline, diesel fuel, heating oil, kerosene, jet fuel, bunker fuel, LPG, aviation gasoline and tractor fuel.

The refining process releases- a lot of waste water as 20-70 litres of waste water is produced per litre of crude oil processed. The waste water contains acidic discharges as well as phenolic compounds of which chlorophenol, p-cresol etc. are more important which are often found to percolate deep and contaminate the ground water. If such waters are consumed, it may cause serious health problems like nervous disorders or even cancer.

The oil refineries also cause air pollution. There are hydrocarbons, Sox, Nox, CO and SPM emissions from the refineries. Sulphur contents of the crude oil varies from 0.2 to 2.5%.

The sulphur dioxide emissions are responsible for acid rains in the vicinity of the refineries. The Mathura Refinery has been responsible for the corrosion of the white marble of Taj Mahal, the greatest monument of cultural heritage of our country. The acidic emissions cause necrosis and chlorosis of the leaves and corrosion of materials. They also cause respiratory ailments and irritation of eyes and skin.

2.2.4.5 Impact of oil shale production

The spent shale, after the burning of oil shales produce huge bulks which are to be disposed off. They often contaminate the groundwater and surface waters. The oil shale production pollutes the atmosphere also by releasing sulphur oxides, nitrogen oxides; heavy metals and various organic pollutants - all toxic to humans and wildlife.

Oil shale retorts also require huge volumes of cooling water about 2.5 barrels per barrel of oil produced and thus precious fresh water gets contaminated.

Thus, energy production from fossil fuels as well as their consumption have far reaching environmental impacts.

2.3 SUMMARY

Fossil fuels are derived from plant and animal remains buried in the earth millions of years ago. Fossil fuels i.e. Coal, petroleum and natural gas provide 85-90% of energy demand of the modern world. Coal is of three types – Anthracite (with maximum carbon and energy), bituminous and lignite. Coal is processed by different techniques like coal gasification to produce gas that burns as cleanly as natural gas. Coal liquification is done to produce a thick, oily substance. Petroleum is most widely used fossil fuel. It is also obtained from oil shales, which is a sedimentary rock and tar sands. On fractional distillation petroleum yields a large variety of substances. Natural gas, mainly comprising methane is the cleanest fossil fuel. While fossil fuels are the backbone of development and economy, they are also major sources of environmental pollution. Burning of coal results in gaseous emissions including oxides of sulphur and nitrogen, suspended particulate matter and heavy metals. Oil spills causes Marine pollution and harm to marine biology. Mining of these fossil fuels also result in large scale degradation of land and ecology.

2.4 KEY WORDS

Subsidence - Sinking of land surface

Oil shale - Oily residue in sedimentary rocks.

Tar sand - Oily residue in sand-stone layers.

2.5 SELF-ASSESSMENT QUESTIONS

1. What are the different types of coal? Discuss their properties and use.
2. Write a brief note on the following.
    a) Coal gasification
    b) Fluidized Bed Combustion
    c) Coal Liquefaction
3. Describe petroleum resource, oil shales and tar sands.

4. Discuss the impacts of coal mining and burning.
5. Which fossil fuel is the cleanest? Discuss.
6. What are the environmental impacts of petroleum production and use?

2.6 SUGGESTED READINGS

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1.0. TIDAL ENERGY

All flowing waters carry with them kinetic energy. When such water encounters a turbine, part of the momentum of the flowing water is transferred on to the turbine, causing it to rotate. The rotation of the turbine can then be used to generate electricity. Whether the water is in the open ocean, an estuary or a river, its motion can thus be utilized in generating energy. The tides occurring in the oceans are one such source of energy based on the movement of water.

Tides are generated by the action of gravitational forces of the sun and the moon on the oceans, due to the spinning of the earth around its axis and the relative positions of the earth, moon and the sun.

The tides are the periodic vertical rise and fall of ocean water. The period between consecutive high tides is 12.5 hours. The tidal rise and fall of water is accompanied by periodic horizontal to and fro motion of water called tidal currents. Tides and tidal currents are intimately related.

Tidal movement differs from wave-movement. Waves have a period of only about 6 seconds whereas tides have a period of 12.5 hours. Waves are caused by surface winds, whereas, tides are caused by the gravitational forces of moon and sun on ocean water.

The amplitude of tides covers a wide range from 25 cm to 10 m. The speed of tidal currents is in the range of 1.8 km/h to 18 km/h. The tides and tidal currents possess renewable energy.

The rise and fall of the water level follows a sinusoidal curve, shown with point A indicating the high tide point and point B indicating the low tide point. The average period of time for the water level to fall from A to B and then rise from B to C is each approximately equal to 6 hours 12.5 min. (Figure 1.1).

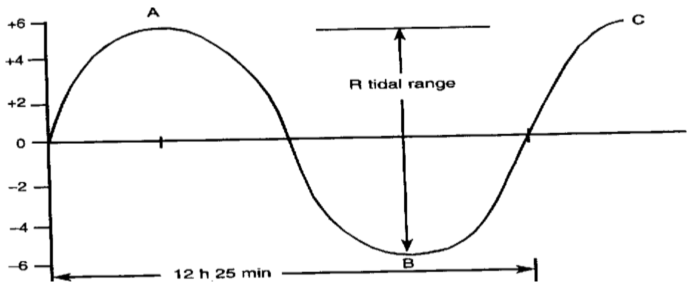

Figure 1.1. The tides of sea.

The difference between high and low water levels is called the range of the tide. The tidal range R is defined as :

R = water elevation at high tide - water elevation at low tide.

Because of the changing positions of the moon and sun relative to the earth, the range varies continuously. There are however, some characteristic features of this variation.

During full or new moon, when sun, moon and earth are approximately in a line, the gravitational forces of sun and moon are enhanced. The tidal range is then exceptionally large, the high tides are higher and low tides are lower than the average. These high tides are called spring tides. On the other hand, near the first and third quarters of the moon, when the sun and moon are the right angles with respect to the earth, neap tides occur. The tidal range is then exceptionally small; the high tides are lower and the low tides higher than the average. Hence the range is not constant. It varies during the 29.5 day lunar month (Figure 1.2), and is maximum at the time of new and full moons (called the spring tides), and minimum at the time of the first and third quarter moons (called the neap tides). The spring-neap tidal cycle lasts one-half of a lunar month. A typical mean range is roughly one third of the spring range. The actual variations in range are somewhat complicated by seasonal variations caused by the ellipticity of the earth's orbit around the sun.

The variations in the periodicity and monthly and seasonal ranges must, of course, be taken into account in the design and operation of tidal power plants. The tides, however, are usually predictable and fairly accurate tide tables are usually available.

Tidal ranges vary from one earth location to another. They are influenced by such conditions as the profile of the local shoreline and water depth. When these are favourable a resonance like effect causes very large tidal ranges. Ranges have to be very large to justify the huge costs of buildings dams and associated hydroelectric power plants. Such tides occur only in a few locations in the world.

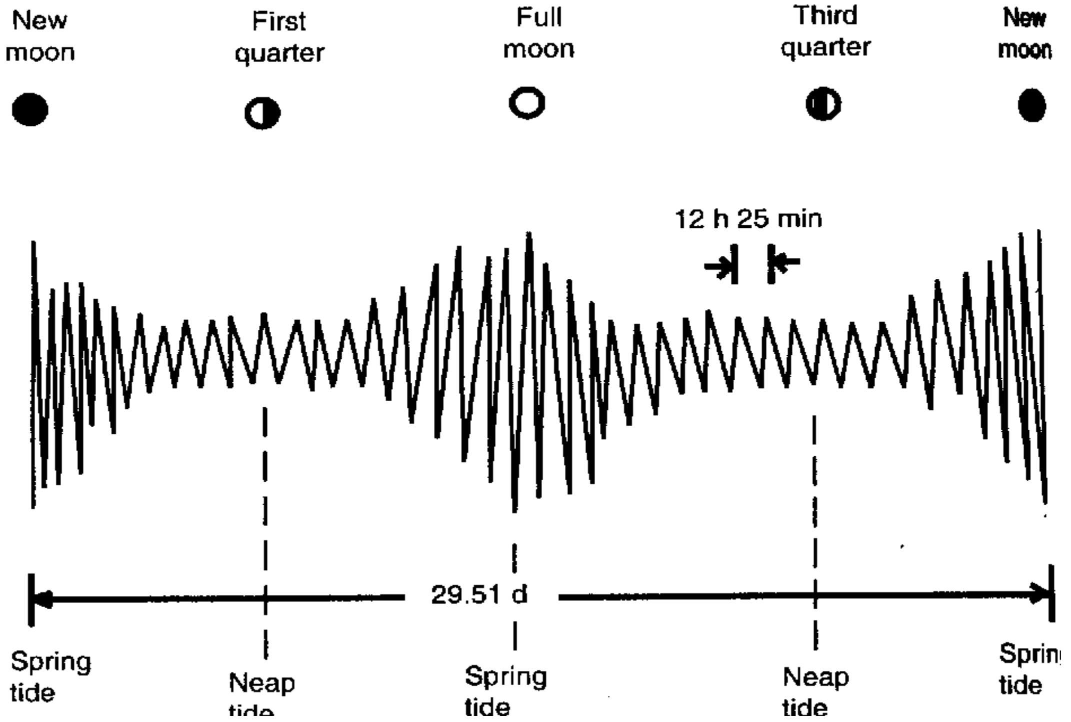

Figure 1.2. Relative high and low tides showing variation in range during lunar month.

The tides along most coastlines are amplified by a funneling action, they may rise by 10 meters or more. It is in these constricted areas that the most effective tidal power plants may be located. A dam or sluice gate is placed across an ocean bay or estuary. An incoming tide fills up the enclosed basin while passing through a row of hydraulic turbines. After the basin is filled with water, the gates are closed and the turbines are shut down. Then the turbine blades are reversed and the gates opened again to let the water surge out. Thus turbines would be rotated either way generating electric power.

The tides are daily movement of large bodies of water driven by gravitational attractions between the sun, earth and moon. Twice a day, large volumes of water flow in and out of bays and river opening on the coast to produce high and low tides. The principle of tidal power generation is the same as that employed in a hydroelectric plant. What is needed is a bay with an opening to sea narrow enough to be closed by dam having gates that can be opened and closed. The bay fills as the tide comes in through open gates. The gates are then closed to flow out the water through a turbine that generates electricity (Fig. 1.2). Some tidal energy schemes use only out flowing tide to produce energy while others use both in flowing and out flowing tides to generate energy.

1.2.1. Potential of tidal power and present status of its utilization

The idea of harnessing tidal energy came to man hundreds of years ago. First tidal mill appeared on the Brittany coast of France in 12th century. Thereafter many tidal mills were reported to have been in operation along the Atlantic Coast of Europe, mostly in Great Britain, France and Spain. However, construction of modern tidal electric stations have been attempted only in 1960. The first modern tidal electric mill La Rance capable of generating 240 MW was built in the Rance Estuary (France) in November 1966. It uses both the inflowing and outflowing tides. The Bay of Fundy in Canada has great (as yet untapped) potential for producing tidal power, because it has the highest tidal height (18 m) in the world. India is fortunate to be endowed with a few potential sites worthy of consideration for tidal power development. The important potential tidal sites are shown in Table 1.

Table 1. Tidal power potential in India.

Site	Maximum tidal range	Average tidal range	Tidal power potential
Gulf of Cambay	11 m	6.77 m	7,000 MW
Gulf of Kutch	8 m	5.23 m	1,000 MW
Ganga delta of Sunderbans	5 m	2.77 m	1,000 MW

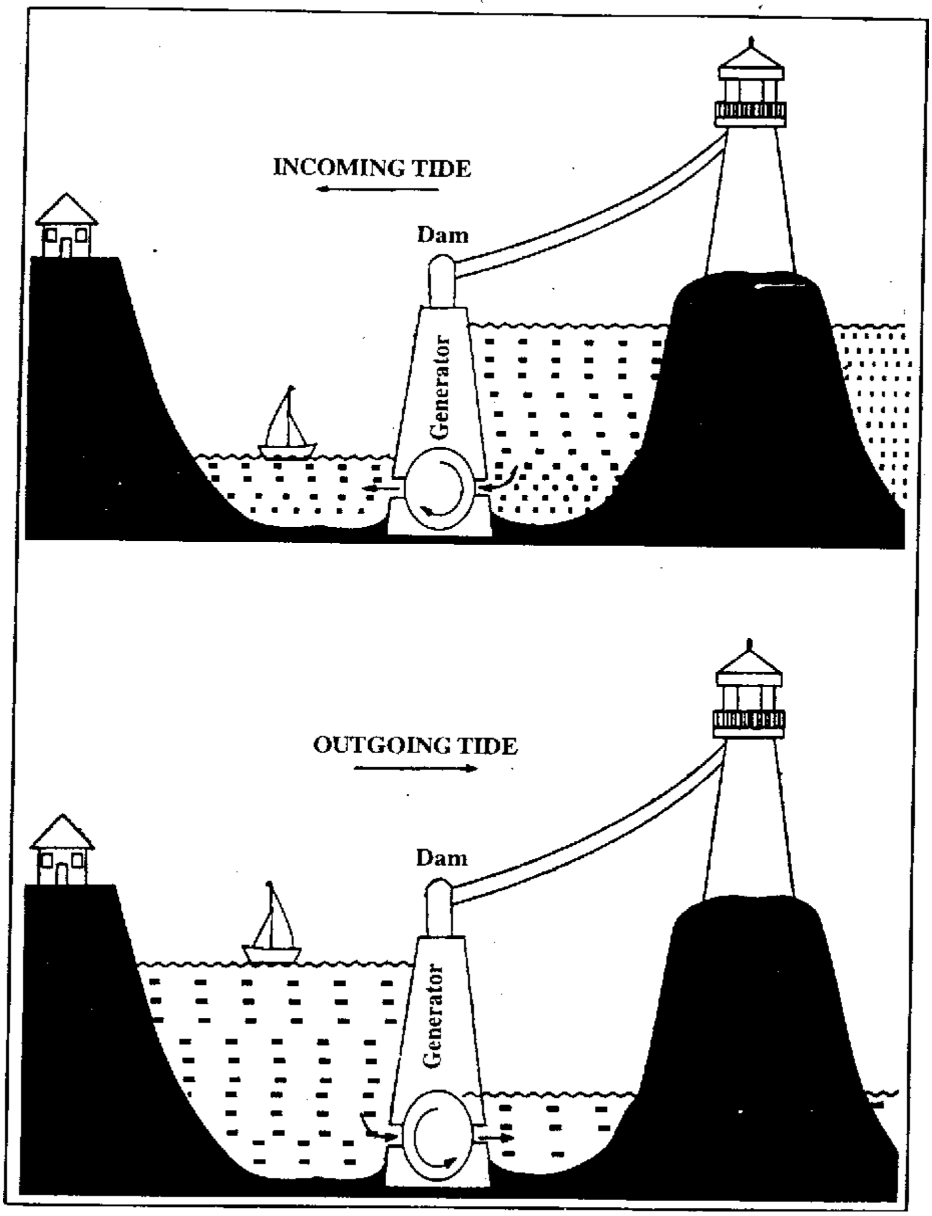

Figure 1.3. Diagrammatic representation of a tidal power station.

The identified tidal power potential in India is around 9000 MW. According to an official report, the proposal to set 900 MW power plant by National Hydropower Corporation during the ninth and tenth plans is under consideration. The proposed Kutch Tidal power Project envisages generating 1660 GWh per annum. It is estimated to cost about Rs. 1460 crores.

1.2.2. Tidal power schemes in India

The most attractive tidal power sites are the Gulf of Cambay and the Gulf of Kutch where the maximum tidal range is of the order of 11 m and 8 m respectively and the average tidal range is of the order of 6.8 and 5.2 m, respectively. The techno-economic feasibility of the Gulf of Kutch Scheme was taken up by the Central Electricity Authority, Government of India. The scheme envisages a single basin, single effect development with an installed capacity in the range 800-1000 MW. The main tidal barrier is about 3.25 km. The scheme is expected to cost Rs. 6000 crores, according to 1993 prices. But this project was not taken up as it was too expensive when compared to the conventional hydropower projects. Another potential site is the Sunderbans with a maximum tidal range of 5.0 m and an average tidal range of 3.0 m.

The promising sites for tidal power plants are located in Gujarat state and West Bengal state. Survey of other sites in Orissa, Tamil Nadu, Kerala, Karnataka and Maharashtra, Andaman Nicobar etc . is being done by the Non-conventional and Renewable Energy Department. The sites have good prospects but require extremely high investments compared to conventional power plants of the same rating. The estimated tidal power potential in India is about 15000 MW.

1.2.3. Advantages and limitations of tidal power generation

Advantages :

1. The biggest advantage of tidal power, besides being inexhaustible, is that it is completely independent of the uncertainty of precipitation (rain). Even a continuous dry spell of any number of years will have no effect whatsoever on the tidal power generation.
2. Tidal power generation is free from pollution, as it does not use any fuel and also does not produce any unhealthy waste like gases, ash, etc.

3. These power plants do not require large areas of valuable land because they are on the bays (sea shore).
4. Peak power demand can be effectively met when it works in combination with thermal or hydroelectric systems.

Limitations : There are a number of reasons why the tidal power generation is still a novelty, rather than a normal source of energy. The reasons are:

1. The fundamental drawback to all methods of generating tidal power is the variability in output caused by the variations in the tidal range.
2. The tidal ranges are highly variable and thus the turbines have to work on a wide range to head variation. This affects the efficiency of the plant.
3. Since the tidal power generation depends upon the level difference in the sea and an inland basin, it has to be an intermittent operation, feasible only at a certain stage of the tidal cycle.
4. The tidal range is limited to a few metres. As the bulb turbine technology was not well developed for this range, use of conventional kaplan runners was the only alternative. This was found to be unsuitable. Now with the development of reversible flow bulb turbines, this difficulty is overcome.
5. The duration of power cycle may be reasonably constant but its time of occurrence keeps changing, introducing difficulties in the every day planning of the load sharing in the grids. This handicap can be removed now with the help of computerized programming.
6. Sea water is corrosive and it was feared that the machinery may get corroded. However, stainless steel with a high chromium content and a small amount of molybdenum and the aluminium bronzes proved to be good corrosion resistant materials at La Rance project. The vinyl paint exhibited good results.
7. Construction in sea or in estuaries is found difficult.

8. Cost is not favourable compared to the other sources of energy.
9. It is feared that the tidal power plant would hamper the other natural uses of estuaries such as fishing, or navigation.

1.1. WIND ENERGY

For centuries wind has been used to move ships, grind grains, pump water, and do other forms of work. In recent times, wind has been used to generate electricity. There is enough wind energy available on the earth to generate more than ten times the electricity now used worldwide. Global wind generating capacity has expanded at an annual rate of 25.7 per cent during the 1990s, and in April 1998 it stood at more than 10,000 MW. It is the fastest growing of all renewable energy sources. Denmark, Spain, Germany, USA and India have emerged as leaders in wind energy development. These countries account for more than 80 per cent of world capacity. For Europe alone, the European Wind Energy Association has set a target of 40,000 MW by 2010 and 1,00,000 MW by 2020. With technological advances the cost of generating wind power has continued to decline, and wind promises to become a major power source globally in the next millennium. India today is the fourth largest producer of wind power in the world after Germany, USA and Denmark (See table).

1.3.1. Wind Energy Development in India

In India wind power is untapped but potentially very important source of energy. It appears to be the most feasible and cost-effective for supplementing these conventional means of power generation on a large scale. Its advantage are :

- It is perennial source, available all over the day and night;
- It is an ideal source of energy for the small farmers cottage, micro and small industries;
- It is most useful source of energy for those living in isolated hilly, coastal and other regions which are far away from electric transmission network;

- The power is cost effective; and
- It is inexhaustible, Eco-friendly, non-polluting and freely available.

Table 2. Wind power installed capacity at global level (India ranks fourth in the world).

State	Total installed wind capacity (in MW)
Germany	2,081
United States	1,611
Denmark	1,116
India	940*
Spain	512
The Netherlands	329
United Kingdom	328
China	146
Sweden	122
Italy	103
Greece	29
Canada	25
Japan	18
France	13
Australia	11
Russia	5
Brazil	3
Total	7,392

*1175 MW achieved very recently.

Source: Anon 1998, Denmark: Birthplace of Modern Wind Power (One-seven), Green peace – International, Amsterdam, mimeo (See Down to Earth, June 30, 1999, p.36).

Ministry for Non-conventional Energy Sources (MNES) recently reassessed and upgraded the gross wind power potential in the country from 20,000 MW to 45,000 MW (Down to Earth, January 31, 2000).

However, the present technical potential is limited to about 9,900 MW governed by the grid capacity in the potential States. The Kutch and Saurashtra in Gujarat and the South Tamil Coastal areas offer some of the best known windy locations in the country where wind energy is ready to take its place alongside conventional resources as a clean reliable source of electricity generation. More than 192 sites having total wind power potential over 5000 MW have already been identified in thirteen States/Union territories including Tamil Nadu, Karnataka, Madhya Pradesh, Gujarat, Maharashtra, Andhra Pradesh, Kerala, Lakshadweep, West Bengal, Uttar Pradesh and Rajasthan.

However the country by March 2000, was able to harness only a little over 5 per cent (~ 1140 MW) of the total wind energy potential (See table 2). With the 766 MW of energy generation capacity, Tamil Nadu ranks first among the states in the number of energy generators installed and power produced, followed by Gujarat and Maharashtra. The other Wind Power generating states – Andhra Pradesh, Karnataka, Madhya Pradesh, Kerala and Orissa – have their installed capacity far short of their gross potential. Currently the wind power installed capacity of the country has reached to 1175 MW.

Table 3. Wind energy installed capacity in India (1999-2000) (in MW).

State	Installed capacity	Available technical potential
Tamil Nadu	766.480	2,000
Gujarat	168.420	1,271
Andhra Pradesh	68.290	1,231
Maharashtra	75.970	2,108
Karnataka	33.700	687
Madhya Pradesh	21.920	775
Rajashthan	2.000	397
Kerala	21.250	353
Orissa	0.575	338
Others	0.575	775
Total	1140.055	9,935

*currently, the installed capacity has reached to 1175 MW.

Source: CMIE, June 2000 (Hindu 17-08-2000).

Within the developing world, the largest wind industry is India. The Washington – based World Watch Institute recognized India as a Wind Superpower. Wind power development in India has been rather rapid at selected sites. One such site is Muppandal in Tamil Nadu, which has an installed capacity of 400 MW. Muppandal today has the highest concentration of wind farms in Asia and the third highest in the world. In India, wind energy development boomed during the period 1993-97 and the country rose to become one of the world's fastest - growing markets for wind energy, both in terms of potential and rate in installation. The growth of wind power in the country during 1990-2000 is shown in Fig. 1.4.

1.3.2. Wind Energy Programme

In the State of California (USA), over 17,000 wind electric generators (WEGs) producing over 14,000 MW of electric power have been developed. This has been achieved through development of a number of WEGs in a cluster to form wind farm or wind park. Grid connected power generation programmes have also commenced in a few European countries, such as Denmark, the Netherlands, UK, etc.

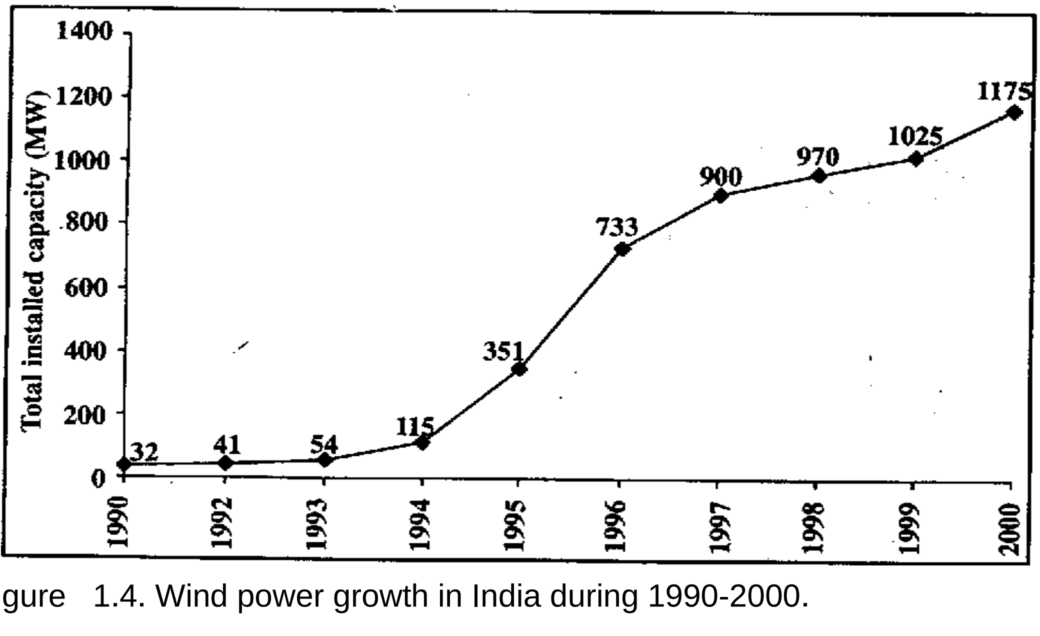

Figure 1.4. Wind power growth in India during 1990-2000.

In India, DNES has designed a broad-based energy programme to harness available wind power potential. The major activities included in the programme are:

- Strengthening of the wind data base;
- Pumping water;
- Power generation, and
- International cooperation

Wind data base programme is very significant in locating the wind potential sites for installation of wind/power monitoring and mapping activities. The programme/demonstration wind farms in the country was commenced in 1985. Wind power capacity of nearly 8 MW was established in the country by the end of 1987. This includes the installation of 7 wind farms at Okha and Mandvi (Gujarat). Tuticorin and Kayattar (Tamil Nadu), Puri (Orissa), Deogarh (Maharashtra) and Talcaevery (Karnataka). Under the international cooperation programme, two wind farms each at Kayattar (Tamil Nadu) Lamba (Gujarat) have been installed with support from Danish International Development Agency (DANIDA) of Denmark. Lamba is the largest wind farm of Asia. Till 1990, a total of 12 wind farms have been set up. By that time, about 57 million units of electricity had been fed into respective state grids since the programme began in 1986.

Tamil Nadu, is one of the most windy regions of the world accounting for about 10% of the total installed global wind energy capacity and over 70% of the country’s total installed capacity. The estimated cost of setting up wind farm project comes to Rs. 35 to 45 million per MW. Recently, in Rajasthan wind energy projects have been set up at Devgarh village in Chittorgarh district and at Amarsagar in Jaisalmer district.

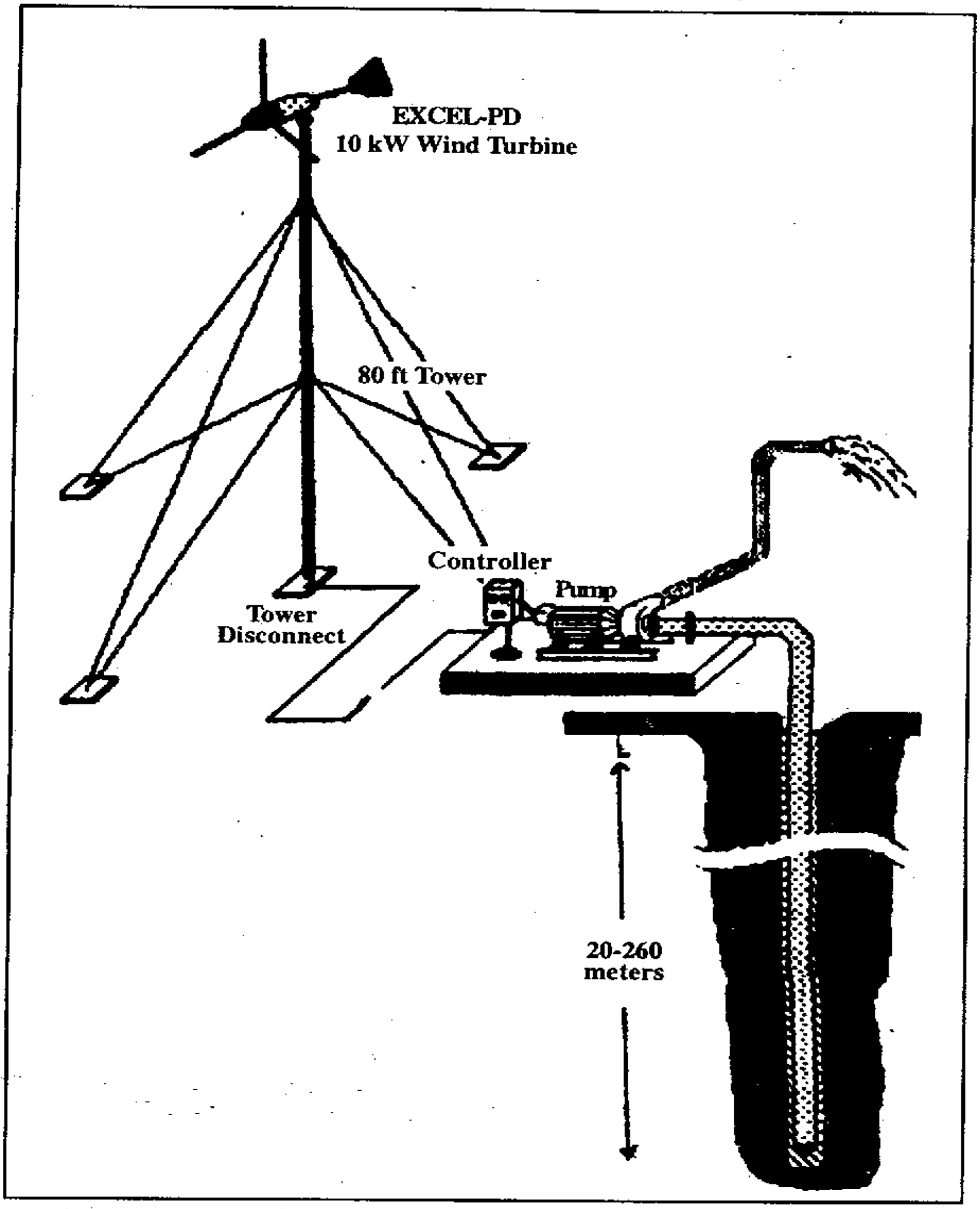

Figure 1.5. Wind electric water pumping system.

Wind generators have certain disadvantages :

- They are large in size giving unattractive outlook to the landscapes.
- They can be extremely noisy, and disturb residents of the area.

- Often their blades may interfere with television reception or with microwave communications used by telephone companies.
- Wind does not blow all the time, so backup systems are needed and the electricity must be stored until it is used.

1.2. HYDROPOWER

Hydropower is recognized as a renewable source of energy, which is economical, non-polluting and environmentally benificial. Hydropower projects involve the construction of dams to produce the waterfalls that power turbines. Although hydropower is renewable, the dams and reservoirs needed to capture this energy have limited life spans. The reservoirs behind dams invariably filled with sediments, giving the typical dam a life span of 20 to 100 years. Once a hydropower site is filled with sediments, it is gone forever. Dams also often create many environmental problems. This means that hydroelectric power is unlikely to expand much faster in developed as well as developing countries.

The world’s leading generator of electricity from hydropower is the United States (71,000 MW capacity), Europe, Japan, the eastern Soviet Union and Southern Canada harnessed the hydropower potential to the maximum. In South America, 73 percent of the electricity used comes from hydropower compared to 44% in the developing world as a whole. Norway gets 99 percent of its electricity from hydropower. The World Energy conference estimates that the electricity produced by hydropower will increase six times by the year 2020. The developing countries, which have developed about 10 percent of their hydropower, will experience most of this growth.

Because of the escalating cost and environmental damage from large dams, many of these countries have developed small hydropower plants (“Minihydro:-less than 10 MW and “microhydro”-less than, 1 MW) in remote areas to supply electricity. China has built over eighty thousand such small projects and the United States has nearly fifteen thousand. However, these small hydropower plants will not solve the problem of how to supply energy to the huge and rapidly growing cities of developing countries.

Hydel power has several advantages :

- It is a clean source of energy;
- It provides irrigation facilities; and
- It provides drinking water to people living, particularly in desert of Rajasthan and Gujarat.

The large hydropower projects, however, involve several environmental and socio-economic problems:

- Submerge forest and agricultural land;
- Cause loss of biodiversity;
- Displace local people and create problems of rehabilitation;
- Cause water logging and siltation;
- Affect adversely fish population and other aquatic organisms; and
- Increase seismicity due to large volume of water impounded.

1.4.1. Hydel Power Potential in India :

India has a large hydel potential totaling about 84,044 MW, which can be tapped. However, 75% of it is concentrated in the Himalayan region, which is tectonically very unstable. Out of the total potential, only about 23,627 MW installed generating capacity has been achieved as of January 2000.

The history of hydropower generation in India is more than 100 years old. The first-hydropower station in India was a small hydropower station of 130 kW commissioned in 1897 at Sidrapong near Darjeeling in West- Bengal. Subsequently, many small hydropower stations were set up. With the advancement in technologies and increasing requirement of electricity, emphasis was shifted to large sized hydropower stations. The growth of hydropower in the country since 1990 to 2000 is shown in Fig 1.6. This hydropower capacity is about 25 percent of the total installed capacity for electricity generation. Ministry of Power in the Government of India is responsible for the development of large hydropower projects in India, while

MNES has recently been assigned to develop small hydropower projects (3- 25 MW) in the country.

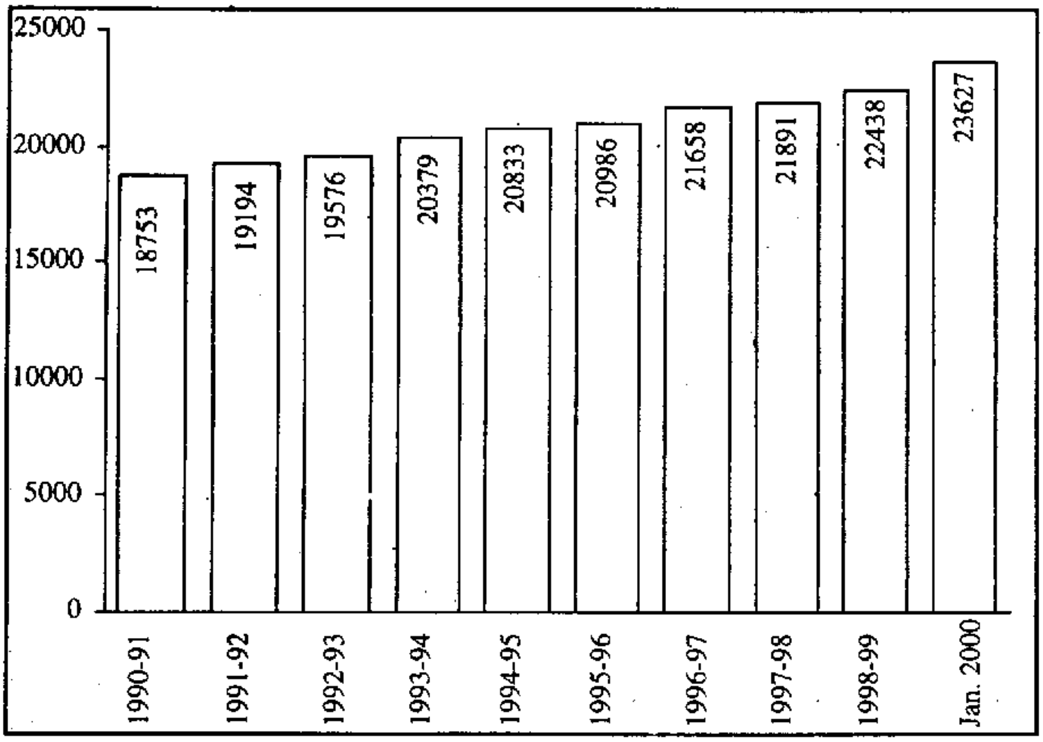

Figure 1.6. The growth of hydropower in the country (installed power generating capacity in MW)

Hydropower still remains the cheapest source of electricity in the country. Hence, more stress now has been laid on the construction of mini/micro hydel plants with generation capacities between 3 MW and 15 MW to avoid the soci-economic and environmental problems created by big dams.

1.4.2. Small Hydel Projects in India

An estimated potential of about 10,000 MW of small hydropower projects exists in India. MNES has identified 3349 sites with an aggregate potential of 2,852 MW for small hydro projects up to 3 MW capacity and 662 sites with an aggregate potential of 5,519 MW for projects upto 3-15 MW capacity. Presently, the country has exploited 217 MW with the construction of 271 small hydropower projects (up to 3 MW capacity). Over 130 projects in this range, with an aggregate capacity of 133 MW, are under construction. In the last 10 years, the capacity of small hydro projects has increased 3 fold from 63 MW to 217 MW. Table 4 lists the existing and ongoing small hydro power plants in the country as on June 1997.

Table 4. List of installed/ongoing micro/mini hydel projects upto 3 MW capacity as on June 15, 1997

State	Projects installed		Projects under construction	
	Number	Capacity (MW)	Number	Capacity (MW)
Andrhra Pradesh	7	7.01	36	42.10
Arunachal Pradesh	30	20.15	17	20.63
Assam	2	2.20	-	-
Bihar	4	0.04	5	2.46
Goa	-	-	2	2.90
Gujarat	1	2.00	2	2.60
Haryana	1	0.20	1	0.10
Himachal Pradesh	15	9.49	18	11.19
Jammu and Kashmir	15	4.37	10	11.20
Karnataka	8	10.10	22	30.64
Kerala	4	3.52	6	14.00
Madhya Pradesh	5	3.25	8	14.40
Maharashtra	4	4.32	5	8.70
Manipur	6	4.10	4	3.50
Meghalaya	1	1.51	7	0.28
Mizoram	9	5.36	9	8.80
Nagaland	5	3.17	4	5.50
Orissa	3	1.26	7	9.92
Punjab	4	3.90	8	9.50
Rajasthan	5	4.30	2	1.04

Sikkim	8	9.25	2	3.20
Tamil Nadu	3	4.75	4	6.40
Tripura	2	1.01	1	0.10
Uttar Pradesh	60	31.04	26	21.23
West Bangal	8	7.98	7	9.23
Andaman and Nicobar Islands	-	-	1	2.25
Total	210	144.28	214	241.87

Note : The total installed capacity of small hydro power plants now has reached to 217 MW with the installation of 271 projects.

Source : Ministry of Non-conventional Energy Sources. Annual Report 1996-1997.

Small and minihydel projects have the potential to provide energy to remote and hilly areas where extension of grid system is uneconomical. Realizing this fact, government of India is encouraging development of small and mini hydel projects in the country.

Micro hydel projects are more feasible so far as the socio-economic and environmental consequences are concerned. They do not pose the problems of deforestation, submergence and rehabilitation. Also, entail no wastes, no production of toxic gases and no adverse effects on environment. However, economically they are not viable because of:

- Higher capital cost;
- Equipment availability, especially for ultra low head regions;
- Higher cost of construction control and management; and
- Load factors.

1.3. GEOTHERMAL ENERGY

The earth contains large amounts of geothermal energy with temperature as high as 4400^0C. This energy comes from magma, molten rock material beneath the surface of the earth or from radioactive decay of thorium, potassium and uranium dispersed throughout the earth’s interior. In some regions of the earth this molten material sometimes breaks through the earth’s crust and produces volcanoes. In other regions, the hot material is close enough to the earth’s surface to heat the underground water trapped by impermeable rock and form steam. Geysers and hot springs are natural areas where hot water and stream come to the surface. In such areas geothermal energy is tapped by drilling wells to obtain steam. At present, geothermal energy is only practical in areas where the molten mass is near the surface.

There is large scope for utilization of geothermal energy to uplift the socio-economic status and the life style of the people, particularly those living in far remote areas of the country and where this source of energy is in abundance. Besides space heating and power generation, the energy could be utilized:

- In small and cottage industries;
- Drying and processing of conventional and cash crops;
- Animal husbandry, dairy, poultry and fishery development;
- Silviculture;
- Spinning, weaving, painting and garment industry;
- Hard and soft board manufacturing and pulp making; and
- Brewing of low alcoholic beverages.

1.5.1. Geothermal Energy Prospects in India

Keeping in view the severe energy crisis which is going to occur in the near future as a result of rapidly growing population in India, much attention has been paid by the planners and scientists to exploit alternate energy resources to supplement the existing conventional energy potential. Geothermal energy has received much attention for exploitation since 1973 and sufficient scientific studies relating to places of occurrence, geotectonic associations, geochemical and thermal characteristics were carried out by scientists. On the basis of these studies, certain geothermal areas/fields have been identified, giving energy potential of each area and prospective uses.

Even through geothermal energy is manifested to the surface mostly in the form of hot springs, in several areas the degree of heat potential, chemical composition of water, and quantity vary greatly. Geothermal reservoirs emitting hot water with high temperatures normally occurred in volcanic regions. Such regions occur mostly along continental plate margins and in some inter plate regions.

The geological history of India reveals that except the large scale volcanic activity in the Deccan plateau during the tertiary period, no such activity during recent periods is known to have occurred anywhere except in Barren and Narcondom islands of Andaman and Nicobar group.

1.5.2. Major Geothermal Regions of India

Based on tectonic and thermal histories, the following seven major geothermal regions have been identified after conducting studies by the scientists of National Geographical research Institute (NGRI) with regard to occurrence of geothermal water manifestations. In each region the use of this energy for various purposes have been also mentioned.

The Himalayan Geothermal Region: Thermal springs in Himalayan region manifest themselves mostly along the banks of certain rivers or their tributaries. They are found even in Karakoram-Kailash mountain region beyond the Northern Himalayas . In fact a belt of thermal springs starting from North-Western Himalayas continues through Nepal and Bhutan towards North-Eastern Himalayas to Burma and finally to Barren island. Due to continuing uplift of Himalayas, a large fracture system has developed in them, which facilitated the emergence of thermal springs of which some have even high temperature. Some of them have mild geyser activity emitting steam at regular intervals alongwith hot water. The temperatures range from 120^0C to 240^0C $\underline{+}$ 20^0C.

In this Himalayan geothermal region, seven sub-regions, i. e. Puga valley, Chumtong in Ladakh, Parbati, Beas and Sutlej valleys in Himachal

Pradesh, Topoban region, Alakananda valley in Chamoli district of U.P. and Kashmir valley basin have been also identified on the basis of geothermal characteristics of each sub-region and the use of energy for various purposes in each sub-region.

In Puga valley of Ladakh with estimated reservoir temperature of 240^{0}C ± 20^{0}C and with observed temperature of 84^{0}C of thermal springs it has been suggested that the heat energy can be utilized for space heating, extraction and refining of borax, sulpur, generating electricity of 1000 kW using binary cycle, poultry farming, mushroom cultivation and sheep farming.

In Chumtong region of Ladakh where geothermal reservoir temperature is about 180^{0}c ± 20^{0}C and the observed temperature of thermal springs is 87^{0}C the hydrothermal energy can be utilized for green house cultivation, electricity generation, space heating, poultry farming, mushroom cultivation and fish culture etc.

In Parbati valley, Kulu of Himachal Pradesh where the estimated reservoir temperature is about 160^{0}C ± 20^{0}C and the observed temperature of springs is about 96^{0}C the energy can be utilized for generating electricity, space heating, food processing, poultry farming, green house cultivation, etc. In Beas and Sutlej valley of Kulu the estimated reservoir temperatures are about 120^{0}C ± 20^{0}C and the observed spring temperatures are 57^{0}C and 60^{0}C, respectively. In both the regions the energy can be used for space heating, cold storage, poultry farming, pasturization of fruit juice and health resorts.

In Tapoban region of Alakananda valley of Chamoli district of U.P., the estimated thermal reservoir temperature is about 160^{0}C ± 20^{0}C and the observed spring temperature is about 64^{0}C. The energy can be used in this region for electricity generation, baths, space heating, poultry farming, tourism etc.

In Kashmir valley where the estimated reservoir temperature is about 100^{0}C ± 20^{0}C and thermal springs temperature is about 56^{0}C the thermal energy can be utilized for space heating for small scale industries like wood processing, carpet, shawl, sari and other garment making, wooden craft, tourism etc.

The West-Coast Konkan Region: A chain of mountains running parallel to the west coast of India between latitude 16^0-30^0 N and 20^0 N have thermal springs mostly in groups at 21 different locations. These are controlled by shear zones, fractures or dykes of Deccan trap and manifest in various river basins along stream courses. Many earthquakes occur in the west coast. The hot springs of this belt are oriented in N-S and NNW-SSE directions indicating that the belt has suffered strong crustal movements and the fractures which control the thermal springs are still active. The temperatures of geothermal systems of this belt are around 100^0C $\pm$ 20^0C.

There are two sub-regions i.e. Unhavare (Khed) and Ganeshpuri- Akloli in this region. In both the regions the estimated reservoir temperature is about 110^0C $\pm$ 20^0C and the observed temperature of springs are about 70^0C and 57^0C respectively. The energy in both the regions can be utilized for refrigeration mushroom cultivation, drying fish, vegetables and brewing.

Narmada-Tapti Geothermal Region : Thermal springs mostly in cluster with temperature varying from 32^0C to 98^0C are found at sixteen locations in this region which is a permanent ancient geological feature of the peninsular India between 21^0 N and 24^0 N in a NNE-SSW direction. The estimated reservoir temperature of this region range from 60^0C to 110^0C except in one case, that is Tatapani Geothermal field (where hot springs having temperature is upto 98^0C) whose estimated reservoir temperature is 160^0C
$\pm$ 20^0C.

In Tapani, Surguja district of M. P., where the observed temperature of hot spring is about 98^0C, the thermal energy can be utilized for electricity (installation of 20 KW binary cycle power plant is planned), sericulture, tourism, drying and curing of light aggregate cement slabs, purification of bauxite, etc.

In Tapti basin of M. P. where the estimated reservoir temperature is 110^0C ± 20^0C and the thermal spring temperature is about 60^0C, the energy can be utilized for electricity generation, sericulture, refrigeration and processing industries.

The Damodar Graben Region : There are a few hot spring areas in Gondwana grabens adjacent to Damodar river valley. All along, the estimated reservoir temperature is about 100^0C ± 20^0C and the observed temperature of springs is upto 80^0C. The energy can be used for electricity generation, rice para boiling, drying of agricultural products and paper pulp manufacture.

Combay Graben Geothermal Region: In the Combay and Kathana fields, the estimated reservoir hot eruptive springs (mixture of water and steam) of temperatures over 100^0C occur. The energy from these springs can be used for electricity generation, refrigeration, processing and drying industries.

Delhi-Mobile Belt Geothermal Region : Springs in Sohna valley in Haryana with estimated reservoir temperature about 90^0C ± 20^0C and observed temperature of 47^0C are found. These springs are found along the pre-Himalayan alignment towards south-west of Delhi with the areas of Delhi folding. The energy can be used for refrigeration and tourism.

Wardha-Pranahita Godavari Valley Graben Geothermal Region : The valley of the river Godavari along with those of Pranahita and Wardha rivers represent a prominent linear graben structure of Indian land mass. It is one of its main Gondwana basins of Permo-carboniferous to lower cretaceous geological periods. Most of its hot springs have temperature slightly over mean annual air temperature. Its hottest spring Agnigundata occurs in the bed of river Godavari and its temperature reached upto 62^0C. Hot water also has been tapped through holes drilled for exploration of coal and ground water resources in various parts of this graben.

In Godavari and Chintalapudi sub-basins, the estimated reservoir temperature varies from 100^0C to 156^0C and the observed temperature of springs from 29^0C to 62^0C. The energy can be utilized for rice para boiling, drying of paddy and chillies.

1.5.3. Classification of Geothermal Systems

The NGRI scientists, on the basis of estimated reservoir temperature and pressure, have classified geothermal systems into three categories of HGS (Hydro Geothermal systems) :

- **High Temperature** (150^0C) **HGS** : These mainly occur in Himalayan region except in Tatapani and Agnigundala area in peninsular region and in the Andaman and Nicobar Islands.

- **Intermediate Temperature** (150^0C-80^0C) **HGS** : These are widely distributed and exist particularly in all geothermal regions of India. These form the common resource base in India.

- **Low Temperature** (<80^0C) **HGS** : These occur generally in limited numbers in almost all geological regions of India.

1.5.4. Heat Energy Potential in India

Based on one hundred well recognized hydrothermal systems the estimated energy heat energy potential would be about 40×10^{18} calories which is equivalent to 27.6 billion barrels of petroleum and there would be a saving of 60,000 million rupees per year. The estimated power potential of the identified systems would be 2000 MW for utilization for a period of 30 years.

The studies carried out so far have indicated good prospects in India for developing geothermal resources for generation of electricity by using binary cycle turbines and for non-electrical applications like space heating, poultry farming, mushroom raising, drying, mineral processing, etc. As mentioned already cold storage could also be developed for preserving fruits and vegetables.

There are good prospects of tapping intermediate (80^0C-150^0C) and high temperature (>150^0C) geothermal fluids at suitable locations in various parts of Himalayan region. Here very cold climate conditions prevail during most part of the year and the work season is very short and the reserves of fossil fuels are meager.

As regards peninsular India, geothermal resource of intermediate (150^0C-80^0C) and low grade (<80^0C) are available at various locations. Good possibilities do exist in peninsular India for developing industrial centres around geothermal fields. The geothermal fluids of these fields could be utilized for hydrothermal processing in ceramic, electronic, magnetic, pigment, inorganic chemicals, food and even iron/steel and non- ferrous metal industries. Hydrothermal processing involves the chemistry of hot water under pressure to carry out leaching and precipitation reactions and it has been emerging as a very potential process these days. It is hoped that several biotechnological units where biochemical reactions require large heat capacities but at lower temperature, would also be established in India by using them. Some of these units could be established near suitable geothermal fields.

Control of coal mine fires occurring mostly in Raniganj and Jharia coal fields, causing huge loss of prime coking and superior quality of non- coking coal, which cost Rs. 100 crore could be possible with the application of emerging technology of the down hole coaxial heat exchanger system. There is great possibility for the economic in-situ extraction both of the geothermal energy and the heat available from the combustion of coal from the coal fields of Jharia and use it for power generation.

By utilizing geothermal and non-conventional energy resources like solar, wind and biomass energy remote and isolated areas like Ladakh and many other parts of India could be economically developed. There is bright future for the utilization of geothermal energy resources on large-scale for socio-economic development in different parts of India.

1.4. SUMMARY

Few countries in the World has placed as much faith in renewable energy sources as India has, when the World was reeling under the oil price stock of 1973 and 1979, every Nation has made a beeline for renewable energy sources as alternatives to fossil fuels. The India has been bestowing upon renewable energy resources is reflected in the numerous policy decisions taken by the Government at the highest level. India is one of the few countries which has a full-fledged Ministry devoted to non-conventional energy sources. This unit covers the important renewable energy resources

– tidal, wind, hydropower and geothermal etc. The tides occurring in the rivers or oceans are sources of energies based on the movement of water. The potential, prospects, development in the field of tidal, wind geothermal and hydropower energy in India has been discussed.

1.5. KEY WORDS

Tides

The periodic vertical rise and fall of ocean water due to gravitational force of moon and sun.

Wind farm

Cluster of small to medium sized wind turbines in a windy area to capture wind energy and convert it into electrical energy.

Hydropower

Electric energy produced by falling or flowing water.

Geothermal energy

Heat transferred from the earth's underground concentrations of dry steam (steam with no water droplets), wet steam (a mixture of steam and water droplets) or hot water trapped in fractured a porous rock.

Renewable resource

Resource that can be replenished rapidly through natural processes.

1.6. SELF ASSESSMENT QUESTIONS

1. What is meant by renewable energy resources? Explain briefly.
2. What is the basic principle of tidal energy?
3. Write down the potential of tidal power in India.
4. What are the advantages and limitations of tidal power generation?
5. What is wind energy? Discuss wind energy development in India.
6. What are the advantages and disadvantages of wind energy conservation system?
7. Write down the potential of hydel power in India.
8. What is meant by geothermal energy?
9. What are the main applications of geothermal energy?
10. What is the classification of geothermal system?
11. Give a brief note on the prospects of geothermal energy in context to India.

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2.0. INTRODUCTION BIO ENERGY

The second most important source of renewable energy is biomass. Biomass is organic matter produced by plants both terrestrial (those grown on land) and aquatic (those grown in water) and their derivatives. It includes forest crops and residues crop grown especially for their energy content on “energy farms” and animal manure. Biomass produced by these plants can also be considered a form of solar energy as the solar energy is used indirectly to grow these plants by photosynthesis. The capture of solar energy as fixed carbon in biomass via photosynthesis is initial step in the growth of biomass.

$$CO_2+H_2O + \text{Chlorophyll} + \text{Light} \longrightarrow (CH_2O)_6 + O_2$$

Hence : Solar energy → Photosynthesis → Biomass → Energy generation

Biomass resources fall into three categories :

i) Biomass in its traditional solid mass (wood and agricultural residues) and,

ii) Biomass in non-traditional form converted into liquid fuels. The first category is to burn the biomass directly and get the energy. In the second category, the biomass is converted into ethanol and methanol to be used as liquid fuel in engines. The third category is to ferment the biomass an aerobically to obtain a gaseous fuel called biogas.

2.1. BIOGAS

Biogas is a clean, non-polluting, convenient and low-cost fuel for rural areas. It is generated through anaerobic digestion of organic matter like cattle dung, wastes (human waste, garbage and sewage) and various other types of biomass (rice straw, sugarcane, bagasse etc.). The potential of biomass in India is estimated at 1250 Mt per year. Energy available from such a massive biomass is equivalent to about 300 Mt of oil. India having a largest cattle population in the world, i. e. 240 M head offers a tremendous potential for the development of biogas technology. From cattle dung alone, over 22,425 Mm^3 biogas per year can be produced. There are about 75 M farm families, out of which nearly 44 per cent own 4 or more cattle. This is the minimum number of cattle needed to have a small size of biogas plant. India has been one of the pioneering countries in the development and use of biogas technology. A gobar gas plant having a capacity of 60 cft can produce gas sufficient for a family consuming one LPG gas cylinder per month.

The biogas is rich in Methane (CH_4), which is inflammable, so it can be used safely as cooking gas. In addition, a biogas plant also produced enriched high quality organic manure for use in agriculture. Besides, biogas is used in running engines and generation of electricity.

2.3.1. Biogas Programme in India

The Ministry of Non-conventional Energy Sources (MNES) has taken up following programmes for development and harnessing of biogas potential in the country :

- National Project on Biogas Development (NPBD) for setting up family type biogas plants.
- Community, Institutional and Night Soil based Biogas Plant Programme (CBP/IBP/NBP).
- Research and Development on Biogas Production and Utilization technology.

The NPBD started in 1981-82 with the following objectives :

- To provide fuel for cooking purposes and organic manure to rural households.
- To mitigate drudgery of rural women, reduced pressure on forest and accentuate social benefits; and
- To improve sanitation in villages by linking toilets with biogas plants. The

biogas programme has becoming popular in many parts of the country. Various models of biogas plants approved by NPBD are listed in Table 1.

Table 1. Models of approved biogas plants

Model	Capacity (m^3/day gas production)
Floating Drum Type Biogas Plant-KVIC Model	1 to 10
Model with ferro cement digester	1 to 10
Deenbandhu Model	1 to 6
Pragati Model	1 to 6
Bag digester made of rubberized nylon fabric – Flxi model	1 to 6

The most remarkable achievement of this programme has been the acceptance by the rural people of human-night soil as feed material in addition to other biodegradable materials like animal dung, kitchen wastes, water hyacinth etc. Apart from the family-size biogas plants, community and institutional biogas plants are also being installed for different applications.

These plants are estimated to generate fuel equivalent to saving of about 3 Mt of firewood valued at Rs. 435 crores per year. Besides, these plants are producing about 38 Mt of enriched organic manure containing nitrogen equivalent to about 0.85 Mt of urea per year for supplementing chemical fertilizers and improving soil fertility.

Up to 31st March 2000, 3.03 M family-type biogas plants have been installed (Table 2). Further, NPBD has fixed target to install 1,80,000 biogas plants during 2000-2001.

Table 2. Cumulative achievement up to 31st march 2000 under NPBD,

against estimated potential of biogas plants.

State	Number of Biogas plants		
	Estimated potential	Installed during 1981-82 to 1999-2000	Coverage of estimated potential in % age
Andhra Pradesh	10,65,600	2,82,557	27
Arunachal Pradesh	7,500	742	10
Assam	3,07,700	41,896	14
Bihar	9,39,900	1,16,621	12
Goa	8,000	3,188	40
Gujarat	5,54,000	3,35,315	61
Haryana	3,00,000	39,865	13
Himachal Pradesh	1,25,600	42,547	34
Jammu and Kashmir	1,28,500	1,862	1
Karnataka	6,80,000	2,77,561	41
Kerala	1,50,500	64,816	43
Madhya Pradesh	14,91,200	1,78,304	12
Maharashtra	8,97,000	6,47,443	72
Manipur	38,700	1,793	5
Meghalaya	24,000	1,279	5
Mizoram	2,200	1,976	90
Nagaland	6,700	1,097	16
Orissa	6,05,500	1,60,010	26
Punjab	4,11,600	56,348	14
Rajasthan	9,15,300	65,185	7
Sikkim	7,300	2,494	34
Tamilnadu	6,15,800	1,96,545	32
Tripura	28,500	1,164	4
Uttar Pradesh	20,21,000	3,40,312	17
West Bengal	6,95,000	1,68,297	24
A & N Islands	2,200	137	6
Chandigarh	1,400	97	7
Dabra & Nagar Haveli	2,000	169	8
Delhi	12,900	673	5
Pondicherry	4,300	539	13
Total	1,20,49,900	30,30,832	25.15

Community, Institutional and Night-soil based Biogas Plants Programme caters to the needs of village communities and institution. Biogas so produced is utilized for generation of motive power and electricity also. The programme was started in 1982-83. The objective of the programmes are :

- To recycle organic wastes for harnessing fuel-gas at community and institutional levels for various usages, including generation of motive power and electricity.
- To provide benefits of biogas technology to weaker sections of the society; and
- To recycle human waste through linking of community and institutional toilets with biogas plants for improving sanitation.

Upto 31st March 2000, 3075 Community/Institutional/Night Soil biogas plants (CBP, IBP and NBP) were installed in the country (Table 3).

Table 3. Cumulative achievement up to 31st march 2000 under community, institutional and night soil based biogas plants programme

State/U. T.	Number of CBP/IBP/NBP
Andhra Pradesh	105
Assam	2
Bihar	37
Goa	20
Gujarat	147
Haryana	41
Himachal Pradesh	7
Jammu and Kashmir	4
Karnataka	48
Kerala	45
Madhya Pradesh	116
Maharashtra	413
Manipur	4
Meghalaya	2
Nagaland	7
Orissa	33
Punjab	558
Rajasthan	55
Tamilnadu	201
Uttar Pradesh	1146
West Bengal	51
Delhi	32
Pondicherry	1
Total	3075

Biogas programmes have provided immense opportunities to rural people for lighting and pumping water for irrigation and drinking requirements. Night-soil based biogas plants are considered as low-cost sanitary disposal system and converting human wastes for manurial purposes. The programme has become acceptable in Punjab, Gujarat, Tamil Nadu, Uttar Pradesh, Orissa and Maharashtra. A community – based biogas plant, with a design capacity of 42.5 cum/day, has operated successfully for nearly a decade and met the fuel, lighting and water pumping requirements of Pura village [World Science News, 29 : 12 (1992)]. Taking the average life span of the plants to be about 20 years, large economic benefit would thus be generated to the country. In addition, the programme has created employment of about 90-100 lakh man-days per year in rural areas.

2.3.2. Commonly used biogas plants in India

There are two types of biogas plant.

2.3.1.1. Fixed Dome Biogas plant : They are Janta Biogas plant and Deen bandhu Biogas plant.

Janta Biogas Plant. This was first developed by the planning, Research and Action Division Lucknow in 1978. It is an improved version of the Chinese fixed-dome biogas plant. The plant is shown in Fig. 2.0, with its different parts.

The foundation of Janta biogas plant is laid at the base of the underground pit on a levelled ground which bear the load of the slurry as well as digester walls. Digester is cylindrical in shape constructed with bricks and cement. It holds the dung slurry for a retention time so that the biogas is produced from the slurry in the digester. It should be noted that the diameter and height ratio of the digester is kept 1.75 : 1. The gas is stored in gas portion, which is an integral part of plant, between dome and digester, where the usable gas is stored. The height of the gas portion is above the inlet and outlet openings to beginning of dome and is equal to maximum volume of the gas to be stored (30-40 per cent of plant capacity) and equal o volume of slurry to be displaced at inlet and outlet.

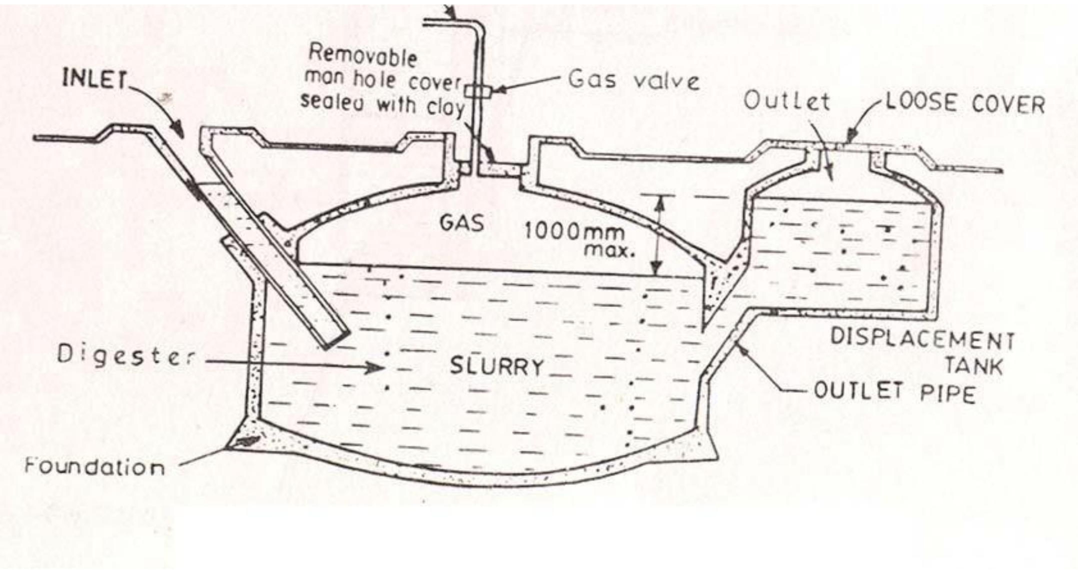


Figure 2.0. Common fixed dome digester (China)

Dome is constructed over the gas portion, with volume of 60 percent of the plant capacity. It must be constructed very carefully integrating it with digester and gas portion so that no leakage of gas can take place. The gas outlet pipe is fixed at the top of the dome for laying the line.

Inlet and outlet portions are constructed for putting the fresh slurry inside the plant and to take the digested slurry out. The inlet and outlet are of larger sizes, provided on each side of the digester, facing each other. The opening to the digester for feeding the waste material and effluent outlet from it are also of large sizes. The discharge of slurry out of the plant is due to pressure of the gas in the plant. Over the inlet portion, an inlet mixing tank is also constructed to mix the dung and water.

It has now been replaced by Deenbandhu plant in the field.

Deenbandhu Biogas Plant: This is also a fixed dome plant developed by Action for Food production, New Delhi, which is a low cost biogas plant. The principle of working of this plant is same as that of Janta model, except configuration of inlet entrance and digester.

The foundation of the plant is constructed in the segment of spherical shape as shown in Fig. 2.1. On the other periphery of this foundation, the dome shaped digester is constructed with same base diameter. In this way the digester, gas portion and dome look as a single unit. The surface area of the biogas plant is reduced with same digester volume, reducing the earth work and cost of construction without sacrificing the efficiency. The higher compressive strength of the brick masonary and concrete makes it a safe structure as the plant is always masonary and concrete makes it a safe structure as the plant is always under compression. A spherical structure loaded from the convex side will be under compression and therefore the internal load will not have any residual effect on the structure.

At the top of the foundation, a window opening is kept (outlet portion) for the outward movement of the digested slurry. The asbestos cement pipe of 15 cm diameter is used for inlet instead of separate opening. The pipe is embedded in the digester wall at a fixed position, just opposite to outlet opening, to avoid short circuiting of fresh material and digested slurry.

The volume of the outlet is increased to produce requisite gas pressure through the weight of the displaced slurry. At the top of the dome a gas outlet pipe is fixed as in the case of Janta plant.

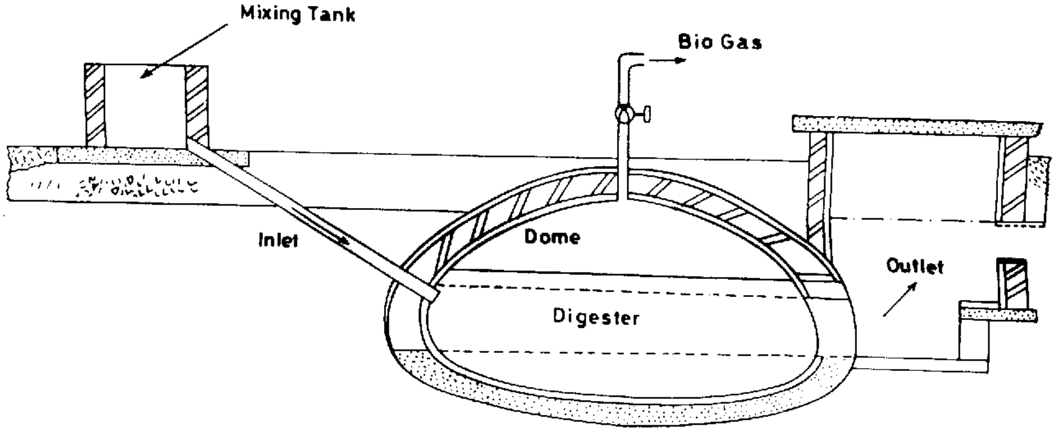


Figure 2.1. Deenbandhu biogas plant

Advantage and Disadvantages

Advantages :

1. It has low cost compare to floating drum type, as it uses only cement and no steel.
2. It has no corrosion trouble.
3. In this type heat insulation is better as construction is beneath the ground. Temperature will be constant.
4. Cattle and human excreta and long fibrous stalks can be fed.
5. No maintenance.

Disadvantages :

1. This type of plant needs the services of skilled masons, who are rather scarce in rural areas.
2. Gas production per cm^3 of the digester volume is also less.
3. Scum formation is a problem as no stirring arrangement.
4. It has variable gas pressure.

2.3.1.2. Floating Gas Holder Plant : In floating gas holder plant the biogas is stored in a drum, which moves up and down on a guide, according to quantity of gas stored in it. The gas holder rests on a guide frame which is fixed in a digester walls.

The drum may be made of steel, ferro cement HDPC or fibre glass. The pressure of gas in the floating drum type biogas plant is always constant, which is equivalent to weight of gas holder over unit area. It can be increased also by putting additional weight on the gas holder.

The sides of the gas holder remains in the slurry to seal the leakage of gas to the atmosphere.

The cost of this plant is more as the cost of the gas holder itself is high. Besides, it requires regular check and maintenance.

Khadi and Village Industries type Biogas Plant. As stated earlier the KVIC type plant is a floating gas holder or drum type biogas plant which was used in India earlier than all other types of biogas plants.

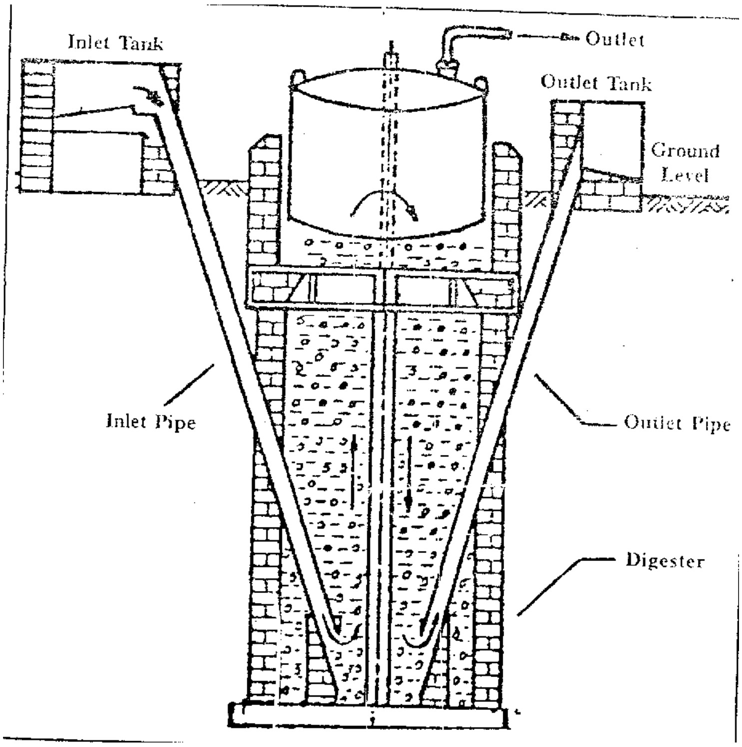


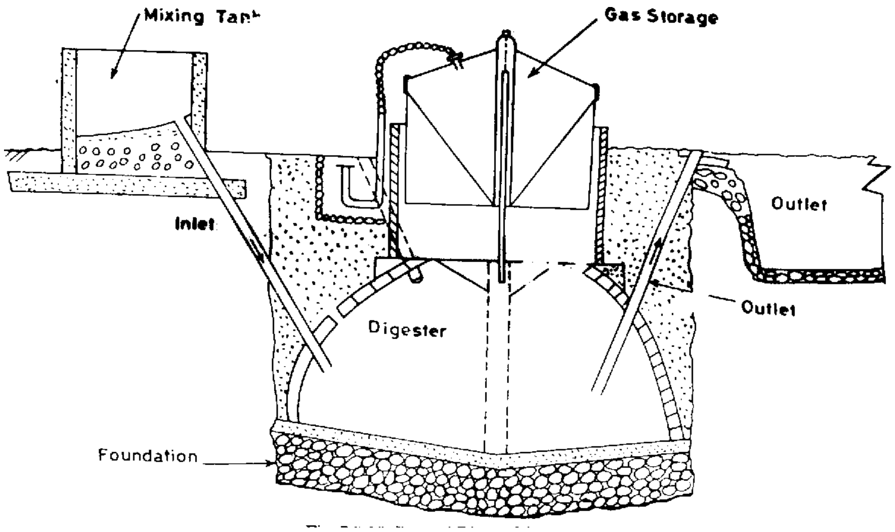
Figure 2.2. Schematic diagram of KVIC type Biogas plant.

The design was developed and perfected in India in the year 1954. This was taken up for propagation in the villages in the year 1962, by Khadi and Village Industries Commission, Bombay, therefore, it is known as KVIC design. The design is available in sizes of 1 cum to 140 cum gas per day. In

KVIC plant the gas is stored in mild steel drum of storage capacity of 30-40 per cent of plant size at a pressure of about 10 cm of water column, which is sufficient to carry it upto a length of 20 meters to 100 meters, depending on the size of the plant.

Pragati Design Biogas Plant. The design has been developed by United Socio-Economic Development and Research Programme (UNDARP) Pune, in order to have a cheaper floating drum biogas plant. In this design the depth of pit is less than KVIC plant so that it can be constructed in hill and high water table areas. The cost of Pragati plant is 20% less than KVIC plant.

Figure 2.3. Pragati biogas plant



The design shown in Fig. 2.3 indicates its different parts. The foundation of this plant is of conical shape, with difference of one feet between outer periphery and its’ centre so as to reduce the earth and digester wall work. It is constructed at the base of the pit with cement, sand and concrete, keeping the site conditions in view so that it can bear the load due to weight of slurry in the digester.

The digester of Pragati design plant starts from the foundation in dome shape thereby reducing the constructional area, for same digester volume, thus reducing the cost of construction of the plant. The wall thickness of digester is kept 75 mm only. Dome shape construction takes place upto a collar base, where a central guide frame is provided. The digester wall above guide-frame is constructed in cylindrical shape.

Partition wall is constructed in the digester for 4 Cum. and bigger sizes so as to control the flow of slurry inside the digester. It divides digester into two parts separating inlet and outlet.

The inlet is through pipe, placed while constructing digester wall. It is used for feeding daily slurry into the digester and is generally of 100 mm diameter. The outlet pipe is also 100 mm in diameter and fixed while constructing digester wall. The asbestos cement pipe can be used for inlet and outlet.

The guide frame is made of angle iron and steel pipe, is embedded in the digester wall at top of spherical portion of digester. The central guide pipe holds gas holder which is also made of M.S. sheet and angle iron. It floats up and down along pipe depending on the quantity of gas in the drum.

Ganesh Biogas Plant. It is basically a KVIC plant constructed with bamboo and polythene sheet. It was developed in district. Rampur of Uttar Pradesh. Only the digester is made of an angle iron frame, bamboo and polythene sheet. The KVIC gas holder and guide frame are used in this design also. The cost of this plant is 70 percent of KVIC plant.

Ferro Cement Digester Biogas Plant. Ferro-cement is a form of reinforced concrete made of a wire mesh, sand, water and cement. In this composite material layers of thin wire mesh distributed throughout the thickness of element are integrated with thick cement mortar over an inverted mould. In fact, it is reinforced mortar having high resistance to cracking and permeability.

In the ferro-cement digesters the periphery is divided into 4 or 6 segments, which are casted at a central place over a prepared masonary or wooden mould. These pre-casted segments are then transported and erected at the plant site. This type of digester is an ideal substitute for brick digester in areas where good quality bricks are not available and also solves the problems of leakage through masonary joints. All the systems of the plant are of KVIC design and specifications.

Table 4 . Differences between fixed and floating-drum biogas designs in India

Fixed dome	Floating drum
Digester and gas holder, masonry or concrete structure	Digester, masonry Gas holder, mild steel or fibre glass
Requires high masonary skills	Low masonry or fabricating skills
Low reliability due to high construction failure	High reliability, gas holder prefabricated
Variable gas pressure	Constant gas pressure
Digester could be inside the ground	Requires space above ground for three tanks; inlet, digester, outlet
Low cost (2 m^3=Rs 5000)	High cost of plant due to gas holder (cost for 2 m^3 = Rs 8000)

Table 5. Cost of family biogas plant (in Rs) different capacities (in m^3)

Design	$2m^3$	$3m^3$	$4m^3$
Floating-drum KVIC type	8030	9500	10700
Fixed dome (Deenabandhu type)	5325	6400	7800
Subsidy from government in plains	2200	2600	2600
Subsidy as % of KVIC floating-drum cost	28	29	33
Subsidy as % of fixed-dome cost	41	40	24
Subsidy in north-east and hilly districts of Uttar Pradesh	5100	6200	6200
Subsidy as % of floating-drum KVIC design in north-east and hilly districts	63	65	58

Advantages and Disadvantages of Floating Drum Plant :

Advantages :

1. It has less volume related trouble because solids are constantly submerged.

2. No separate pressure equalizing device needed when fresh waste is added to the tank or digested slurry in withdrawn.
3. In it, the danger of mixing oxygen with the gas to form an explosive mixture is minimized.
4. Higher gas production per cubic meter of the digester volume is achieved.
5. Floating drum has welded braces, which help in breaking to scum (floating matter) by rotation.
6. No problem of gas leakage.
7. Constant gas pressure.

Disadvantages :

1. It has higher cost, as cost is dependent on steel and cement.
2. Heat is lost through the metal gas holder, hence it troubles in colder regions and periods.
3. Gas holder requires painting once or twice a year, depending on the humidity of the location.
4. Flexible pipe joining the gas holder to the main gas pipe requires maintenance, as it is damaged by ultraviolet rays in the sun. It may be twisted also, with the rotation of the drum for mixing or scum removal.

2.2. KEYWORDS

Biomass

Organic matter produced by plants and other photosynthetic producers, total dry weight of all living organisms that can be supported at each trophic level in a food chain or wet, dry weight of all organic matter in plants and animals in an ecosystem, plant material and animal waste usedas fuel.

Biofuel

Gas or liquid fuel (such as ethyl alcohol) made from plant material biomass.

Biogas

Biogas is a clean, non-polluting, convenient and low cost fuel for rural areas. It is generated through anaerobic digestion of organic matter.

Combustion

Direct burning of biomass to produce energy.

Gasification

A solid fuel is converted by a senses of thermo-chemical process into a gaseous fuel.

Pyrolysis

It is the thermal decomposition of organic materials or the burning of biomass in the absence of oxygen or air.

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UNIT – II – SOLAR ENERGY – SEEA3010

UNIT_II
SOLAR ENERGY

2.1 INTRODUCTION

Solar energy equivalent to almost 75000 TkWh hits the earth surface every day. A mere 0.1% of this staggering figure is sufficient to meet world energy needs. Use of solar energy has grown steadily at the rate of 16% during 1990-98. According to Worldwatch the solar market is expected to reach 10600 MW if there is a constant annual growth of 25% each year. Japan is the largest solar power-utilizing nation. More than 6,800 SPV systems were installed in the country by 1998.

India is one of the few countries blessed with plenty of sunshine with an annual insolation of 5000 TkWh and with 300 clear sunny days in most parts of the country. The average insolation incident over India in about 5.5 kWh/m^2 over a horizontal surface. With this, it is possible to generate 20 MW solar power per square kilometer land area.

2.2 SOLAR COLLECTORS

A solar collector is a device for collecting solar radiation and to transfer the energy to a fluid passing in contact with it. Utilization of solar energy requires solar collectors. There are two general types :

i) The flat-plate collector.
ii) The concentrating (focussing) collector.

2.2.1 Flat-plate collector

A flat-plate collector is one in which the absorbing surface for solar radiation is essentially flat. Flat-plates can collect and adsorb both direct and diffuse solar radiation, they are consequently partially effective even on a cloudy day when there is no direct radiation.

The majority of the flat-plate collectors have five main components as follows :

2.2.1.1 A transparent cover which may be one or more sheets of glass or radiation transmitting plastic film or sheet.

2.2.1.2 Tubes, fins or channels are integral with the collector absorber plate or connected to it, which carry the water, air or other fluid.

2.2.1.3 The absorber plate, normally metallic or with a black surface.

2.2.1.4 Insulation, which should be provided at the back and sides to minimize the heat losses. Standard insulating materials such as fibre glass, are used for this purpose.

2.2.1.5 The container which encloses the other components and protects them from the weather.

Advantages of flat-plate collectors :

i) They can utilize both the diffuse and direct solar radiation.
ii) They do not require orientation towards the sun.
iii) They are easily manufactured.
iv) They require little maintenance.
v) Construction is relatively simple.

Flat-plate solar collectors may be divided into two main classes based on the type of heat transfer fluid used.

i) A typical liquid collector.

ii) A typical air collector.

2.2.2 A typical liquid collector:

They are used for heating water and non freezing aqueous solutions. It basically consists of a flat surface with high absorptivity for solar radiation, called the absorbing surface. Typically a metal plate usually of copper, steel, or aluminium material with tubing of copper in thermal contact with the plate, are the most commonly used material. The absorber plate is usually made from a metal sheet 1 to 2 mm in thickness, while the tubes, which are also made of metal, range in diameter from 1 to 1.5 cm. They are soldered or clamped to the bottom of the absorber plate with the pitch ranging from 5 to 15 cm.

Heat is transferred from the absorber plate to a point of use by circulation of fluid (usually water) across the solar heated surface. Thermal insulation of 5 to 10 cm thickness is usually placed behind the absorber plate to prevent the heat losses from the rear surface. Insulation material is generally mineral wool or glass wool or a heat resistant fibre glass.

The front covers are generally glass (may be one or more) that is transparent to incoming solar radiation and opaque to the infrared re- radiation from the absorber. The glass covers act as a convection shield to reduce the losses from the absorber plate beneath. Glass is generally used for the transparent covers but certain plastic films may be satisfactory. Glass is the most favourable material. Thickness of 3 or 4 mm are commonly used.

The usual practice is to have 1 or 2 covers with a width ranging from 1.5 to 3 cm. Advantages of second glass which is added above the first one are :

i) Losses due to air convection are further reduced. This is important in windy areas.

ii) Radiation losses in the infra-red spectrum are reduced by a further 25%, because half of the 50% which is emitted outwards from the first glass plate is back-radiated.

It is not worthwhile to use more than two glass plates. This is due to the fact that each plate reflects about 15% of the incoming sunlight.

Some plastic glazings have been recommended. Slagwood, fibre glass, polyurethane foam, hay in polythene bags (to keep the moisture out) are suitable materials for insulating the sides and bottom of collector. The collector box support all the components and provides weather protection.

For water streams the absorber plate can be any metal, plastic or rubber sheet that incorporates water channels, while for air systems the space above or below the collector plate serves as the conduit. The surface finish of the absorber plate may be a flat black paint with an appropriate primer. The primer coat should preferably be thin since a thick under coat of paint would increase the resistance to heat transfer. Black painted absorbers are preferred because they are considerably cheaper.

The liquid heated is generally water. However sometimes mixtures of water and ethylene glycol are used if ambient temperatures below 0^0C are likely to be encountered.

Typical collector dimensions are 2 m x 1 m x 15 cm.

2.2.3 Typical air collector :

A flat-plate collector where an air stream is heated by the back side of the collector plate. Fins attached to the plate increase the contact surface. The back side of the collector is heavily insulated with mineral wool or some other material. The most favourable orientation of a collector, for heating only, is facing towards the south at an inclination angle to the horizontal equal to the latitude plus 15^0 ($s = \square + 15^0$).

Air can be passed in contact with black solar absorbing surface such as finned plates or ducts as mentioned above, corrugated or roughened plates of various materials, several layer of metal screening and overlapped glass plates. Flow may be straight, through, surpentine, above, below or on both sides of the absorber plate or through a porous absorber material.

The flat-plate is a simple and effective means of collecting solar energy for applications that require heat at temperatures below about 100^0C. These collectors have been used successfully for providing domestic hot water, space heating, air conditioning, power generation, water pumping cooking and other purposes.

The advantages of flat-plate collectors, as compared with focussing collectors are :

2.2.3.1.1 No complicated tracking mechanisms are involved.
2.2.3.1.2 Construction is relatively simple.
2.2.3.1.3 They can utilize both the diffuse and direct components of the available solar radiation.
2.2.3.1.4 They are easily manufactured.

The advantages are their temperature limitation (about 100^0C) and the fact that the collector heat exchanger area must equal the collector aperture area.

2.2.4 Physical principles of the conversion of solar radiation into heat

The fundamental process now in general use for heat conversion is the green house effect. The name comes from its first use in green houses in which it is possible to grow exotic plants in cold climates through better utilization of the available sunlight.

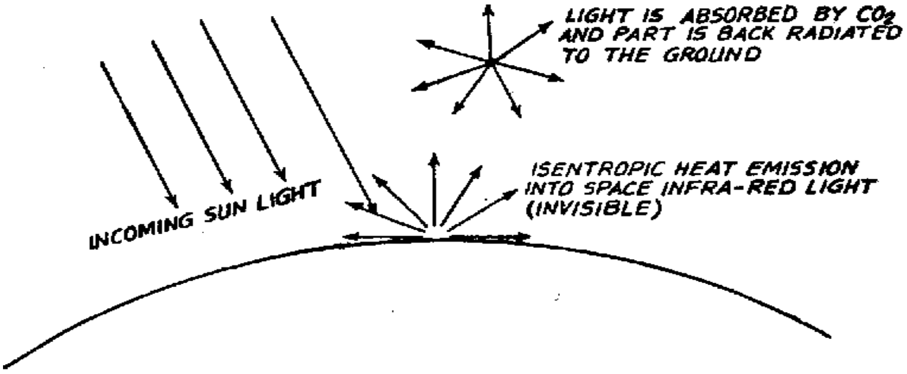

Figure 1.1. The green house effect related to the CO_2 contents of the atmosphere.

Show how temperature on earth is affected by the green house effect. Visible sunlight is absorbed on the ground at a temperature of 20^0C for example emits infra-red light at a wave length of about 10 m but CO_2 in the atmosphere absorbs light of that wave length and back radiates part of it to earth. (CO_2 does not absorb the incoming sunlight which has a shorter wavelength). Hence the 'green house effect' brings about an accumulation of energy on the ground.

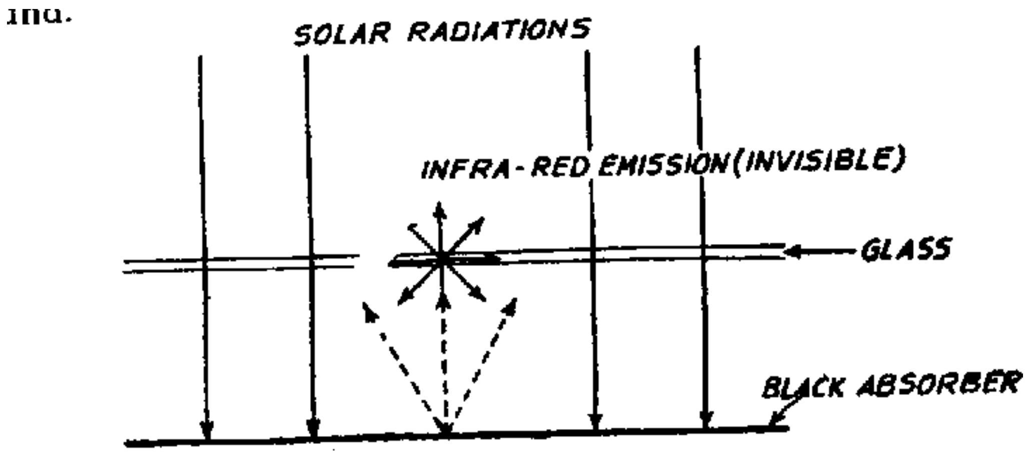

Figure 2.2. Principle of green house effect.

A black-painted plate absorbs the incoming sunlight. About it, is fixed a plate of ordinary window glass. When the temperature of the black-plate increases, it emits an increment of thermal beat in the form of infra-red light. The black absorber has the properties of a black body, ideal black bodies have not only the highest absorption rate but also the highest emission, coefficient for all wavelengths of light. Emission increases with temperature. The re-emitted light is of progressively shorter wavelength and greater energy as the temperature of the black body increases.

2.2.5 Concentrating collector : Focussing type :

Focussing collector is a device to collect solar energy with high intensity of solar radiation on the energy absorbing surface. Such collectors generally use optical system in the form of reflectors or refractors. A focussing collector is a special form of flat-plate collector modified by introducing a reflecting (or refracting) surface (concentrator) between the solar radiation and the absorber. These type of collectors can have radiation increase form low value of 1.5-2 to high values of the order of 10000. In these collectors, radiation falling on a relatively large area is focussed on to a receiver (or absorber) of considerably smaller area. As a result of the energy concentration, fluids can be heated to temperature of 500^0C or more.

2.2.5.1 Types of concentrating collectors

Concentrating or focussing collectors may be considered in two general categories : line focussing and point focussing types.

In practice, the line is a collector pipe and the point is a small volume through which the heat transport fluid flows. Because the sun has a finite size, focussing does infact occur over a small area or volume rather than a line or point. As per the number of concentrating collector geometries, the main-types of concentrating collectors are :

- Parabolic through collector.
- Mirror strip reflector
- Flat plate collector with adjustable mirrors
- Compound parabolic concentrator (C. P. C.).

(a) Parabolic trough reflector. The principle of the parabolic trough collector, which is often used in concentration collectors, is shown by the cross-section in Fig. 1.3, solar radiation coming from the particular directions collected over the area of the reflecting surface and is concentrated at the focus of the parabola if the reflector is in the form of a trough with parabolic cross-section, the solar radiation is focussed along a line. Mostly cylindrical parabolic concentrators are used in which absorber is placed along focus axis. The collector pipe, preferably with a selective

absorber coating, is used as an absorber. The dimension of parabolic trough or parabolic cylindrical collector can vary over a wide range. The length of a reflector unit may be roughly 3 to 5m and the width about 1.5 to
2.4 m, Ten or more such units are often connected end to end in a row, several rows may also be connected in parallel. Parabolic trough reflectors have been made of highly polished aluminium, of silvered glass or of a thin film of aluminized plastic on a firm base. Instead of having a continuous form, the reflector may be constructed from a number of long flat strips on a parabolic base.

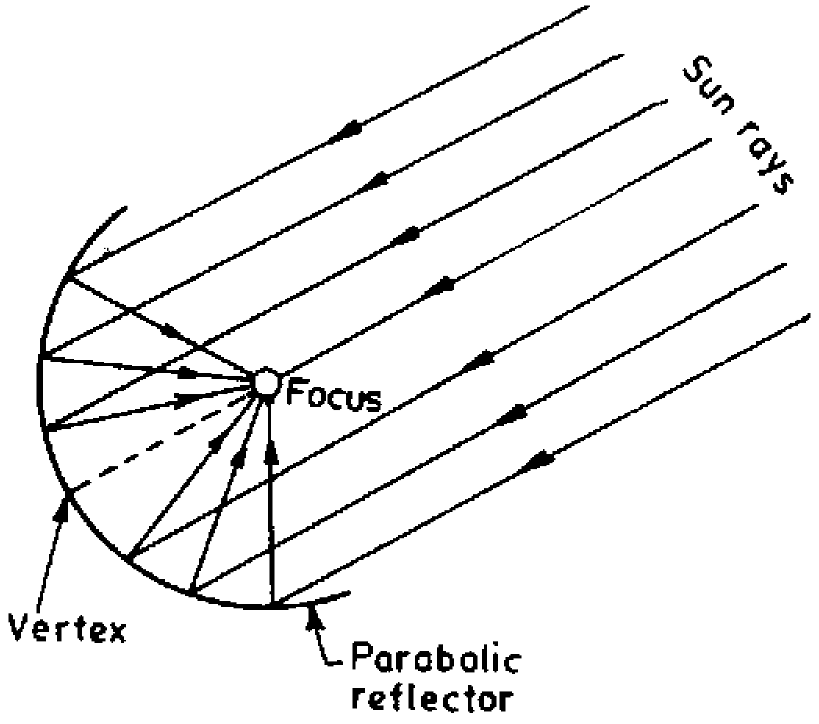

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Figure 2.3. Cross-section of parabolic trough reflector

For the solar radiation to be brought to a focus by parabolic trough reflector, the sun must be in such a direction that it lies on the plane passing through the focal line and the vertex (i. e., the base) of the parabola. Since the elevation of the sun is always changing, either the reflector trough or the collector pipe (absorber) must be turned continuously about its long axis to maintain the required orientation. Both schemes are used in different practical-designs. Either the trough/cylindrical reflector or the pipe is turned by partial rotation around a single axis parallel to the trough length. Trough type collectors are generally oriented in the east-west or north-south directions. For the east-west orientation, the collectors are laid flat on (or parallel, to) the ground. For the north-south orientation, however, the north end of the trough is raised so that the collectors are sloped facing south, just like flat-plate collectors. Ideally, the slope angle should be changed periodically; it is simpler, but less efficient, however to use a fixed angle design.

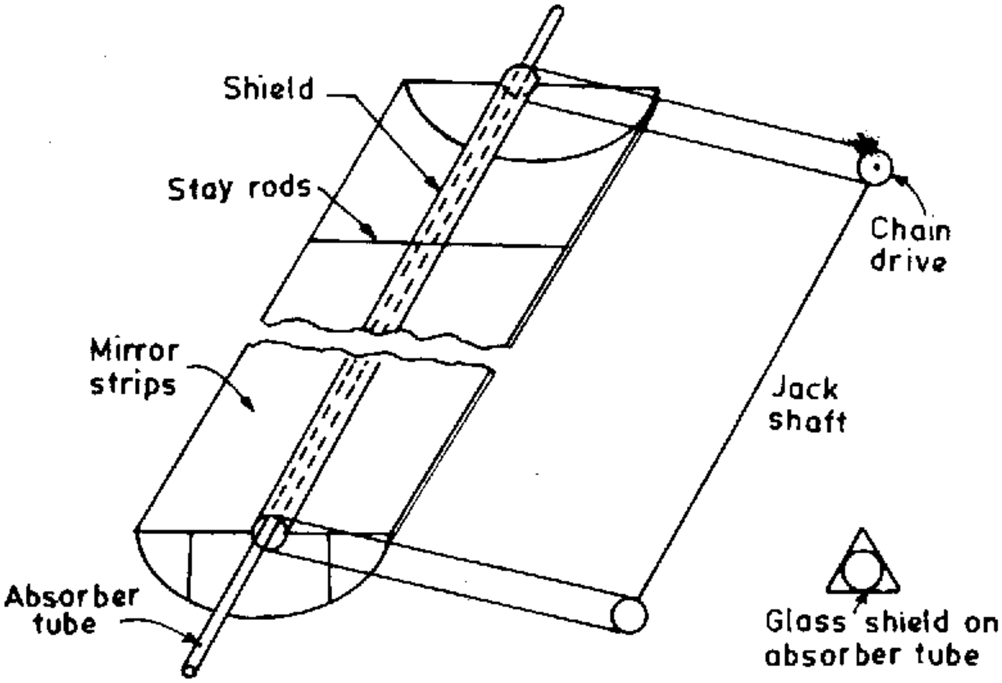

Figure 2.4. A typical cylindrical parabolic system

The north-south orientation permits more solar energy to be collected than the east-west arrangement, except around the winter equinox. On the other hand, construction costs are higher for the north-south (sloping) type. Moreover, a system of such collectors requires a larger area to allow for the shadowing effect of the sloping troughs. The increased separation distance between rows of collectors also results in increased pipe line costs and greater pumping and thermal losses. Finally the sun set position and little or not ever night adjustment is required. For the north-south orientation, however, the trough (or receiver) must be turned through a large angle from sunset to sunrise. The choice of orientation in any particular instance depends on the foregoing and other considerations.

(b) Mirror-Strip Reflector: In another kind of focussing collector, a number of plane or slightly curved (concave) mirror strips are mounted on a flat base. The angles of the individual mirrors are such that they reflect solar radiation from a specific direction on the same focal line. The angles of the mirrors must be adjusted to allow for changes in the sun's elevation, while the focal line (for collector pipe) remains in a fixed position. Alternatively, as mentioned for parabolic trough collectors, the mirror strips may be fixed and the collector pipe moved continuously so as to remain on the focal line.

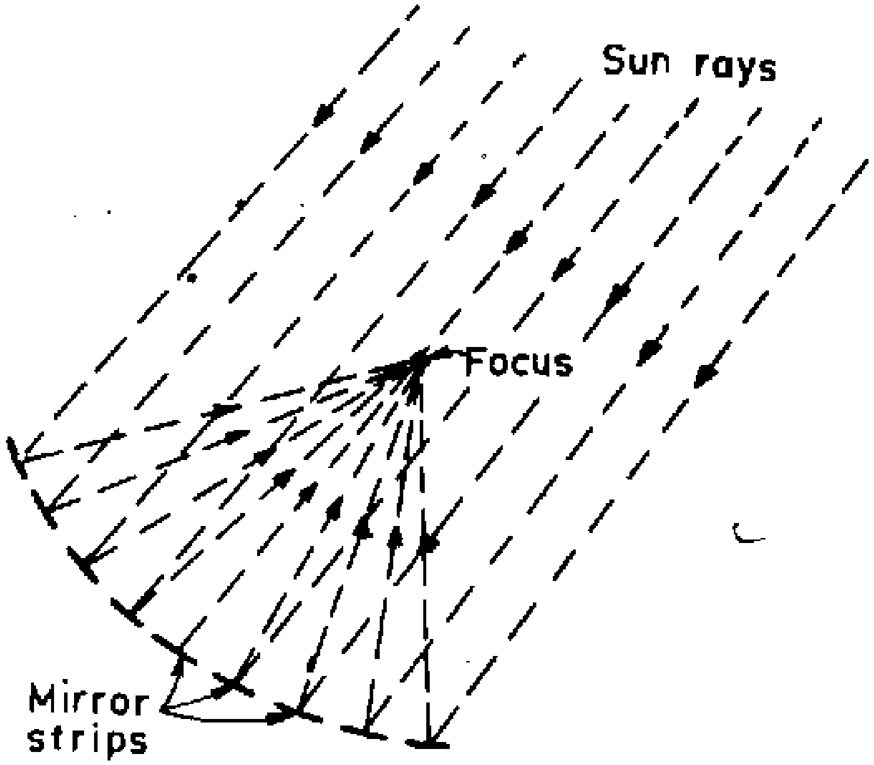

Figure 2.5. A mirror-strip solar collector.

Point Focussing Collector (paraboloidal type).

A paraboloidal dish collector brings solar radiation to a focus at a point actually a small central volume. A dish 6.6 m internal diameter has been made from about 200 curved mirror segments forming a paraboloidal surface. The absorber, located at the focus, is a cavity made of a zirconium-copper alloy with a black chrome selective coating. The heat-transport fluid flows into and out of the absorber cavity through pipes bonded to the interior. The dish can be turned automatically about two axes (up-down and left-right) so that the sun is always kept in a line with the focus and the base (vertex) of the paraboloidal dish. Thus, the sun can be fully tracked at essentially all times.

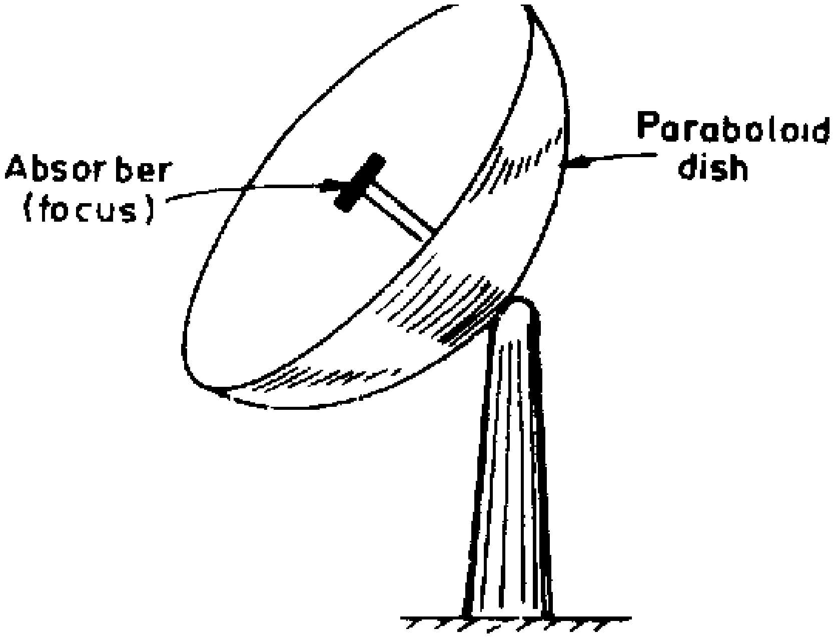

Figure 2.6. Point focus solar collector (Paraboloid).

The concentration ratios (concentration ratio is the ratio of the area of the concentrator aperture to the energy absorbing area of the receiver, it determines the effectiveness of a concentrator), are very high in the case of parabolic system and therefore can be used where high temperature are required. In a cylindrical parabolic system, the concentration ratio is lower than paraboloid counter-parts. In both the cases, the receiver is placed at the focus i. e., along the focal line in cylindrical parabolic or parabolic trough system and at the focus point in paraboloidal system.

Concentration ratios of about 30 to 100 or higher would be needed to achieve temperature in the range 300 to 500^{0}C or higher. Collectors designed for such high concentration ratio necessarily have small angles of field of view and hence need to track the sun continuously. A broad classification of such collector is :

i) The linear focus collector in the form of a parabolic trough or the ones employing faceted mirror strips.

ii) Spherical and conical mirror (Axicon) with aberrated foci. The physical upper limit to the concentration ratios achievable with paraboloids and parabolic troughs is determined by their f/d ratios (focal length/diameter) and are about 10000 and 100 respectively for the two cases. The concentration ratios achieved in practice are about 1/3 to ½ of the above values because of surface irregularities of the reflector, tracking errors etc.

iii) Central receiver collector, such as the paraboloidal mirror and the tower power plant using heliostat mirrors.

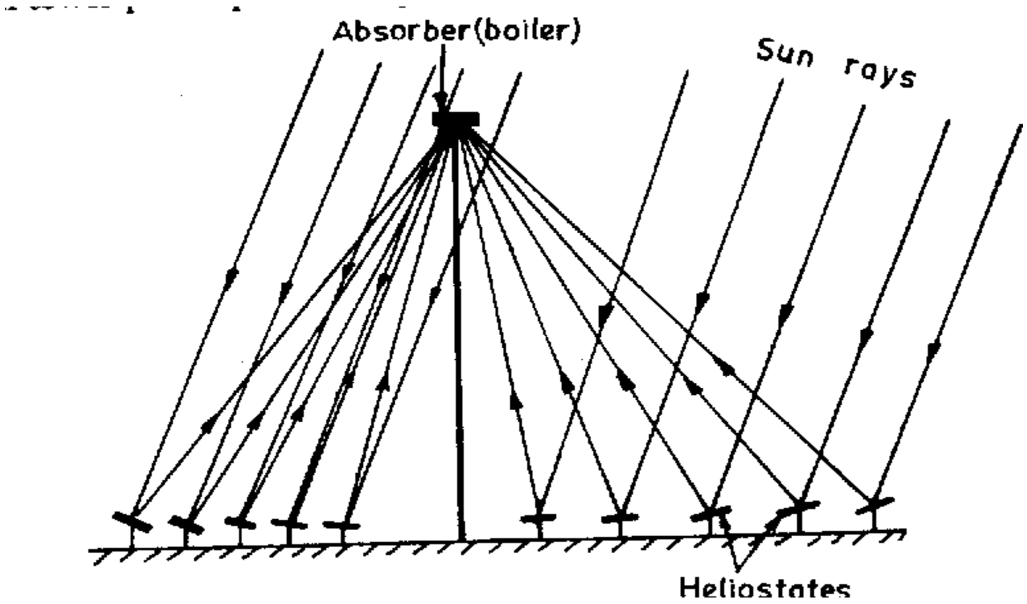

Figure 2.7. Distributed heliostat point-focussing reflector.

A system equivalent to very large paraboloidal reflector consists of a considerable number of mirrors distributed over an area on the ground. Each mirror, called a heliostat, can be steered independently about two axes so that the reflected solar radiation is always directed towards an absorber mounted on a tower. This type of collector is classified as central receiver collector. This is mostly used in tower power plants for generation of electrical energy.

2.2.6 Concentrating collectors : Non-Focussing Type. The simplest type of concentrating collector is the mirror-boosted, flat plate collector. Is the mirror-boosted flat plate collector. It consists of a flat plate facing south with mirrors attached to its north and south edges. If the mirrors are set at the proper angle, they reflect solar radiation on to the absorber plate. Thus the latter receives reflected radiation in addition to that normally falling on it. The mirrors cut off part of the scattered radiation that would otherwise have reached the absorber plate, and only part of the scattered radiation falling on the mirrors will be reflected onto the absorber. Thus the concentration effect arises mainly from the increase in direct radiation reaching the absorber plate.

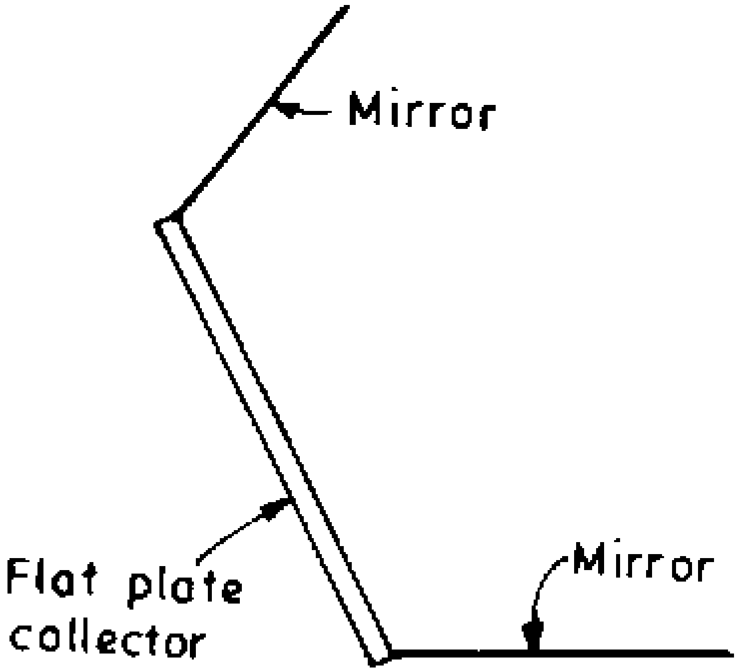

Figure 2.8. Flat plate collector augmented with mirrors.

When a number of collectors are combined in two or more rows, as they often are, the rows must be set further a part in the north-south directions to allow for the additional sun shading caused by the mirror extensions. Furthermore, in order for the mirrors to be effective, the angles should be adjusted continuously as the sun's attitude changes. For these reasons and they can provide only a relatively small increase in the solar radiation falling on the absorber, flat-plate collectors with mirrors are not widely used.

2.2.7 Advantages and Disadvantages of concentration collectors over flat-plate type collectors :

Advantages. The main advantages of concentrator systems over flat-plate type collectors are :

1. Reflecting surfaces required less material and are structurally simpler than flat-plate collectors. For a concentrator system the cost per unit area of solar collecting surface is therefore potentially less than that for flat-plate collectors.
2. The absorber area of a concentrator system is smaller than that of a flat-plate system for same solar energy collection and therefore the insolation intensity is greater.
3. Because of the area from which heat is lost to the surroundings per unit the solar energy collecting area is less than that for flat- plate collector and because the insulation on the absorber is more concentrated, the working fluid can attain higher temperatures in a concentrating system than in a flat-plate collector of the same solar energy collecting surface.
4. Owing to the small area of absorber per unit solar energy collecting area, selective surface treatment and/or vacuum insulation to reduce heat losses and improve collector efficiency are economically feasible.

5. Focussing or concentrating systems can be used for electric power generation when not used for heating or cooling. The total useful operating time per year can therefore be large for a concentrator system than for a flat-plate collector and the initial installation cost of the system can be regained by saving in energy in a shorter period of time.
6. Because the temperature attainable with concentrating collector system is higher the amount of heat which can be stored per unit volume is larger and consequently the heat storage costs are less for concentrator systems than for flat-plate collectors.
7. In solar heating and cooling applications, the higher temperature of the working fluid attainable with a concentrating system makes it possible to attain higher efficiencies, in the cooling cycle and lower cost for air conditioning with concentrator systems than with flat-plate collectors.
8. Little or not anti-freeze is required to protect the absorber in a concentration system whereas the entire solar energy collection surface requires anti-freeze protection a flat-plate collector.

Disadvantages :

1. Out of the beam and diffuse solar radiation components only beam component is collected in case of focussing collectors because diffuse component can not be reflected and is thus lost.
2. In some stationary reflecting systems it is necessary to have a small absorber to track the sun image; in others the reflector may have to be adjustable more than one position if year round operation is desired; in other words costly orienting systems have to be used to track the sun.
3. Additional requirements of maintenance particular to retain the quality of reflecting surface against dirt, weather, oxidation etc.
4. Non-uniform flux on the absorber whereas flux in flat-plate collectors is uniform.

5. Additional optical losses such as reflectance loss and the intercept loss, so they introduce additional factors in energy balances.
6. High initial cost.

2.10 SOLAR PHOTOVOLTAICS

The term photovoltic is derived by combining the Greek word for light, photos with volt, the name of the unit of electromotive force. The volt was named after the Italian physicist count Alessando Volta, the inventor of battery. The term photo-voltaic therefore signifies the generation of electricity from solar energy.

Historical background :

The discovery of the photovoltic effect is generally credited to the French physicist Edmond Becquerel. When he was working with ‘wet cell’ battery in the course of which he found that the battery voltage increased when its silver plates were exposed to sunlight.

In year 1883 a new York electrician Charles Edgar Fritts, constructed a selenium solar cell that was some what similar to the silicon solar cells of today. It was made up of thin wafers of selenium covered with semi- transparent gold wires and a protective sheet of glass. But his cell was very inefficient (i.e. @ 1%).

But the real breakthrough that occurred in 1950’s that set in motion the development of modern high-efficiency solar cells. It occurs in Belt’s Labs in USA, where work was going on to study effect of light on “semi- conductors”. Semi-conductor are non-metallic materials such as germanium and silicon whose electrical characteristics lie between those of conductor and insulators. Hence the term semi-conductor. Transistor are made from semi-conductor in extremely pure form, into which tiny quantities of carefully selected impurities, such as boron or phosphorous have been deliberately diffused. This process is known as ‘doping’. Doping alters the electrical behaviour of semi-conductors in very useful manner.

The first successful demonstration of use of PV solar cell as a power source for space craft was carried out in 1958, to power a small Radio transmitter in second US Space Satellite Vinguard 1.

2.10.1 Cell structure and principle

PV cells consists of junction between two thin layers of dissimilar semi-conducting material known as P (positive)-type semi-conductor and N-(negative) type semi-conductor. These semi-conductors are usually made from silicon.

N-type semi-conductor are made from crystalline silicon that has been doped with small quantities of an impurity [usually phosphorous] in such a way that the doped material possesses a surplus of free electrons. As there is a net negative charge after doping so it is known as N- type semi-conductor.

P-type semi-conductor are also made from crystalline silicon, but are doped with very small amount of different impurity (usually boron) which causes the material to have a deficiency of free electrons. These missing electrons create holes. Since deficiency of an electron causes a net +ive charge. Hence the name P-type semi-conductor.

A PN junction is created by joining these dissimilar semi-conductors. This sets up an electric field in the region of the junction. This electric field will cause negatively and positively charged particle to move in the opposite direction.

As light is consist of a stream of tiny particles of energy called “photons”. When photons of light of a suitable wave length falls with in the P-N-Junction they can transfer their energy. Some of the electrons in the material so promoting them to higher energy level. In normal state [i. e. without excitation] these electrons help to hold the material together by forming valance bonds with adjoining atoms and can’t move. But in their excited state however, the electrons become free to conduct electric current by moving through the material and while moving electron leaves behind holes (i. e. deficiency of electron) in the material which can also move.

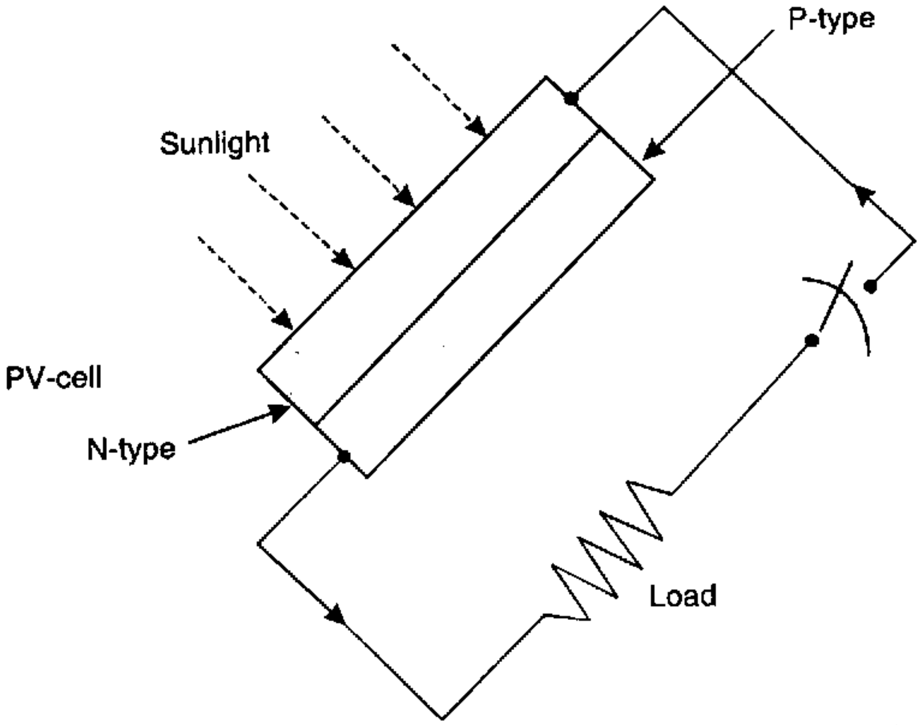

Figure 2.9. Schematic diagram of a solar cell.

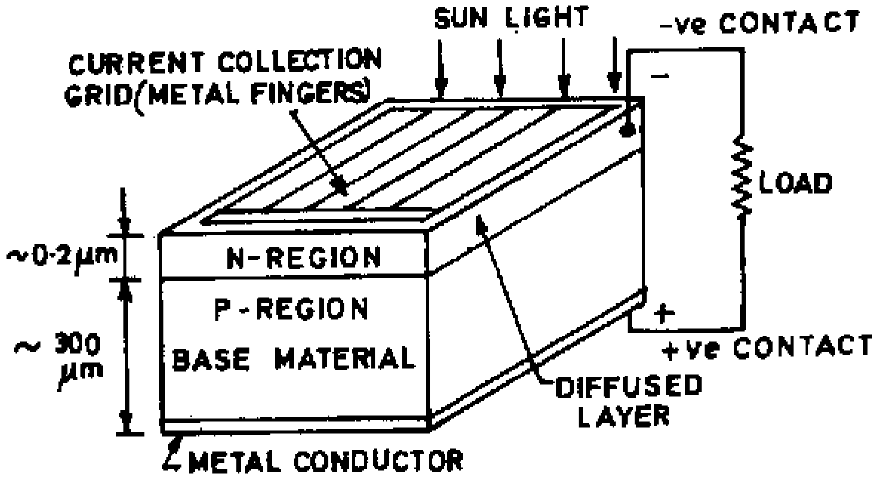

Figure 2.10. Schematic of completely covering back a typical solar cell showing the physical arrangement of the major components.

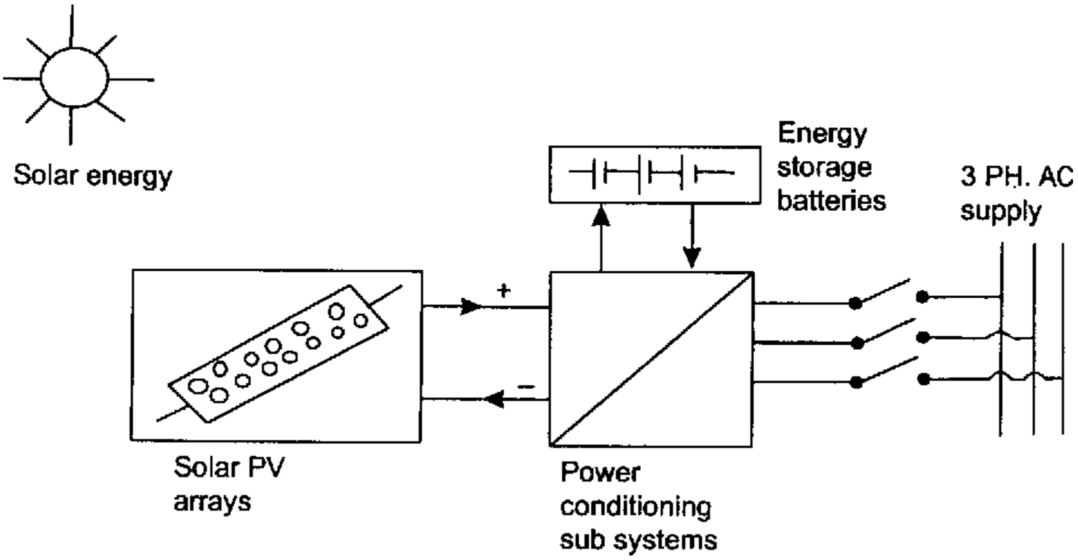

Figure 2.11. Schematic diagram of solar PV system.

When the P-N-Junction is formed some of the electrons in the immediate vicinity of the junction are attracted from the N-side to combine with the holes on P-side. Similarly holes on the P-side near the junction are attracted combine with the hole on the nearby N-side. The net effect of this is to set up around the junction a layer on the N-side that is more +vely charged that it would otherwise be and on the P-side a layer that is more – vely charged then it would be. This means a reverse electric field is set up around the junction and the region around the junction is known as zone of depletion as it is depleted of charged carriers (electrons holes).

When an electron in the junction region is stimulated by an incoming photon to jump into the conduction band it leaves behind a hole in the valance band. Two charge carriers (an electrons hole pair) are thus generated under the influence of the reverse electric field around the junction. The electron will tend to move into the N-region and holes into the P-region. The flow of electron to the N-region is an electric current if there is an external circuit for the current to flow through, the moving electrons will eventually flow out of the semi-conductor via one of the metallic contact on the top of the cell. The holes will flow in the opposite direction through the material until they reach another metallic contact at the bottom of the cell where they are filled by electron from the other half of the external circuit.

The generation of electric power requires both voltage and current so in order to provide power the PV cell must generate voltage as well as the current provided by the flow of electron. This voltage is provided by the internal electric field set up at the P-N-Junction. A single PV cell produce a voltage of about 0.5 volt at a current of up to around 2.5 amperes. So the peak power of cell is – I x V = 0.5 x 2.5 = 1.25W.

2.10.2 **Type of PV cells** :

- Mono crystalline silicon cells
- Poly crystalline silicon cells
- Poly crystalline silicon thin film.
- Gallium arsenide cells.
- Thin film PV cells.
    - Amorphous silicon
    - Copper indium diselenide
    - Cadmium telluride.

Mono crystalline silicon cells

These are made from extremely pure mono-crystalline silicon in the sophisticated but expensive Czochralski process. The most efficient mono-crystalline cell have an efficiency of around 16%. These cells are made in pyramid-shaped texture on the top surface to increase the amount of light trapped.

Poly-crystalline silicon cells

Here wafers of cell are made from poly crystalline silicon. These poly crystalline are easier to manufacture but are less efficient (around 10%). Main advantage is that these can be manufactured in square shapes which virtually eliminated any inactive area between cells.

Poly crystalline thin film silicon cells

These are manufactured by depositing thin film @ 20 micron thick of poly crystalline silicon on ceramic substrate. The efficiency is about 15%.

Gallium arsenide (GA) cells

GA is more suitable than silicon because it has high light absorption co-efficient and also it has a band gap wider than that of silicon and close to the theoretical optimum for absorbing the energy in the terrestrial solar spectrum. So cells made of GA are very efficient. Another advantage is that they can operate at relatively high temperature without the appreciable performance degradation from which silicon and many other-semi-conductor suffers. So GA is more suitable in concentrating PV systems. But they are very costly and used mostly in space applications.

Thin film PV cells

Amorphous silicon :

Amorphous silicon is less structured form of silicon in which the silicon atoms are much less ordered than in the crystalline form Solar cell using a-Si have a some what different form of Junction between the P and N-type material. A so called a PN junction is formed, consisting of an extremely thin layer of P-type a-Si or top followed by a thicker intrinsic layer (i layer) made up of un-doped a-Si and then a very thin layer of N-type a-Si.

Advantages of a-Si :

- Cheaper to produce
- Much better absorption of light.

Disadvantages of a-Si :

- less efficient than poly crystalline
- Efficiency degrades after few month of exposure to sun light.

In 1990- a-Si cells accounted for 30% of PV sales worldwide.

Copper Indium Diselenide (CIS) film

CIS is a compound of copper indium and selenium, which is a semi-conductor. These have attained an efficiency of 12.5%. These modules don't suffer the problem of degradation in performance as in a-Si. Although indium is expensive but quantity required is very small.

Cadmium telluride (Cd Tc)

It is another semi-conductor. CdTc modules can be made using a simple and in-expensive electroplating type of process. Efficiency of over 10% are claimed without performance degradation as in a-Si.

2.10.3 Multiple Junction PV cells

One way of improving the overall efficiency of PV cells and modules is the multi-junction approach, in which two (or more) PV junctions of thin film type are layered one on top of the other, each layer extracting energy from a particular portion of spectrum of coming light.

Concentrating PV systems :

Another way of getting more energy out of a given number of PV cells is to use mirrors or lenses to concentrate incoming solar radiation to the cells.

Array sizing and selection

- First estimate AC and DC load at the chosen site.
- To account for energy losses in battery charge/discharge cycle estimated load is enhanced by 20%.
- Then estimate the sun shine at site i. e. equivalent sun shine hours.

- Next the array wattage = $\dfrac{\text{Avg. daily load (Amp hr)}}{\text{Available sunshine (hours)}}$

- $\text{Number of modules} = \dfrac{\text{Array wattage (A)}}{\text{Module wattage}}$

Available sunshine hours can be found from solar radiation maps.

2.10.4 Photovoltaics in India

PV programme in India is initiated in 1976. But commercial production of solar cells and modules began in 1983 when central electronics Ltd. (CEL) entered in this line. In 1992 designated capacity for manufacturing PV systems was CEL (2mw), REIL (1mw), Suryavonics Ltd. (1.2 mw), BHEL (300 kw) Tata BP solar (500 kw) and Indian metal and carbide limited (300 kw). Indian capabilities cover complete cell manufacture module lamination and system development. By 1995 total installed capacity for solar pv systems was 7 mw out of which 4 mw was towards street lightening and remaining 3 mw by way of domestic lightening, community TV, water pumping railway signalling.

In India MNES plans and co-ordinate R and D activities in photo- voltaics carried out by different govt. agencies and voluntary organization.

2.10.5 **Incentive from Govt. for promotion of PV** :

i) No license for setting up PV systems.

ii) Custom rates are considerably reduced.

iii) IREDA provide term loan upto 1.5 crore for financing PV programmes.

During eighth plan (1992-1997) an outlay of Rs 90 crore was allocated for financing PV programmes.

Large scale expansion in PV technology is largely contramed by high system costs which is due to low cell efficiency and high material and manufacturing costs and these need to be improved.

2.10.6 Application of solar photovoltaic system

Various solar photovoltaic systems have been developed and installed at different sites for demonstration and field trial purposes. The terrestrial applications of these include provision of power supply to :

i) Water pumping sets for micro irrigation and drinking water supply,
ii) Radio beacons for ship navigation at ports,
iii) Community radio and television sets,
iv) Cathodic protection of oil pipe lines,
v) Weather monitoring,
vi) Railway signalling equipment,
vii) Battery charging,
viii) Street lighting.

The major application of photovoltaic lies in water pumping for drinking water supply and irrigation in rural areas. The photovoltaic water pumping system essentially consists of :

a) a photovoltaic (PV) array,
b) storage battery,
c) power control equipment,
d) motor pump sets, and
e) water storage tank.

2.10.7 Advantages and Disadvantages of photovoltaic solar energy conversion :

Advantages :

i) Direct room temperature conversion of light to electricity through a simple solid state device.
ii) Absence of moving parts.

iii) Ability to function unattended for long periods as evidence in space programme.

iv) Modular nature in which desired currents, voltages and power levels can be achieved by mere integration.

v) Maintenance cost is low as they are easy to operate.

vi) They do not create pollution.

vii) They have a long effective life.

viii) They are highly reliable.

ix) The consume no fuel to operate as the sun's energy is free.

x) They have rapid response in output to input radiation changes; no log-on time constant is involved, as on thermal systems, before steady state is reached.

xi) They have wide power handling capabilities from microwatts to kilowatts or even megawatts when modules are combined into large area arrays. Solar cells can be used in combination with power conditioning circuit to feed power into utility grid.

xii) They are easy to fabricate, being one of the simplest of semi conductor devices.

xiii) They have high power to weight ratio, this characteristic is more important for space applications than terrestrial, may be favourable for some terrestrial applications. The roof loading on a house-top covered with solar cells, for example, would be significantly lower than the comparable loading for conventional liquid solar water heaters.

xiv) Amenable to on site installation i. e. decentralized or dispersed power; thus the problem of power distribution by wires could be eliminated by the use of solar cells at the site where the power is required.

xv) They can be used with or without sun tracking, making possible a wide range of application possibilities.

Their principal disadvantages are their high cost, and the fact that, in many applications, energy storage is required because of no insolation at night. Efforts are being made worldwide to reduce costs through various technological innovations.

2. SUMMARY

Solar energy is a infinite source of energy and at the same time non-polluting and free of environmental hazards. Solar energy can be utilized in three ways (a) using the heat form sunlight (b) converting solar energy directly into electrical energy and (c) using photosynthesis and biological processes. Solar energy can be directly used for multiple purpose using flat- plate collectors, focusing collectors and solar cells. Two barriers to successful utilization of solar energy are : (i) It is diffused at low temperature
(ii) it requires storage system for use when the sun is not visible.

KEY WORDS

Solar collector

Device for collecting radiant energy from the sun and converting it into heat.

Photovoltaic cell

Device which converts radiant (Solar) energy directly into electrical energy.

Solar capital

Solar energy from the sun reaching the earth.

Insolation

Amount of solar radiation falling on the earth.

Semi-conductor

Semi-conductors are non-metallic materials such as germanium and silicon whose electrical characteristics lie between those of conductor and insulators.

Doping

Contamination of extremely pure form of semi conductor with tiny quantities of carefully selected impurities such as boron or phosphorus to alter electric behaviour.

SELF ASSESSMENT QUESTIONS

1. What is meant by solar cell ? Enumerate the advantages and disadvantages of the solar cell system ?
2. Define semi-conductor. What is meant by N-type and P-type semi-conductor? Explain.
3. Explain the photovoltaic principle.
4. Describe the different types of solar cells which are mostly used.
5. What are the main applications of solar PV systems? Describe briefly.
6. What are the advantages and disadvantages of focussing type collector over a flat plate collector ?
7. What are solar collectors? Enumerate the types of solar collectors.
8. What are flat plate collectors? Describe types of flat plate collectors?
9. What are the advantages of flat-plate collector ?

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APPLICATION OF SOLAR ENERGY IN INDIA

2.0. OBJECTIVES

After studying this unit, you should be able to understand about

- Various techniques that is being used to harvest solar energy for the useful purpose and benefits of man kinds.

- Energy conservation as well as strategy for energy management.

2.1. INTRODUCTION

Sun is a primary source of energy, all the forms of energy on the earth are derived from it. The solar energy can be harnessed either by deriving energy directly from sunlight or by indirect method.

Since fossil fuels-coal, oil and natural gas originate from living matter, their energy is really solar energy that has been converted and stored for millions of years. In fact, only nuclear energy, geothermal and to a large extent, tidal energy, do not originate from the sun. Based on above classification, direct solar energy application are discussed below in the following order.

i) Solar water heater.
ii) Solar desalinization.
iii) Solar pumping.
iv) Solar cooking.
v) Solar Pond

2.2. SOLAR WATER HEATER

The basic elements of a solar water heater are :

i) Flat plate collector.
ii) Storage tank.
iii) Circulation system and auxiliary heating system.
iv) Control of the system.

There are two types of solar water heaters:

i) Natural circulation solar water heater.
ii) Forced circulation solar water heater.

2.2.1. Natural circulation solar water heater

It consists of a titled collector (South facing), with transparent cover glasses, a separate highly insulated water storage tank, and well insulated pipes connecting the two (Fig. 2.1). The bottom of the tank is at least 1 ft.

(0.3 m) the top of the collector and no auxiliary energy is required to circulate water through it.

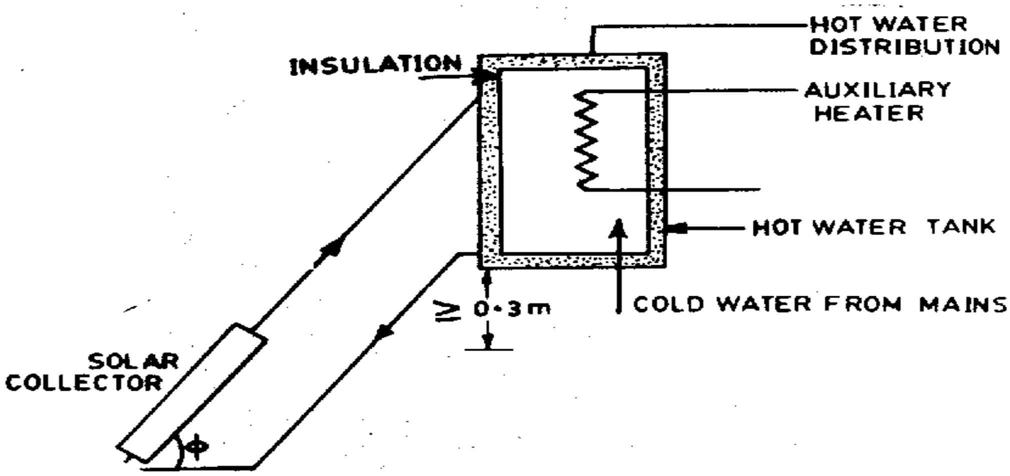


Fig. 2.1. Schematic of a natural circulation solar water heater

Circulation occurs through natural convection, or thermo-siphoning. As the water is heated in its passage through the collector, its density decreases and hence rises and flows into the top of the storage tank. Colder water from the bottom of the tank has a higher density and so tends to sink and enter the lower heater of the collector for further heating. The density difference between the hot and cold water thus provides the driving force (convection) for the circulation of water through the collector and the storage tank. Hot water is drawn off from the top of the tank as required and is replaced by cold water from the service system. As long as the sun shines the water will quietly circulate, getting warmer. After sunset a thermosiphon system can reverse its flow direction and loss heat to the environment during the night. To avoid reverse flow, the top heater of the absorber is kept as stated above 0.3 m below the cold leg fitting on the storage tank. To provide heat during long, cloudy periods, an electrical immersion heater can be used as a backup for the solar system. A non-freezing fluid such as ethylene glycol, propylene glycol, silicon oils etc., may be used in the collector circuit. The thermosiphon system is one of the least expensive solar hot-water systems and should be used whenever possible.

2.2.2. Forced circulated solar water heater

In forced circulation system, by including an electric pump in the return circuit between the bottom of the storage tank and the lower head of the collector. (Fig. 2.2 a,b). The tank can be placed at a more convenient level (e.g. in the house basement). This is now an active system. A control unit permits the pump to operate only when the temperature of the water at the bottom of the tank is below that of the water in the upper head.

A check valve is needed to prevent reverse circulation and resultant night time thermal losses from the collector. In this example, auxiliary heater is shown as provided to the water leaving the tank and going to the load. When there is a danger of freezing, the water may be drained from the collector; alternatively, a slow reverse flow of the warmer water may be permitted through the collector on cold nights. The freezing danger can be overcome although at some increase in cost by using an antifreeze solution such as ethylene glycol, propylene glycol solutions, silicon oils etc., as the heat-transport medium. The heat is then transferred to water in the storage tank by way of a heat exchanger coil (Fig. 2.2c). A solar collector area of30-

40 sq. ft. in combination with an insulated of 200-400

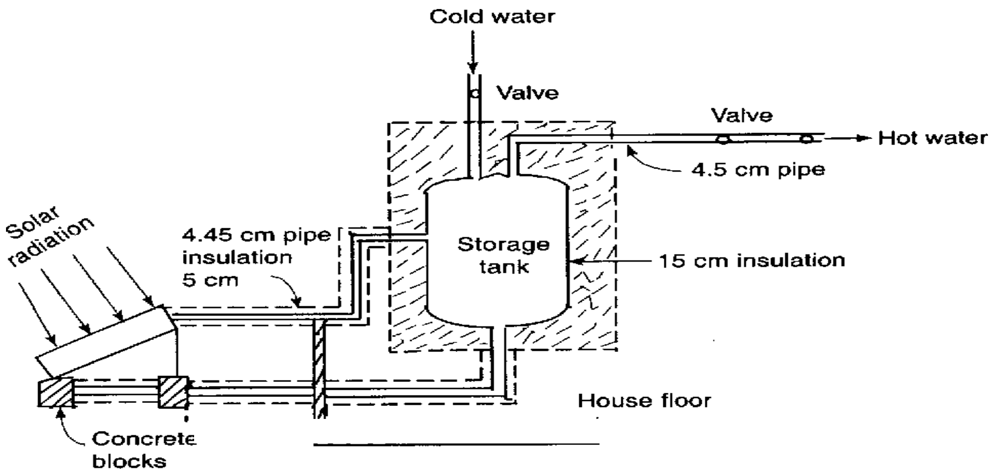


Figure 1.4a A typical solar water heater.

Figure 2.2.a . A typical solar water heater

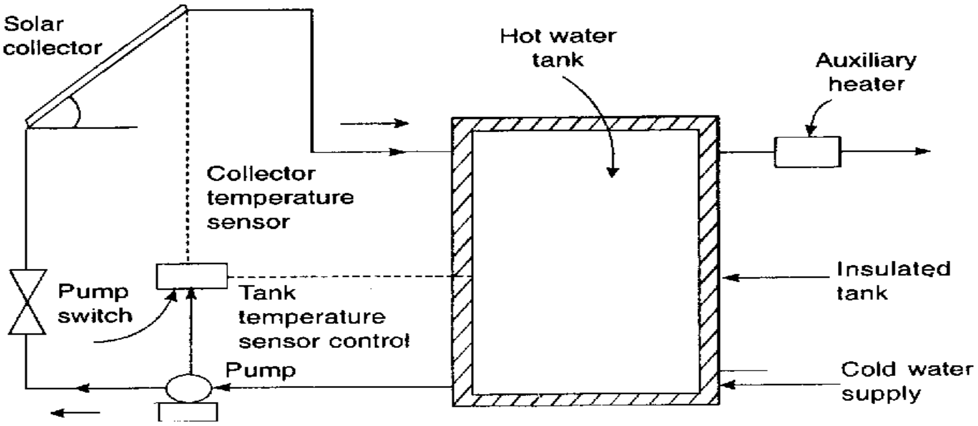


Figure 2.2.b. Schematic diagram of a forced circulation solar water heater.

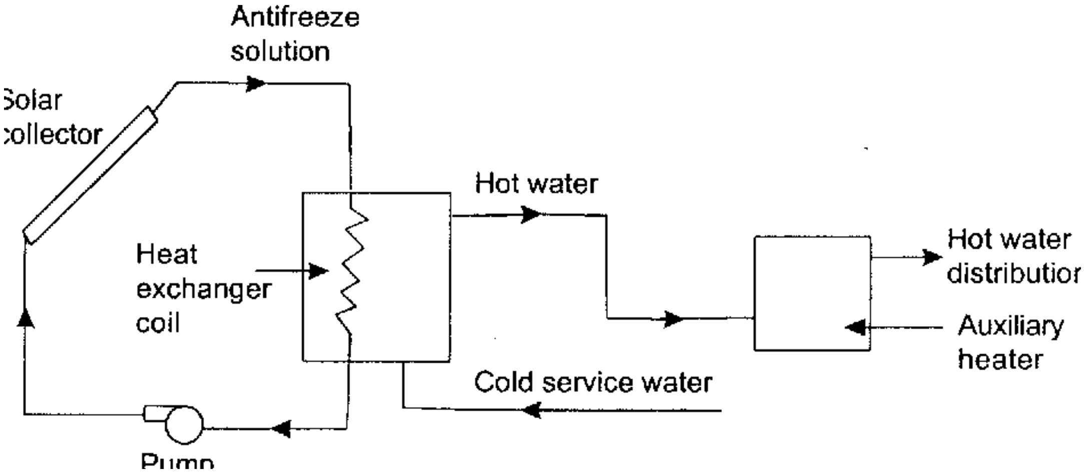


Figure 2.2 C. Solar water heating system with anti freeze

litre capacity tank can provide 200-300 litre of hot water at about 60^{0}C per average sunny day in a favourable climate.

2.3. SOLAR COOKER

In our country energy consumed for cooking shares a major portion of the total energy consumed in a year. In villages 95% of the consumption goes only to cooking. Variety of fuel like coal, kerosene, cooking gas, firewood, dung cakes and agricultural waste are used. The energy crisis is affecting every one. It is affecting the fuel bills for those who use it for heating the houses and cooking their food. The poor of the developing countries who have been using drywood, picked up from the fields and

forests as domestic fuel, have been affected in their own way, due to scarcity of domestic fuel in the rural areas. At present, firewood and cow dung cakes are the most important sources of fuel to cook food. Cow dung too precious to be allowed to be used for burning and cooking. It is very useful to improve the fertility of the soil, if used in proper way. The supply of wood is also fast depleting because of the indiscriminate felling of trees in the rural areas and the denudation of forests. There is a rapid deterioration in the supply of these fossil fuels like coal, kerosene or cooking gas. The solution for the above problem is the harnessing of solar energy for cooking purposes.

Thus solar cookers have a very relevant place in the present fuel consumption pattern. Various designs of solar cookers have been developed in our country. The first solar cooker was developed in the year 1945 by Mr. M. K. Ghosh of Jamshedpur a freedom fighter. He developed a box type solar cooker with a reflecting mirror and a copper coil inside, on which the food materials used to be placed in pots. Later in 1953 National Physical Laboratory (NPL) of India developed a parabolic solar cooker. The main reasons for non-acceptance of these devices was the cheap availability of cooking fuel during these days. The problem of harnessing and utilization of solar energy arised after the fuel crisis of the 1970s, which also affected the rural areas.

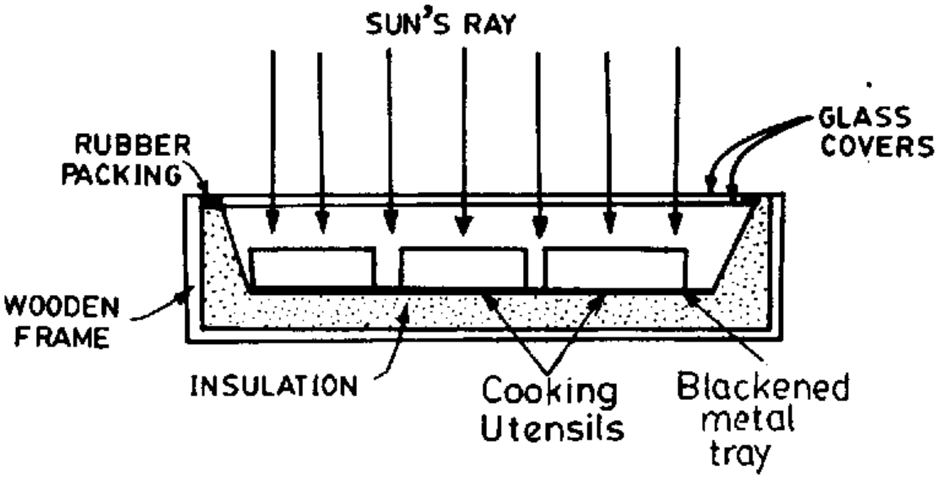
Basically there are three designs of solar cooker :

i) Flat plate box type solar cooker with or without reflector.
ii) Multi-reflector type solar oven and,
iii) Parabolic disc concentrator type solar cooker.

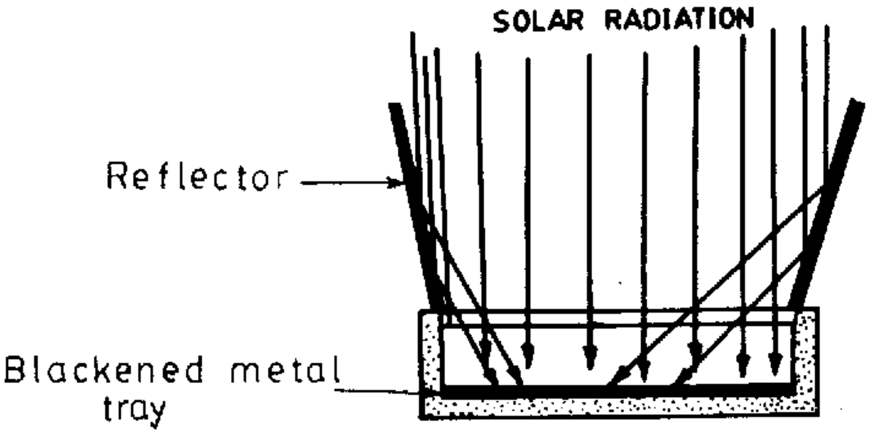
Flat plate box type design is the simplest of all the designs. Maximum no load temperature with a single reflector reaches upto 160^0C. In multi reflector oven four square or triangular or rectangular reflectors are mounted on the oven body. They all reflect the solar radiations into the cooking zone in which cooking utensils are placed. Temperature obtained is of the order of 200^0C. The maximum temperature can reach upto 250^0C, if the compound cone reflector system is used. With parabolic disc concentrator type solar cooker, temperatures of the order of 450^0C can be obtained in which solar radiations are concentrated onto a focal point. Principle of operation of solar cookers is shown in Fig. 2.3.

2.3.1. Principle and constructional details of a box type solar cooker

The solar rays penetrate through the glass covers and absorbed by a blackened metal tray kept inside the solar box (Fig. 2.3). The solar radiation entering the box are of short wavelength. The higher wavelength radiation is not able to pass through the glass cover i. e. re-radiation from absorber plate to outside the box is minimized by providing the glass cover. Two glass covers are provided to again minimize the heat loss. The loss due to convection is minimized by making the box air tight by providing a rubber strip all round between the upper lid and the box. Insulating material like glasswool, paddy husk, saw dust or any other material is filled in the space between blackened tray and outer cover of the box. This minimizes heat loss due to conduction. When this type of cooker is placed in the sun, the blackened surface starts absorbing sun rays and temperature inside the box starts rising. The cooking pots, which are also blackened are placed inside with food material, get heat energy and food will be cooked in a certain period of time depending upon the actual temperature attained inside. The temperature attained depends upon the intensity of solar radiation and material of insulation provided. The amount of solar radiation intensity can be increased by providing mirror or mirrors.



(*a*) Principle of box type cooker.



(*b*) Reflector type solar cooker.

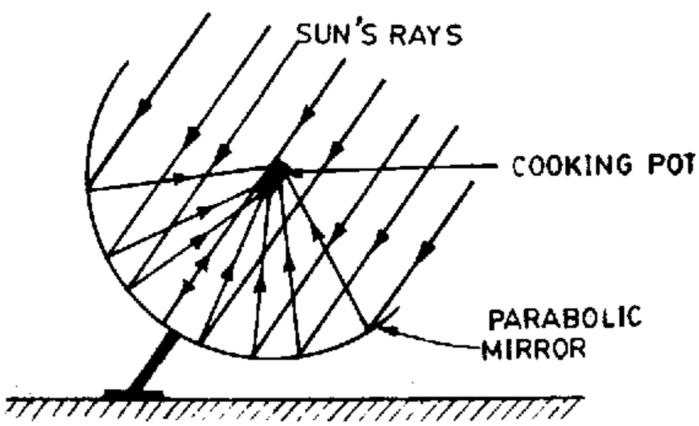


Figure 2.3. Principle of operation of Solar cooker

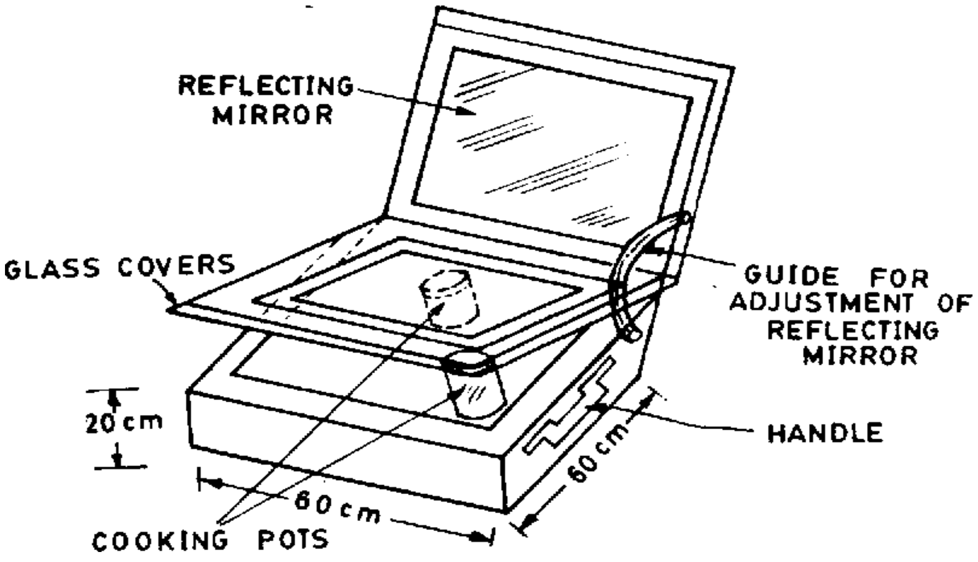


Figure 2.4. Details of a box type cooker

The solar cooker is made up of inner and outer metal or wooden boxed with double glass sheet on it. Absorber tray (blackened tray) is painted black with suitable black paint. This paint should be dull in colour so that it can withstand the maximum temperature attained inside the cooker as well as water vapour coming out of the cooking utensils. The top cover contains two plain glasses each 3 mm thick fixed in the wooden frame with about 20 mm distance between them. The entire top over can be made tight with padlock hasp. Neoprene rubber sealing is provided around the contact surfaces of the glass cover and the cooker box. A small vent for vapour escape, is provide in the sealing. Collector area of the solar cooker is increased by providing a plane reflecting mirror equal to the size of the box, and hinged on one side of the glass frame. A mechanism (guide for adjusting mirror) is provided to adjust the reflector at different angles with the cooker box. A 15 to 25^0C rise in temperature achieved inside the box when reflector is adjusted to reflect the sun rays into the box. In winter, when sun rays are much inclined to horizontal surface, reflector is a most useful addition.

Overall dimensions of the latest model are 60 X 60 X 20 cm height. This type of cooker is termed as family solar cooker as it cooks sufficient dry food materials for a family of 5 to 7 people.

The temperature inside the solar cooker with a single reflector is maintained from 70 to 110^{0}C above the ambient temperature. This temperature is enough to cook food slowly, steadily and surely with delicious taste and preservation of nutrients. Maximum air temperature obtained inside the cooker box (without load) is 140^{0}C in winter and 160^{0}C in summer. Depending upon the factors such season and time of the day, type of the food and depth of the food layer, time of the cooking with this cooker ranges from 1 to 4 h. Meat should be allowed to stay for 3-4 hours. Vegetables take from ½ to 2½ hours. All types of *Dals* can be cooked between 1½ to 2 hours. Rice is cooked between 30 minutes and 2 hours. The best time of the day for cooking is between 11 am and 2 pm. Cooking is faster in summer than in winter due to high ambient temperature. Merits of a solar cooker are:

i) No attention is needed during cooking as in other devices.
ii) No fuel is required.
iii) Negligible maintenance cost.
iv) No pollution.
v) Vitamins of the food are not destroyed and food cooked nutritive and delicious with natural taste.
vi) No problem of charring of food and no over flowing.

Limitations of a solar cooker are :

i) One has to cook according to the sun shine, the menu has to be preplanned.
ii) One can not cook at short notice and food can not be cooked in the night or during cloudy days.
iii) It takes comparatively more time.

iv) Chapaties are not cooked because high temperature for baking is required and also needs manipulation at the time of baking.

2.4. SOLAR DESALINIZATION

Fresh water is a necessity for the sustenance of life and also the key to man’s prosperity. It is generally observed that in some arid, semi arid and coastal areas which are thinly populated and scattered, one or two family members are always busy in bringing fresh water from a long distance. In these areas solar energy plentiful and can used for converting saline water into distilled water. The pure water can be obtained by distillation in the simplest solar still, generally known as the “basin type solar still”. It consists of a blackened basin containing saline water at a shallow depth, over which is a transparent air tight cover that encloses completely the space above the basin. It has a roof-like shape. The cover, which is usually glass may be of plastic, is sloped towards a collection trough. Solar radiation passes through the cover and is absorbed and converted into heat in the black surface. Impure water in the basin or tray is heated and the vapour produced is condensed to purified water on the cooler interior of the roof. The transparent roof material, (mainly glass) transmits nearly all radiation falling on it and absorbs very little; hence it remains cool enough to condense the water vapour. The condensed water flows down the sloping roof and is collected in troughs at the bottom. Saline water can be replaced in the operation by either continuous operation or by batches. Although there are numerous configurations of basin type units, their basic theory is identical. The basin type solar still has produced distilled water at a cost per unit of product lower than other types of solar equipment and is the only type in operation. Operating efficiencies of 35 to 50% for basin type still have been achieved in practical units, as compared with a theoretical maximum of slightly more than 60%.

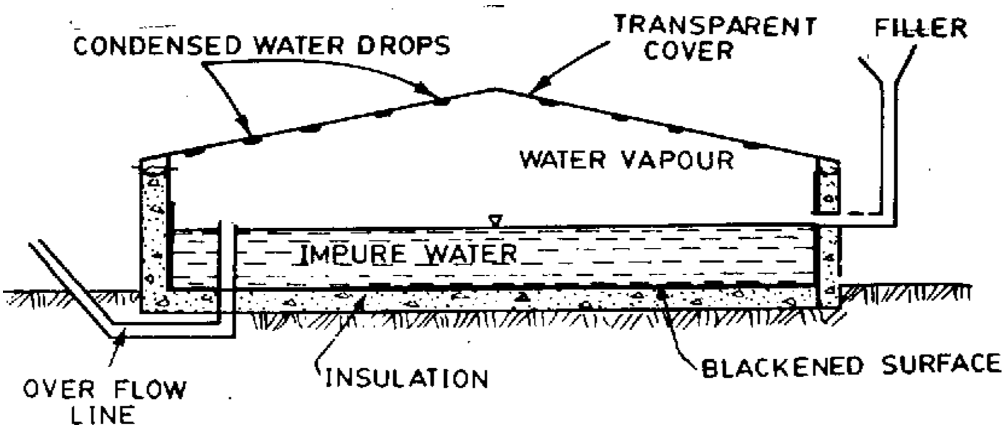


Figure 2.5. Solar Water Still

The performance rating and efficiency of the solar still is determined by plotting the graph of the amount of fresh water produced per unit of basin area in one day versus the solar radiation intensity over the same period.

Such curves for several still are drawn. Efficiency is defined as

$$\square = \frac{w\Delta h}{H}$$

Where w = weight of distillate per square meter per day.

Δh = enthalpy change from cold water to vapour.

H = Solar radiation intensity per square meter per day.

□ = Efficiency of the solar still.

Here area of the water surface is to be considered. Δh includes the latent heat of vaporization, which is being taken as average value 594.5 kcal/kg.

The performance of a solar still is generally expressed as the quantity of water produced by each unit of basin area in a day i. e. cubic meters or litres of water per square meter of basin area per day. This quantity will vary with the design of the still, with the intensity of solar radiation and with the atmospheric conditions in the surroundings. The production rate depends primarily on the amount of solar radiation available but is affected by several other factors; like ambient air temperature, wind speed, atmospheric humidity, sky conditions etc., the effect of design parameters such as orientation of still, single sloped or double sloped, inclination of glass cover insulation of the base etc., and the effect of operating parameters such as water depth in the tray, absorption emittance properties of the still preheating of water etc.

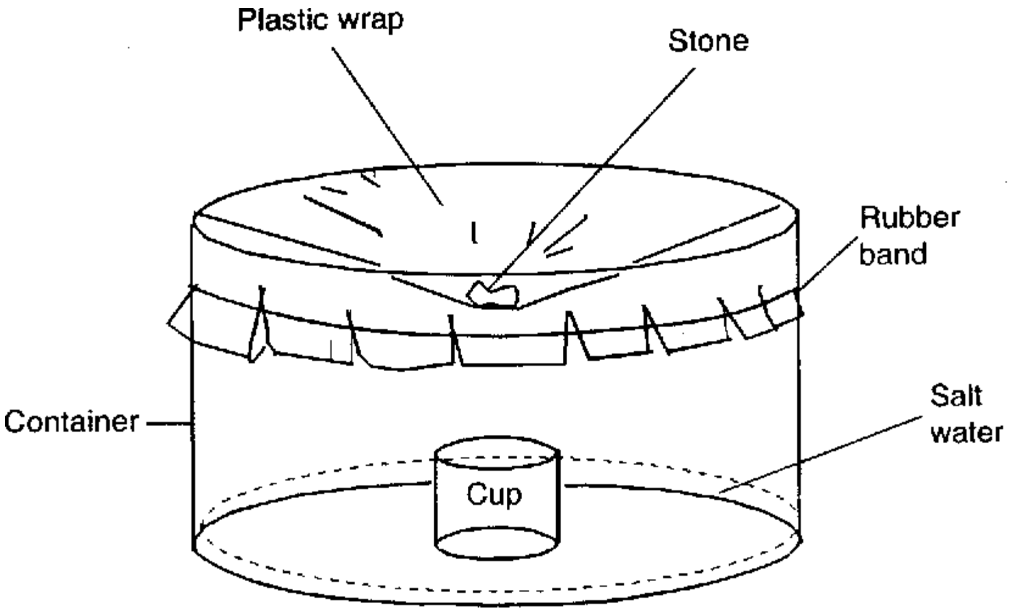


Figure 2.6. A simple device to demonstrate solar desalinization.

Solar still installations may provide about 15 to 50 litres of desalinized water per day per 10 sq. m.

2.5. SOLAR PUMPING

Solar pumping consists in utilizing the power generated by solar energy for water pumping, useful for irrigation.

Solar energy offers several features that makes its utilization for irrigation pumping quite attractive. First, the greatest need for pumping occurs during the summer months when solar radiation is greatest. Second, pumping can be intermittent to an extent. During periods of low solar radiation when pumping decreases, evaporation losses from crops are also low.

A number of recently constructed solar irrigation pump installations are now operational. The major obstacle to increase use of solar irrigation systems at this time is their relatively high capital cost. If the costs of solar pumps can be substantially reduced and assuming that conventional fuel costs continue to rise, solar irrigation could become economical and increased use of such systems might be anticipated in future.

The basic system consists of the following components:

1. The solar collectors, may be
    a) Flat plate collectors or solar pond.
    b) Sun-tracking concentrators (cylindrical parabolic trough concentrator or heliostats).

2. The heat transport system.
3. Boiler or Heat Exchanger
4. Heat engine, it may be
    a) Rankine engine
    b) Brayton cycle gas turbine
5. Condenser.
6. Pump, it may be
    a) Reciprocating pump
    b) Centrifugal pump
    c) Diaphragm pump
    d) Rotary pump.

The solar pump is not much different from a solar heat engine working in a low temperature cycle. The source of heat is the solar collector, and sink is the water to be pumped. A typical solar powered water pumping system is shown in Fig. 2.7. The primary components of the system are an array of flat-plate collectors and an Rankine engine with an organic fluid as the working substance. During operation a heat transfer fluid (pressurized water) flows through the collector arrays. Depending upon the collector configuration, solar flux and the operating conditions of the engine, the fluid will be heated in the collector to higher temperature, the solar energy which is thus converted to the thermal energy. The fluid (water) flows into a heat exchanger (boiler), due to temperature gradient, and comes back to the collector. This water yields its heat to an intermediate fluid in the boiler. This fluid evaporates and expands in the engine before reaching the condenser, where it condenses at low pressure. The condenser is cooled by the water to be pumped. The fluid is then reinjected in the boiler to close the cycle. The expansion engine or Rankine engine is coupled to the pump and it could of course be coupled to an electric generation.

The collector area to a large extend is determined by the overall efficiency of the system η_0.

$\eta_0 = \eta_e$ x η_c

Where η_e is the efficiency of the engine.

η_c is the efficiency of the collectors.

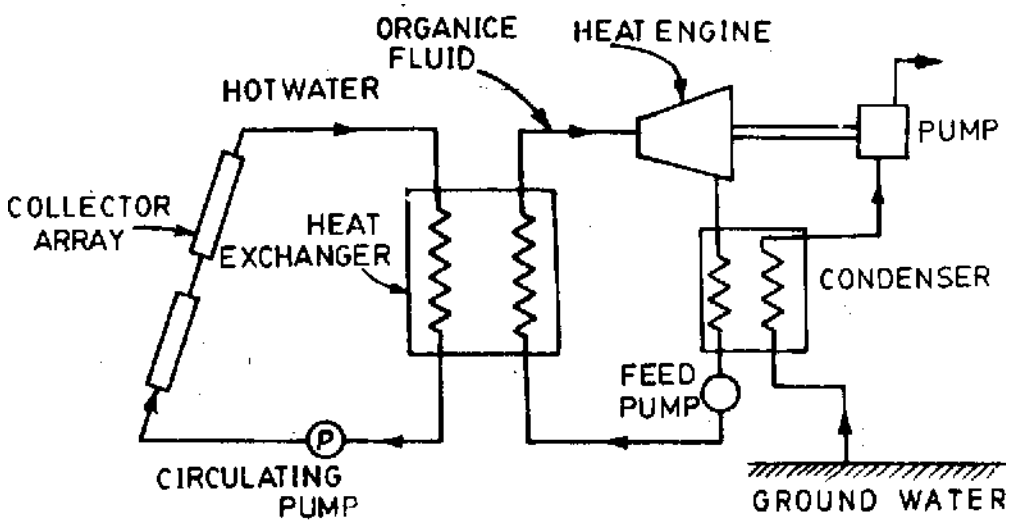


Figure 2.7. Schematic of Solar Pump

For a higher temperature in the boiler, results in a higher engine efficiency, but a higher temperature at the boiler requires a higher collector temperature, which decreases the collector efficiency. There is thus, an optimum range of operating temperatures for the solar pumping system which results in the maximum efficiency for the system.

The working fluids used in the cycle are toluene (CP-25), monochlorobenze (MCB) trifluoro ethanol (TFE-100 and 85), hexa fluro benzene (HFB), pyridine (CP 32), refrigerant-11 (R-11) refrigerant-113 (R- 113), and thiopene (CP-34). R-113 is preferable to all, because of high cycle efficiency, non-toxic in nature and due to low cost.

The irrigation pump operates at a rated power of 19 kW (25 horse power) and delivers water at 500 to 600 gal/min (32 to 38 litres/sec) from a well roughly 30 m deep. The energy efficiency (i. e. percentage of solar energy collected that is converted into useful work) is 13 to 14 per cent, this low value is largely a result of the relatively low temperature of the working fluid entering the turbine. Rankine efficiency will be within acceptable limits, if the temperature of the order of 200 to 400^{0}C is obtained, using proper focusing collector system.

2.6. SOLAR POND

2.6.1. Principle of operation of solar ponds

The solar pond is a simple device for collecting and storing solar heat. Natural ponds convert solar radiation into heat, but the heat is quickly lost through convection in the pond and evaporation from its surface. A solar pond on the other hand, is designed to reduce convective and evaporation heat losses so that useful amounts of heat can be collected and stored.

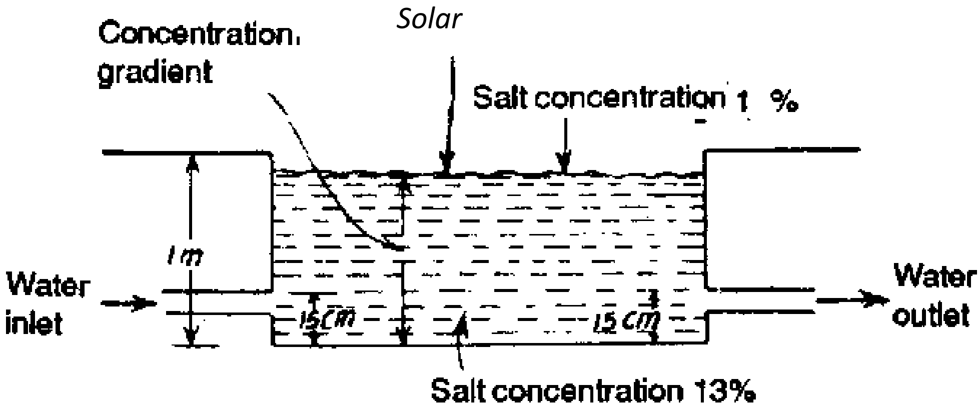


Figure 2.8.a. Schematic of solar pond with vertical concentration gradient of $MgCl_2$.

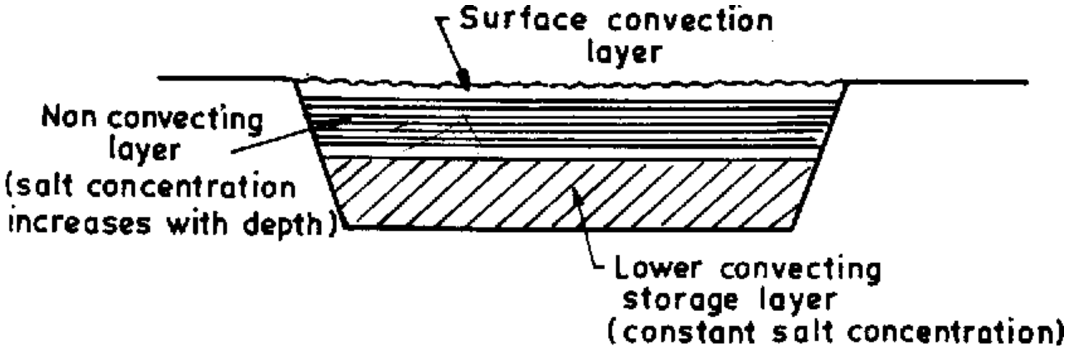


Figure 2.8 b. Salt gradient solar pond

Solar ponds are large-area brine ponds approximately 1 m deep in which vertical gradients of salt concentrations are maintained so that the most concentrated and most dense solutions are at the bottom of the pond. Heat is generated at the bottom of the pond due to absorption of solar radiation-transmitted by the water by the pond's black bottom. In spite of the temperature rise of the brine at the bottom, its specific gravity remains higher than that at the top if a sufficiently large concentration gradient is maintained. Under these conditions, convective mixing is minimized and the bottom layers of brine reach 80-90^{0}C while the top remains at 25^{0}C, which may be withdrawn from the pond and used for power generation, salt production by multiple-effect evaporation of brine water distillation, and so on. To maintain the concentration gradient against the slow upward diffusion of salt, the surface must be slightly "washed" with fresh water and concentrated brine supplied at the bottom.

2.7. ENERGY CONSERVATION

The conventional sources of energy resources are gradually getting depleted at a rapid rate all over the world. It is therefore very necessary to conserve energy as well as to improve the efficiency of all the power systems. If due care is not taken for conservation, the large scale generation of energy, mainly from non-renewable sources to meet the increasing demand will be required, which will certainly cost the environment heavily from project implementation stage onward. There environmental hazards are:

- Habitat loss
- Tropical deforestation
- Loss of bio-diversity
- Loss of genetic materials
- Global warming
- Toxic damps
- Ozone shield damage and
- Acid rain etc.

Again inefficient use of energy leads to energy loss during generation, transmission and distribution at user point, add cost to energy production and fuel. The transmission and distribution loss in our country were around 15% upto years 1965-67, have gradually increased to average of 25% during 1993-94. The continued rising trends in such a loss is a matter of serious concerned

Energy conservation activities had received importance after the first energy crisis in 1973; while in India, it is only in the 8th plan a separate budget allocation of Rs. 10,000 crores was made for 10 percent reduction in energy consumption. Energy conservation is found to be one of the effective solution to the energy crisis and the sustainable development. One MW of energy conserved in equivalent to 2 MW of energy generated as per research finding. By proper implementation of energy conservation measure can same 20 to 30% of energy. Thus there are much scope for energy conservation in all sectors particularly in energy intensive units which are as follows :

Industries	**Conservation potential**
Iron and Steel	8-10%
Fertilizer	10-15%
Cement	10-15%

Pulp and paper 20-
25% Textiles 15-20%

The following comprehensive measure should be taken for energy conservation :

- To make energy auditing compulsory in power plants.
- To provide monetary incentives to install fuel efficient machinery and change over to non-conventional sources of energy wherever possible.
- To enforce some sort of building codes which will ensure conservation, use of solar energy and energy efficiency standards. Sunshines are often blocked by neighbour’s tall buildings in the towns and trees in the villages. The building codes will remove these problems for free or equal excess to sunshines.
- Development and enforcement of new technology for conventional as well as renewable energy sources.
- Legislative measures covering technical, economic, environmental, hygienic, aesthetic as well as safety and security aspects in using different sources of energy.
- Free market regulation for fossil fuels, necessary to control production of fossil fuels and to accelerate the use of renewable energy sources.

2.8. ENERGY MANAGEMENT

The proper planning and management in respect of energy are necessary :

- For proper and effective uses of energy.
- To decrease the burden on the conventional energy sources
- For giving more stress on renewable sources of energy
- To prevent misuse or waste of energy.

- For proper production and distribution.
- For keeping ecosystem and environment free of pollution.

With the advent of new technologies for alternative or renewable energies and with the gradual phasing out of the conventional energy resources it has become necessary to make the following steps for effective energy management;

- It is necessary to have a bank of accurate data on all available energies that may affect a site in any location.
- Energy education to school children through texts, and to all other classes of society through seminars, TV, radio, newspaper, workshops etc.
- Legislation and regulation
- Management training, organization and implementation. The saving of energy is expected from the result of both demand and supply management. Demand management involves.
- Improving efficiency of industrial process
- Recycling wastes
- Promoting energy efficient design and
- Installing solar application in building to minimize energy consumption
- Demand management programmes begin with analysing current consumption trends in different consuming sectors and estimate their likely patterns in future. This is followed by technical and economic evaluation of energy efficiency options available to reduce demand for various end-users.
- In identification of specific measures to reduce demand follows next. Identified specific measure may include soft option such as pricing as well as other monetary incentives, rebate, and involvement of institution and design engineering organisation in the area of energy efficiency.

Supply management relates to the improvement of supply of both conventional and non-conventional sources of energy with a view to minimize gap between supply and demand of energy some of the major options in improving supply can be as follows:

- Promoting increasing use of non-conventional sources of energy.
- Improvement of efficiency in the generation, transmission and distribution system.
- Introducing sweeping reforms in coal mining industry for improving coal productivity.
- Maximizing use of natural gas in industry, power generation.
- Seeking higher involvement of private sector in generation, transmission and distribution of power, exploration and production of hydrocarbon and in solar wind, mini hydel and bioenergy programme.

Significant energy saving can be achieved within a short spell through management, employee training, public awareness programmes, equipment standardization proper maintenance and other house keeping measures.

A major reason for high consumption of energy is the continued use of old machinery and obsolete technology. The existing plant design and equipment in many industries were developed prior to the energy price rise
– when the objective was to save capital and take advantage of low energy cost.

2.8.1. Energy management in India

The impact of population explosion coupled with rapid economic growth could be visualized on our limited natural resources including non- commercial and commercial energy sources. Our requirement of fuel wood is about six times that what our forest resources can provides us on sustainable basis and similarly we are far behind to meet our demand for electricity and energy requirement of other important sectors from commercial sources.

Although we are increased our installed capacity of electricity generation at a fast rate (from 31,025 mw in 1980-81 to 42,749 mw in 1984- 95 to 80,944 mw in 1994-95). Yet the demand which is increasing at a rate of 12 to 15% per annum is far ahead than present rate of installation. It is expected that by end of 9th five year plants (2001-2002) we will have installed capacity of about 1,38,000 mw. It is estimated that the gap between demand and supply is increasing at a accelerated rate in near future as demand is expected to be around 2,09,000 mw by 2007.

At present rate, we are on an average need 4-5 crore rupees to add one mw of electricity in our installed capacity. It is estimated that India requires an investment of 200 billion in power sector over next 15 years if country's 6 % GDP is to be sustained. We have to invite private sector including foreign collaboration to ease out this daunting task. Otherwise it will be disastrous for our overall economic growth as is evident from consumption pattern of commercial energy industries (50%) transport (22%) domestic (12%), agriculture (8%).

However, to some extent, these are two important aspects, which are enumerated below, that may help us to find solution to our growing need through their implementation in electricity generation schemes.

1. Instead of major/super power projects, captive power plants (may be upto 25 mw) need to be installed, wherever feasible and it could either be thermal or hydel.
2. In case of thermal power generation, focus has now been slowly shifting from coal based to oil and finally to gas based power plants. The conversion efficiency of gas based power plants is not only higher than the other two sources, but at the same time emission of pollutants is very low.

2.8.2. Other measures

The following additional steps may be taken to encourage use of alternative source:

- Financial assistance to solar houses at lower interest,
- Conservation assistance to existing buildings,
- Demonstration programmes,
- Solar energy funding programme, and
- Tax relief programme.

2.8.3. Incentives

To reduce the burden on fossil fuels and to attract the use of renewable sources of energy, incentives may be offered to:

Producers : Manufacturers, architects, property developers, contractors etc. in the form of funds for R & D purposes, technical assistance and information, loans, tax relief, etc.

Consumers: Private and rental house owners, commercial and institutional consumers in the form of income tax relief, accelerated depreciation, investment credits, subsidies, loans, etc.

2.8.4. Need of the hour

The finite and depleting nature of fossil fuels and increasing demand of energy have serious implications for the whole world. The future energy scenario will be influenced by new discoveries, production techniques, development of new energy sources, economic, geographical and environmental constraints and other factors. It is now established that the renewable sources of energy are abundant on the surface of the earth and have infinite potential for renewal. They will surely meet the future energy demand.

In the developed countries policies and their implementations have already started to exploit renewable sources of energy to reduce the dependence on fossil fuels. Technologies for harnessing energy from the sunshine, wind, water, oceans, etc. are becoming more and more common. Renewable energy sources, which are available in different forms in developing countries including India, are the potential energy sources for the future development. The Indian Government has already undertaken different projects and policies for harnessing and using these sources. Public awareness and cooperation are necessary for the successful implementation of the programmes. Infact, there are no barriers for using the renewable energy sources and if such barriers exist, they should be tackled through appropriate measures.

2.9. SUMMARY

The sun is a source of all energy on the earth. The solar energy can be harvested either by deriving energy directly from sunlight or indirectly. All the application of solar energy is based on green house effect. The collected solar radiation has been used to heat water, and to provide warm for sprouting seeds and raising flowers and certain vegetables, to heat houses and other buildings, for process – heat application on a small scale, such as cooking, drying and desalinization of waters. The conventional sources of energy resources are gradually getting depleted at a rapid rate all over the world. It is therefore very necessary to conserve energy and steps to be taken for effective energy management.

2.10. KEY

WORDS Solar

cooker

The solar cooker is made up of wooden box with double glass sheet

on it. It works on principle of green house effect.

Solar desalinization

Conversion of saline water into distilled water using solar energy.

Solar pond

It is a simple device for collecting and storing solar heat. It is designed to reduce convective and evaporative heat fosses to the environment so that useful amounts of heat can be collected and stored.

2.11. SELF ASSESSMENT QUESTIONS

1. Describe the solar water heating system.
2. How solar hot water collectors are safe guarded against freezing.
3. Describe the principle of working solar cooker and explain its working in brief.
4. What is the principle of solar pond and explain solar pond system.
5. Enumerate the method of solar desalinization of brine water.
6. What is energy conservation? Suggest the ways to conserve energy.
7. Enumerate the energy management system in India.

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SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT – III – WIND ENERGY – SEEA3010

Unit-III
Wind Energy Systems

3.1 Wind Energy

Wind is simple air in motion. It is caused by the uneven heating of the earth‟s surface by the sun. Since the earth‟s surface is made of very different types of land and water, it absorbs the sun‟s heat at different rates. Energy derived from wind velocity is wind energy. It is a non- conventional type of energy, which is renewable with suitable devices. This energy can be used as a perennial source of energy. Wind energy is obtained with the help of wind mill. The minimum wind speed of 10kmph is considered to be useful for working wind mills for agricultural purpose. Along the sea coast and hilly areas, wind mills are likely to be most successful in Karnataka, Maharastra and Gujarat.

The wind energy over earth is estimated to be 1.6×10^7 M.W, which is equivalent to the energy consumed. But, the wind energy is available in dilute form. The conversion machines are large. The wind energy varies from time to time and place to place. Due to this reason some storage facility is required. The kinetic energy of wind is converted into useful shaft power by wind mills. General applications of wind mills are pumping water, fodder cutting, grain grinding, generation of power etc. In India, wind speed lies between 5 kmph-20 kmph. The high wind velocity is seasonal. The wind energy, if used for power generation, it will be uncertain to generate power. In India, wind power can be used for lifting water in rural areas for drinking and for irrigation purpose.

3.2 Factors affecting the wind

- Latitude of the place
- Altitude of the place.
- Topography of the place 4. Scale of the hour, month or year

3.3 Suitable places for the erection of wind mills

- Off-shore and on the sea coast: An average value is 2400 $kWH/m^2/year$

- Mountains: An average value is 1600 KWH/m^2/year
- Plains: An average value is 750 KWH/m^2/year

3.3.2 Places unsuitable for wind mills

- Humid equatorial region- there is virtually no wind energy
- Warm, windy countries, wind energy may not be usual because of the frequency of cyclones

3.4 Advantages and disadvantages of wind mills

Advantages	Disadvantages
• It is a renewable source of energy • It is non-polluting and no adverse influence on the environment • No fuel and transportation is required • The cost of electricity under low production is comparatively low	• The available wind energy is dilute and fluctuating in nature • Unlike water energy, wind energy requires storage capacity because of its irregularity • Wind energy operating machines are noisy in operation • Large areas are required for wind mill • The present wind mills are neither maintenance free nor practically reliable

3.5 Types of wind mills

There are two types of wind machines (turbines) used today based on the direction of the rotating shaft (axis): horizontal–axis wind machines and vertical-axis wind machines. The size of wind machines varies widely. Small turbines used to power a single home or business may have a capacity of less than 100 kilowatts. Some large commercial sized turbines may have a capacity of 5 million watts, or 5 megawatts. Larger turbines are often grouped together into wind farms that provide power to the electrical grid.

3.5.1 Vertical axis wind mills

a) Savonius or S type wind mill (low wind velocity)
b) Darrius wind mill (high wind velocity)

3.5.2 Horizontal axis wind mills

a) Single blade wind mills
b) Double blade wind mills
c) Multi blade wind mills
d) Bicycle multiblade type i.e., Sail type

3.5.1 Vertical axis wind mills

Vertical axis machines are of simple design as compared to the horizontal axis. The axis of rotation of vertical axis wind turbine is vertical to the ground and almost perpendicular to the wind direction. These turbines can receive wind from any direction. Hence complicated yaw devices can be eliminated. The generator and the gearbox of such systems can be housed at the ground level, which makes the tower design simple and more economical. Moreover, the maintenance of these turbines can be done at the ground level. The major disadvantage of vertical axis machines are that, these turbines usually not self-starting. Additional mechanism may be required to push and start the turbine, once it is stopped.

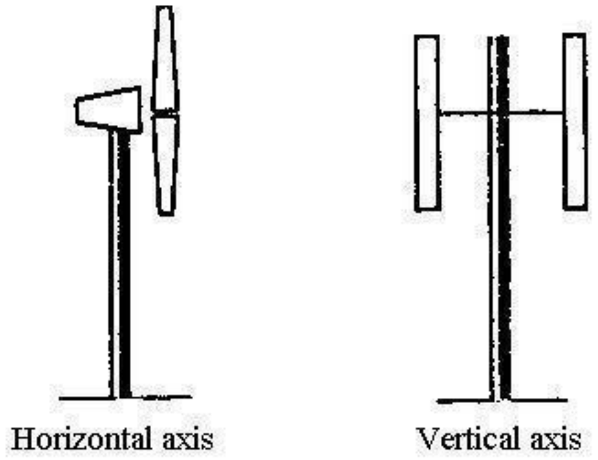


Fig 3.1 Vertical axis wind mill

a) Savonius wind mill

It works on the principle of cup anemometer. This machine has become popular, since it requires low wind velocity for operation. It consists of two half cylinders, which are mounted on a vertical axis perpendicular to the direction of wind, with a gap at the axis between the two cylinders. Two half cylinders facing each other forming an „s‟ shaped cross-section. Irrespective of the wind direction, the rotor rotates such as to make the convex sides of the buckets head into the wind. From the rotor shaft, we can tap power for our use like water pumping, battery charging, grain winnowing etc.

The main action of the wind is very simple, the force of the wind is greater on the cupped face than on rounded face. A low pressure is created on the convex sides of drums. Torque is produced by the pressure difference between the two sides of the half cylinders facing the wind. This design is efficient but requires a large surface area. A savonius wind energy conversion system has a vertical axis which eliminate the expensive power transmission system from the rotor to the axis. Since it is a vertical axis machine it does not matters much about the wind direction. The machine performs even at lower wind velocity ranges (i.e., 8 kmph).

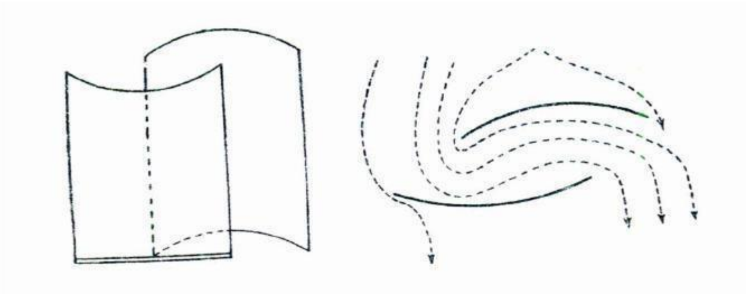


Fig 3.2 Schematic diagram of savonius wind mill

b) Darrieus wind mill

Added advantage with this mill is that it supports its blades in such a way that minimizes bending stresses in normal operation. It requires less surface area as compared to Savonius type. In this machine, the blades are curved and attached to the hubs on the vertical shaft at both ends to form a cage-like structure. The blades look like an egg beater. Darrieus rotors have three symmetrical aerofoil blades, both ends of which are attached to a vertical shaft. Thus, the force in the blade due to rotation is pure tension. This provides a stiffness to withstand the wind forces it experiences.

The blades are made lighter than in the propeller type. When rotating, these aerofoil blades provide a torque about the central shaft in response to a wind direction. This shaft torque is transmitted to a generator at the base of the central shaft for power generation. Both Savonius and darrieus type rotors run independently of the direction of wind because they rotate about a vertical axis. Major advantage of darrieus wind mill is that the rotor blades can accept the wind from any point of the compass. The machine can be mounted on the ground eliminating the tower structures. Disadvantage is that, it may experience lower velocity wind when compared to tower mounted conventional wind energy conversion system.

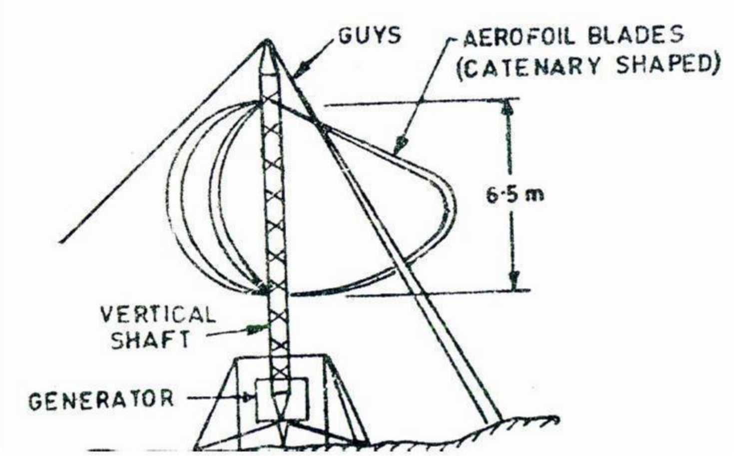


Fig. 3.3. Schematic diagram of darrieus wind mill

13.3.2 Horizontal axis type wind mills

Horizontal axis wind turbines have their axis of rotation horizontal to the ground and almost parallel to the wind stream. Most of the commercial wind turbines fall under this category. Horizontal axis machines have some distinct disadvantages such as low cut-in speed and easy furling. In general, they show relatively high power coefficient. However, the generator and gearbox of these machines are to be placed over the tower which makes its design more complex and expensive. Depending on the number of blades, horizontal axis wind turbines are further classified as single bladed, two bladed, three bladed and multi bladed.

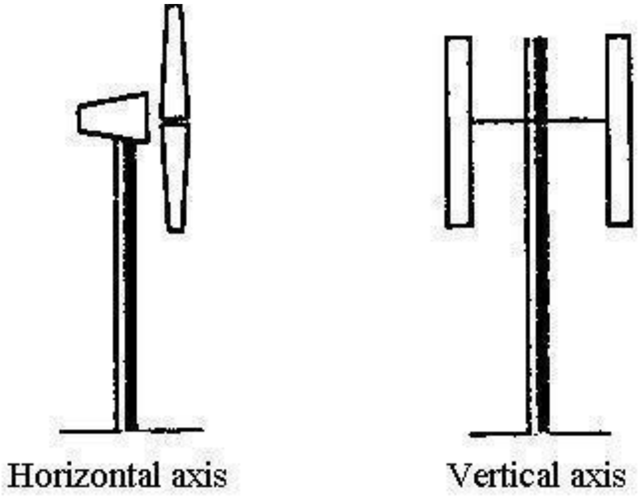


Fig 3.4Horizontal axis wind mill

The horizontal type wind mills have thin cross-section or more efficient thick cross- section of aerofoil blade. The blade is designed such that the tip of the blades makes a small angle with the plane of rotation and almost at right angles to the direction of wind. In a modern wind turbine, the velocity of blades is six times the wind velocity. Ideally, the blade should be twisted, but because of construction difficulties this is not always achieved. The horizontal axis wind mills generally have better performance. These are mainly used for electric power generation and pumping water.

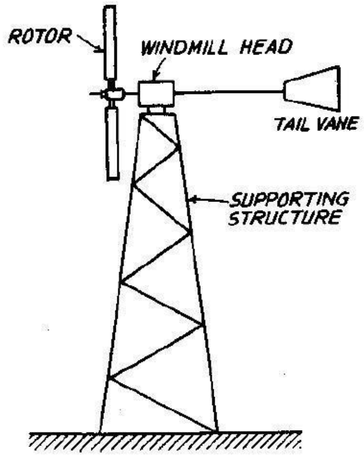


Fig. 3.5 Schematic diagram of horizontal axis wind mill

a) Horizontal axis propeller type wind mill with single blade

In this type of machine, a long blade is mounted on a rigid hub. Induction generator and gear box are arranged as shown in Fig.13.6. If extremely long blades (60 m) are mounted on the hub, large blade root bending moments may occur due to tower shadow, gravity and sudden shifts in the wind directions. To reduce rotor cost, use of low cost counter weight is recommended for balancing long blade centrifugally.

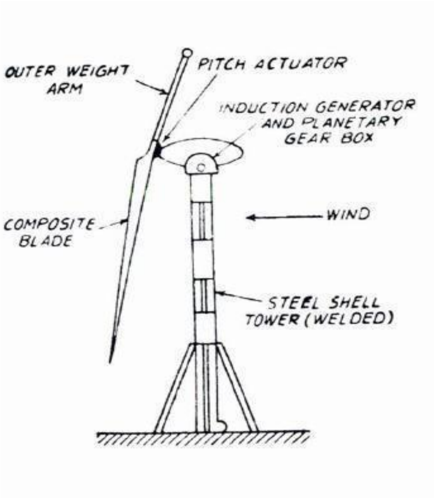


Fig. 3.6. Schematic diagram of horizontal axis single blade wind mill

b) Horizontal axis - two blade wind mill

In this type of design, rotor drives a generator through a step-up gear box. The blade rotor is designed to be oriented downwind of the tower. The components are mounted on a bedplate, which is attached on a pintle at the top of the tower. The arrangement is shown in Fig 13.7. The rotor blades are continuously flexed by unsteady aerodynamic, gravitational and inertial loads, when the machine is in operation. If the blades are made of metal, flexing reduces their life due to fatigue loading. With rotor, the tower is also subjected to above loads, which may cause serious damage. If the vibrational modes of the rotor happen to coincide with one of the natural mode of vibration of the tower, then the mill may get damaged. Due to high cost of blades, the rotor with more than two blades is not recommended. Rotors more than two, say 3 or 4 blades would have slightly higher coefficient.

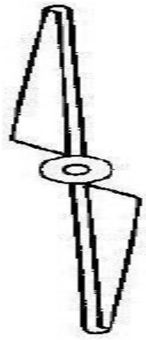


Fig. 3.7 Schematic diagram of horizontal axis two blade wind mill

c) Horizontal axis-multi blade type wind mill

This type of design for multi blades (Fig. 13.8)made from sheet metal or aluminum. The rotors have high strength to weight ratios and are strong enough to with stand a wind speed of 60 Kmph. This type of wind mills have good power coefficient, high starting torque, simple and are low in cost.

d) Sail type wind mill

It is recent development in wind mills. The blades are made by stretching out triangular pieces of canvas cloth or nylon or plastics (Fig.3.9). There is also variation in the used. It runs at 60 to 80 rpm. number of sails

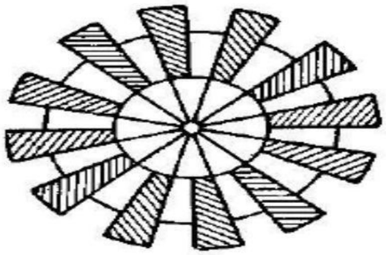


Fig.3.8. Schematicdiagram of horizontal axis multi blade wind mill

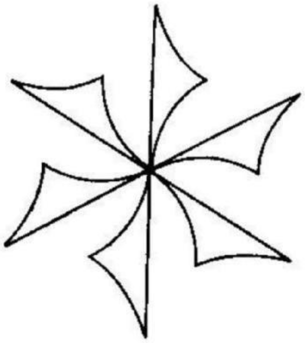


Fig. 3.9. Schematic diagram of horizontal axis sail type wind mill

Construction details and application of wind mills

3.10 Construction details

There are two classes of windmill, horizontal axis and vertical axis. The vertical axis design was popular during the early development of the windmill. However, its inefficiency of operation led to the development of the numerous horizontal axis designs.

Of the horizontal axes versions, there are a variety of these including the post mill, smock mill, tower mill, and the fan mill. The earliest design is the post mill. It is named for the large, upright post to which the body of the mill is balanced. This design gives flexibility to the mill operator because the windmill can be turned to catch the most wind depending on the direction it is blowing. To keep the post stable a support structure is built around it. Typically, this structure is elevated off the ground with brick or stone to prevent rotting.

The post mill has four blades mounted on a central post. The horizontal shaft of the blades is connected to a large break wheel. The break wheel interacts with a gear system, called the wallower, which rotates a central, vertical shaft. This motion can then be used to power water pumping or grain grinding activities.

The smock mill is similar to the post mill but has included some significant improvements. The name is derived from the fact that the body looks vaguely like a dress or smock as they were called. One advantage is the fact that only the top of the mill is moveable. This allows the main body structure to be more permanent while the rest could be adjusted to collect wind no matter what direction it is blowing. Since it does not move, the main body can be made larger and taller. This means that more equipment can be housed in the mill, and that taller sails can be used to collect even more wind. Most smock mills are eight sided although this can vary from 6 to 12.

Tower mills are further improvements on smock mills. They have a rotating cap and permanent body, but this body is made of brick or stone. This fact makes it possible for the towers to be rounded. A round structure allows for even larger and taller towers. Additionally, brick and stone make the tower windmills the most weather resistant design.

While the previous windmill designs are for larger structures that could service entire towns, the fan-type windmill is made specifically for individuals. It is much smaller and used primarily for pumping water. It consists of a fixed tower (mast), a wheel and tail assembly (fan), a head assembly, and a pump. The masts can be 10-15 ft (3-15 m) high. The number of blades can range from four to 20 and have a diameter between 6 and 16 ft (1.8-4.9 m).

3.10.1 Raw Materials

Windmills can be made with a variety of materials. Post mills are made almost entirely of wood. A lightweight wood, like balsa wood, is used for the fan blades and a stronger, heavier wood is used for the rest of the structure. The wood is coated with paint or a resin to protect it from the outside environment. The smock and tower mills, built by the Dutch and British prior to the twentieth century, use many of the same materials used for the construction of houses including wood, bricks and stones.

The main body of the fan-type mills is made with galvanized steel. This process of treating steel makes it weather resistant and strong. The blades of the fan are made with a lightweight, galvanized steel or aluminum. The pump is made of bronze and brass that inhibits freezing. Leather or synthetic polymers are used for washers and o-rings.

3.11 Application of wind energy:

a) **Mechanical application**: mainly (water pumping) Multi-blade windmill used for water pumping shown below:

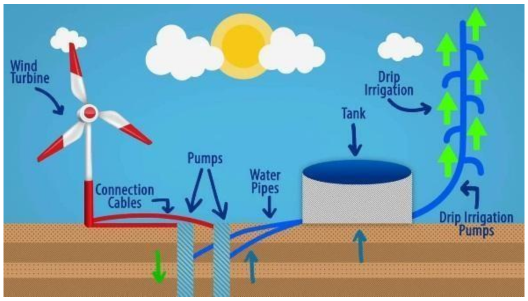


Fig. 3.9 water pumping system using wind mill

b) **Electricity generation:** Wind turbines vary in size and type. They are commercially available for electricity generation. Size of wind turbines (400 Watt-5 MW)

c) Industrial Applications

The number of dedicated industrial applications for wind power continues to grow. Small wind power systems are ideal for applications where storing and shipping fuel is uneconomical or impossible. Wind power is currently being used for the following applications:

- Telecommunications
- Radar
- Pipeline control
- Navigational aids
- Cathodic protection
- Weather stations/seismic monitoring
- Air-traffic control

Wind machines in industrial applications typically encounter more extreme weather than home power systems and must be designed to be robust with very minimal maintenance.

3.12 Power contained in wind:

Power contained in wind is given by the kinetic energy of the flowing air mass per unit time. That is,

The kinetic energy in air of mass “m” moving with speed V is given by the following in SI units:

KineticEnergy=½(mv^2) joules

The power in moving air is the flow rate of kinetic energy per second. Therefore:

Power=1/2(mass flow rate per second)V^2

If we let P = mechanical power in the moving air ρ= air density, kg/m3

A = area swept by the rotor blades, m2 V = velocity of the air, m/s

Then, the volumetric flow rate is A·V, the mass flow rate of the air in kilograms per second is ρ·A·V, and the power is given by the following:

$$P = \frac{1}{2}(\rho A V) \cdot V^2 = \frac{1}{2}\rho A V^3 \ \textit{watts.}$$

Two potential wind sites are compared in terms of the specific wind power expressed in watts per square meter of area swept by the rotating blades. It is also referred to as the power density of the site, and is given by the following expression:

$$\textit{Specific Power of the site} = \frac{1}{2}\rho \cdot V^3 \ \textit{watts per } m^2 \textit{ of the rotor swept area}$$

This is the power in the upstream wind. It varies linearly with the density of the air sweeping the blades, and with the cube of the wind speed. All of the upstream wind power cannot be extracted by the blades, as some power is left in the downstream air which continues to move with reduced speed.

3.12Thermodynamics of Wind Energy:

It is easy to appreciate the fact that though kinetic in nature, wind is low-quality

energy. It is basically a relatively unidirectional motion of air molecules, in that not all the molecules move in the same direction. There is random and disorderly thermal motion of the molecules in all directions. Only the algebraic summation yields a resultant value in one direction. Naturally, the order or organization of this form of energy is low in comparison with the motion of a shaft, where all the molecules share a common motion. Our objective in wind energy conversion is to transform this energy into the rotation of a shaft or the flow of electrons. Only then it becomes useful to mankind.

The second law of thermodynamics states that whenever there is a transformation from low-quality energy to high-quality energy it is impossible to achieve 100 per cent efficiency even in theory. There is always a theoretical maximum limit on the efficiency. In the case of conversion of heat energy into mechanical energy, the limit is given by (1 — T2/T1) where T1 and T2 are the temperatures of the source and the sink, respectively, expressed in absolute scale. Similarly, in the case of conversion of wind energy into the mechanical energy of a rotating shaft , there must be some theoretical upper limit on the efficiency of the conversion. What is that upper limit? We will discuss this limit in the following section.

3.13 Efficiency limit for wind energy conversion:

(Power Extracted from the Wind)

The actual power extracted by the rotor blades is the difference between the upstream and

$$P_o = \frac{1}{2}\ mass\ flow\ rate\ per\ second \cdot \left\{V^2 - V_o^2\right\}$$

the downstream wind powers. That is, using Equation 4-2:
Where Po = Mechanical power extracted by the rotor, i.e., the turbine output power
V = upstream wind velocity at the entrance of the rotor blades Vo = downstream wind velocity at the exit of the rotor blades.

The air velocity is discontinuous from V to Vo at the “plane” of the rotor blades in the macroscopic sense (we leave the aerodynamics of the blades which is beyond

our scope). The mass flow rate of air through the rotating blades is, therefore, derived by multiplying the density with the average velocity. That is:

$$mass\ flow\ rate = \rho \cdot A \cdot \frac{V + V_o}{2}$$

The mechanical power extracted by the rotor, which is driving the electrical generator, is therefore:

$$P_o = \frac{1}{2}\left[\rho \cdot A \cdot \frac{(V + V_o)}{2}\right] \cdot \left(V^2 - V_o^2\right)$$

The above expression can be algebraically rearranged (by multiplying and dividing the first term in the square brackets by ‘V‘ and the second term in normal brackets by V2) :

$$P_o = \frac{1}{2}\rho \cdot A \cdot V^3 \frac{\left(1 + \frac{V_o}{V}\right)\left[1 - \left(\frac{V_o}{V}\right)^2\right]}{2}$$

The power extracted by the blades is customarily expressed as a fraction of the upstream wind power as follows:

$$(P_o = \frac{1}{2}\rho \cdot A \cdot V^3 \cdot C_p$$

Where $C_p = \frac{\left(1 + \frac{V_o}{V}\right)\left[1 - \left(\frac{V_o}{V}\right)^2\right]}{2}$ (1,10)

And Cp is the fraction of the upstream wind power, which is captured by the rotor blades. The remaining power is discharged or wasted in the downstream wind. The factor Cp is called the power coefficient of the rotor or the rotor efficiency.

For a given upstream wind speed, the value of Cp depends on the ratio of the downstream to the upstream wind speeds, that is (Vo/V). The plot of power coefficient versus (Vo /V) shows that Cp is a single, maximum-value function (Figure 4-3). It has the maximum value of 0.59 when the (Vo/V) is one-third. The maximum power is extracted from the wind at that speed ratio, when the downstream wind speed equals one-third of the upstream speed. Under this condition:

$$P_{\max} = \frac{1}{2}\rho \cdot A \cdot V^3 \cdot 0.59$$

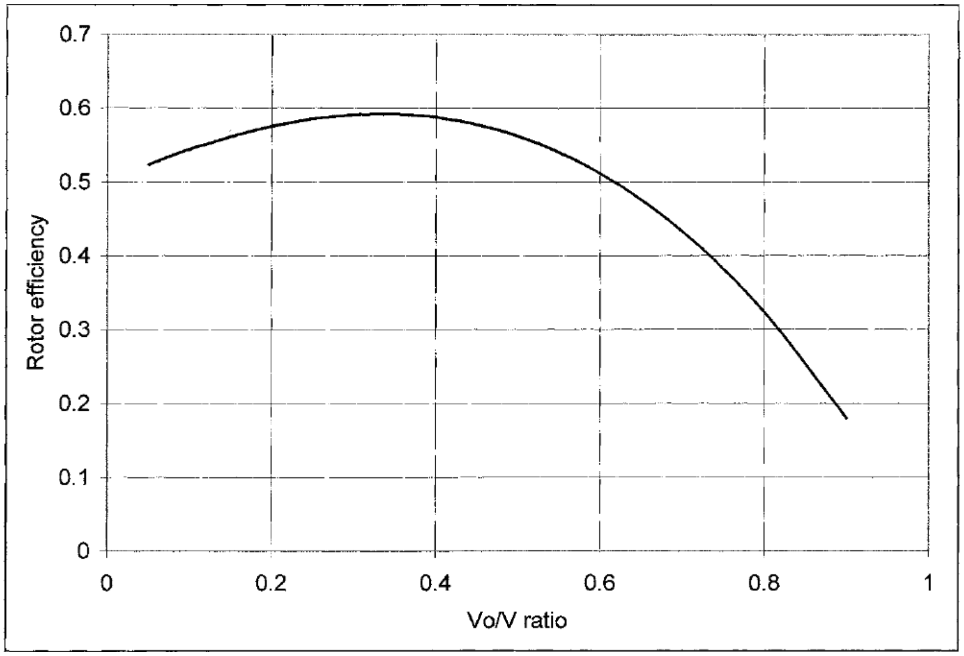


Figure 3: Rotor efficiency versus Vo/V ratio has single maximum. Rotor efficiency is the fraction of available wind power extracted by the rotor and fed to the electrical generator.

The theoretical maximum value of Cp is 0.59. This limit is called ‘Betz Limit’. In practical designs, the maximum achievable Cp is below 0.5 for high-speed, two- blade turbines, and between 0.2 and 0.4 for slow speed turbines with more blades as shown in the figure below. (Figure 1-2).

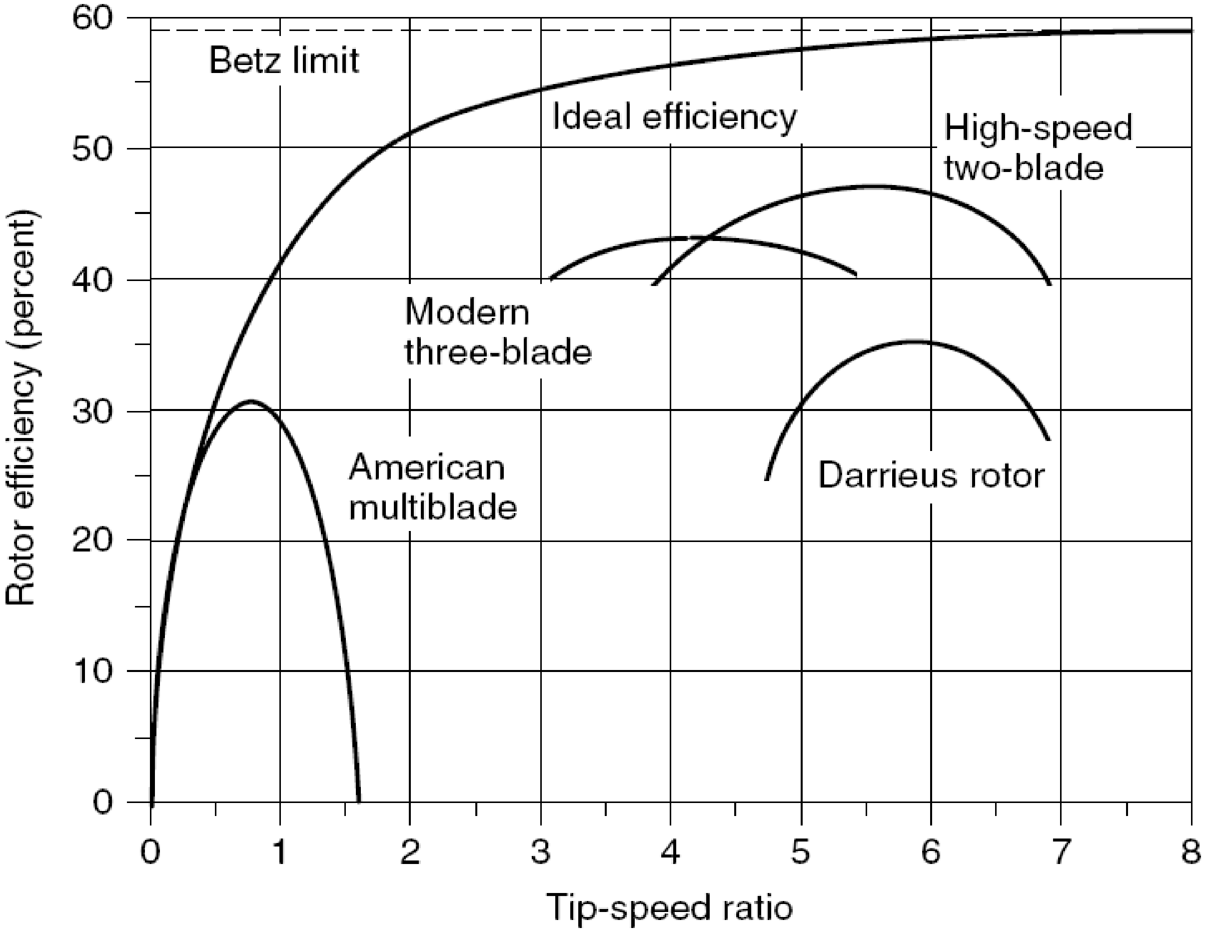


Figure 1-2: Rotor efficiency versus tip speed ratio for rotors with different number of blades. Two-blade rotors have the highest efficiency.

If we take 0.5 as the practical maximum rotor efficiency, the maximum power output of the wind turbine becomes a simple expression:

$$P_{\max} = \frac{1}{4} \cdot \rho \cdot V^3 \text{ watts per m}^2 \text{ of swept area.}$$

3.14 Tip speed ratio:

The tip speed ratio (TSR) of a wind turbine is defined as $\lambda = (2\pi RN)/V$ where λ is the TSR (non dimensional, R is the radius of the swept area (in meters), N is the rotational speed in revolutions per second and V is the wind speed without rotor interruption in meters/second).

The TSRs of Savonius rotor and multiblade water pumping windmills are generally low. In high speed horizontal axis rotors and Darrieus rotors, the outer tip actually turns much faster than the wind speed owing to the aerodynamic shape. Consequently, the TSR can be as high as 9. It can be said that high solidity rotors have in general low TSRs and vice versa.

3.15 Power Coefficient:

The power coefficient of a wind energy converter is given by:

Cp = (Power output from the wind machine)/(Power contained in the wind) The power coefficient differs from the efficiency of a wind machine in the sense thatthe latter includes the losses in mechanical transmission, electrical generation etc. whereas the former is just the efficiency of conversion of wind energy into mechanical energy of the shaft. In high- speed horizontal-axis machines the theoretical maximum power coefficient is given by the Betz limit.

3.16 Design of the wind turbine rotor:

The design of the wind turbine rotor is basically aerodynamics related and its study is beyond our scope. However a basic knowledge of the underlying basic principles of a WT Rotor design is essential even for an Electrical engineer. Hence we will study them briefly in this topic.

The design of a WT Rotor basically involves the design of the blade profile, selection of the number of blades, the Rotor diameter, height of the tower and the type of transmission system & gear box. We will study them one by one.

3.17 Design of the Blade profile:

From the basic principles of Aerodynamics, efficient design of a blade maximizes the lift and minimizes the drag. Minimization of Drag means that the aerofoil should face the relative wind in such a direction that the smallest possible area is exposed to the wind drag. The angle of relative wind is determined by the relative magnitudes of ‘u’ and ‘v’. The wind velocity is constant throughout the rotor area but the blade velocity increases from the inner edge to the tip. So neither the magnitude nor the angle of the relative wind is constant throughout the length of the blade.

From this observation a few qualitative conclusions about the desirable features of a wind turbine blade can be drawn.

First as the aerofoil has to face the relative wind at all points, it should have a varying pitch angle along the blade. In other words, it should have a twist.

Second, as the lift force developed at the blade tip is higher than that at the inner edge due to the difference in the magnitude of ‘w’, the tip tries to move faster than the central parts. This produces a stress that may cause blade failure. Moreover, the tension developed at the inner side due to centrifugal force is more than that at the tip.

Both these problems can be remedied by designing a tapering blade so that the blade area at the tip is less than that at the inner edge. To achieve perfect balance of all these forces at all parts of the blade , it may sometimes be desirable to have a varying aerofoil section along the blade .However some of these features are too expensive to implement , and a compromise is often struck between efficiency and production cost.

3.18 Diameter of the Rotor:

The diameter of the rotor is determined from the operating wind speed and the rated power output. The generated power is given by: v ηmρ ηeρ CpV3

$$\begin{aligned} P &= P_0 \eta_e \eta_m C_p \\ &= \frac{1}{2} \rho A V_\infty^3 \eta_e \eta_m C_p \\ &= \frac{1}{8} \pi \rho D^2 V_\infty^3 \eta_e \eta_m C_p \end{aligned}$$

Where η_m is the efficiency of the mechanical transmission and η_e is the efficiency of electrical generation. If the rated P (W), V (m/s) , and Cp are known ,the diameter in meters can be found out.

In the absence of the above data, the following simple formulae can be used for the initial estimation of the maximum aerodynamic power:

P = 0.15D2V3 for slow rotors P = 0.20D2V3 for fast rotors

3.19 Choice of the number of blades :

It is obvious that the efficiency of power transfer from wind depends on the proper choice of the number of blades. There will be little power extraction if the blades are so close to each other or rotate so fast that every blade moves into the turbulent air created by the preceding blade. It will also be less than optimum if the blades are so far apart or move sso slowly that much of the air stream passes through the wind turbine without interatcting with a blade. Thus the choice of the number of blades should depend on the TSR

Let ‘ta’ be the time taken by one blade to occupy into the position previously occupied by the preceding blade. For a ‘n’ bladed rotor roating at an angular velocity of ‘ω’ ta = 2π/nω

Let tb be the time taken by the distributed wind , caused by the interference of a blade , to move away and normal air to be re-established. It depends on the wind speed ‘v’ and the length of the strongly perturbed air stream, say ‘d’. This length stretching both upward and downward depends on the size and shape of the blades. tb = d/v For maximum power extraction , ta and tb should be more or less equal. Then from the above equations we have

$$2\pi/n\omega = d/v \quad \text{or} \quad \omega/v = 2\pi/nd$$

The choice of the number of blades therefore depends on the value of d, which has to be determined empirically. A large number of blades implies high solidity - hence high torque and low speed. On the other hand , a small number of blades implies low torque and high speed. Therefore a large number of blades are used in wind turbines for pumping water or other mechanical functions that require a high starting torque. For modern electricity generating-wind turbines,the empirical measurement of ‘d’ and the requirement of a high TSR leads to a small number of blades , generally only two or three.

Though both two blade and three blade designs are equally popular, their choice depends on certain factors. The two blade designs have less nacelle weight and are much simpler to erect. Three blade turbines involve 33% more weight and cost , though the power coefficient increases only by 5-10%. On the other hand, the three-blade design has smoother power output and a more balance gyroscopic force and therefore less blade fatigue and lesser chances of failure.

3.20 Choice of the Pitch Angle:

The pitch angle is given by α = I – i. As I varies along the length of blade , α should also vary to ensure an optimal angle of incidence at all points of the blade. Thus the desirable twist along the blade can be calculated easily. The pitch angle should be such that tan ε or

CD/CL is minimum at all points of the rotor. Some authors recommend the use of the Eiffel polar plot for this purpose. In this method , the tangent to the Effel polar plot gives the minumum CD/CL.However for the tangent to represent tan ε , both CD and CL should be drawn to the same scale. This becomes very inconvenient, since for most aerofoils , CL is about two orders of magnitude higher than CD.It is more convenient to plot the curve for CD /CLversus i. Its minimum point will then represent the optimal value of the incidence angle. This method yields a twisted blade i.e. one that has dfferent pitch angles at different distances from the axis. If the constraints in the production method do not permit a twist , the optimal value of α can be chosen for a suitable point on the blade, say r= 0.8R, and the same picth angle maintained through out the blade.

3.21 The Tower:

In a horizontal axis wind turbine, the tower supports the hole machinery, including the blades, the gearbox the genrator and the control equipment. It therefore requires high strentgth,which is achieved with a steel or concrete structure based on tubular or lattice construction. It is necessary to avoid amplification of vibration through careful design of the resonant frequencies of the tower, blades, rotor ,etc. vis-a-vis the wind fluctuation frequencies.

In general, for medium and large turbines, the height of the tower is slightly greater than the Rotor diameter. Small turbines should have taller towers in comparision with their rotor diameters; otherwise the turbine would be too close to the ground surface and would experience poor wind speeds. Turbines with rated output between 10kW and 100 kW have tower heights in the range of 20-30 m;300kWt o 500kW machines would have towers 35m to 40 m high.

3.22 The Transmission System and the GearBox:

In general , the optimal speed of rotation of an electrical generator is much higher than the optimal speed of a wind turbine. In order to ensure that a low speed of the turbine produces a high rotational speed at the Generator, a gear box is inserted in the transmission system. The arrangement in side the generator housing is shown schematically in the figure below.

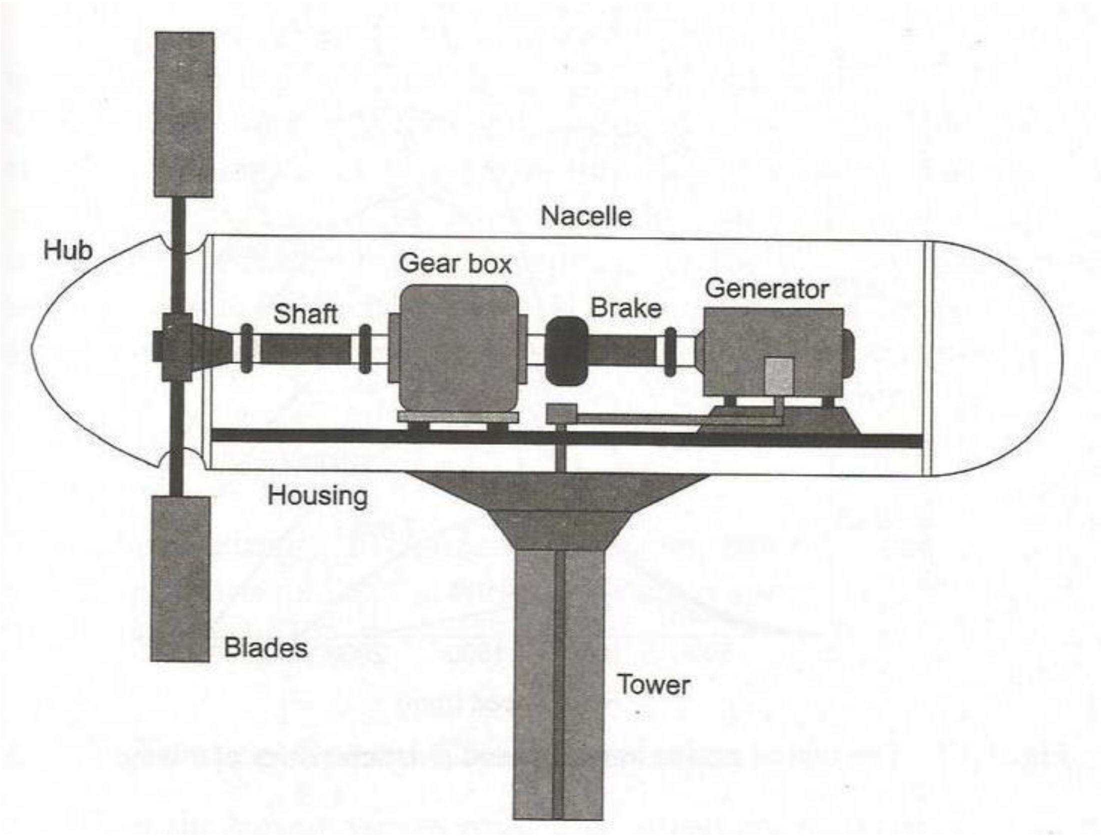


Figure: The Shaft, Gearbox, Generator and Brake inside the Nacelle (Nacelle and the important subsystems inside)

If the generator has a fixed gear ratio , the transmission system is relatively simple and inexpensive. However, in this case the efficiency suffers at low or high wind speeds . It has been found that fpr a particlar site (with particular wind speed distribution characteristics), on eparticular choice of the gear ratio gives the highest system efficiency and the curve falls off on both sides of this opt imalgear ratio. Therefore a judicious choice of the gear ratio is very important. Generally a speed ratio of 20-30 is chosen for wind electrical systems.

For variable speed wind turbine , a better overall efficency may be obatined with a two speed gearbox which can switch from a low gear ratio at high wind speeds to a high gear ratio at low wind speeds so that the speed variation at the generator side is kept minimum.

3.23 Power –Speed Characteristics :

The wind turbine power curves shown in the figure below (1-17) illustrate how the mechanical power that can be extracted from the wind depends on the rotor speed. For each wind speed there is an optimum turbine speed at which the extracted wind power at the shaft reaches its maximum.

Such a family of wind turbine power curves can be represented by a single dimensionless characteristic curve , namely , the CP-λ curve as shown in the figure below (1-12) where the power coefficient is plotted against the TSR. For a given turbine , the power coefficient depends not only on the TSR but also on the blade pitch angle. Figure 1-18 shows the typical variation of the power coefficent with
respect to the TSR λ with blade pitch control.

From equations 1-1 and 1-19 , the mechanical power transmitted to the shaft is given by:

$$P_m = \frac{1}{2}\rho C_p A V_\infty^3$$

Where CP is a function of the TSR λ and the pitch angle α. For a wind turbine with a radius R, equation 1-40 can be expressed as

$$P_m = \frac{1}{2}\rho C_p \pi R^2 V_\infty^3$$

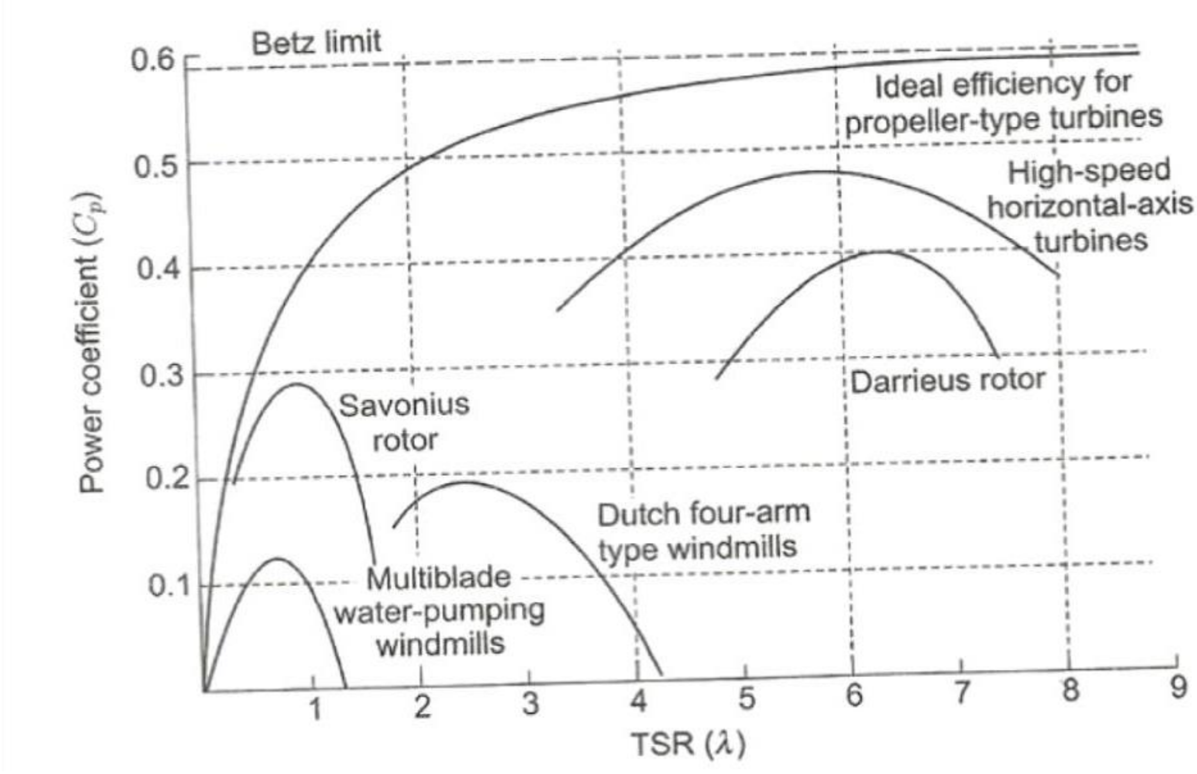


Figure : Curves of C_P vs TSR for various types of wind mills

For a given wind speed , the power extracted from the wind is maximised if CP is maximised. The optimum value of CP, say CPopt,always occurs at a definite value of λ say(= λopt). This means that for varying wind speed, the rotor speed should be adjusted proportionally to adhere this value of λ (= λopt) for maximum mechanical output power from the turbine. Using the relation λ = ωR/V in equation (1-41) , the maximum value of the shaft mechanical power for any wind speed can be expressed as :

$$P_{\max} = \frac{1}{2}\, C_{p,\mathrm{opt}}\pi \left(\frac{R^5}{\lambda_{\mathrm{opt}}^3}\right)\omega^3$$

Thus the maximum mechanical power that can be extracted from wind is proportional to the cube of the rotor speed i.e.$Pmax \propto \omega 3$. This is shown in figure 1- 17.

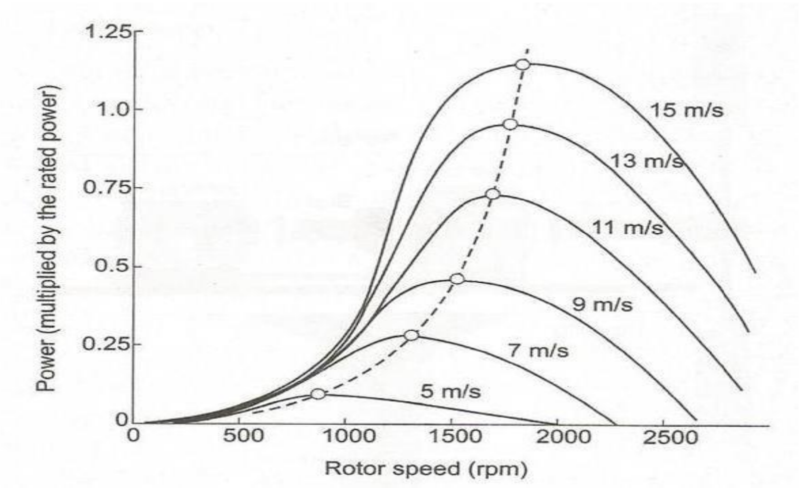


Figure : Typical power vs speed characteristics of a wind turbine

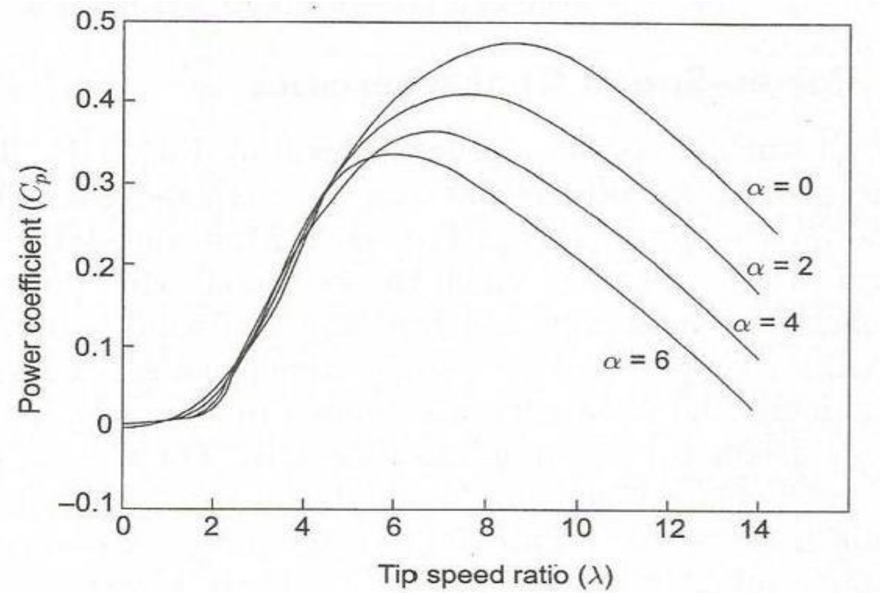


Figure: Typical curves of Power coefficient vs TSR for various Pitch angles

3.24 Torque –Speed Characteristics :

Studying the Torque versus rotational characteristics of any prime mover is very important for properly matching the load and ensuring stable operation of the electrical generator.The typical torque-speed characteristics of the two blade propellor type wind turbine, the Darrieus rotor and the Savonius rotor are shown in the figure below (1-19). The profiles of the torque –speed characteristic curves shown in this figure follow from the power curves, since Torque and power are related as follows:

$T_m = P_m/\omega$

From equation 1-42 , at the optimum operating point ($C_{p,opt}$, λ_{opt}), the relation between aerodynamic torque and rotational speed is:

$$T_m = \frac{1}{2}\rho C_{p,\mathrm{opt}}\pi\left(\frac{R^5}{\lambda_{\mathrm{opt}}^3}\right)\omega^2$$

It is seen that at the optimum operating point on the CP-λ curve, the torque is quadratically related to the rotational speed.

The curves in figure 1-19 show that for the propellor turbine and the Darrieus rotor, for any wind speed , the torque reaches a maximum value at a specific rotational speed and this maximum shaft torque varies approximately as the square of the rotational speed. In the case of electricity production the load torque depends on the electrical loading and by properly choosing the load (or power electronics interface) the torque can be made to vary as the square of the rotational speed.

The choice of the constant of proportionality of the load is very important (see fig1-20) At the optimal value,the load curve follows the maximum shaft power. But at a higher value the load torque may exceed the turbine torque for most speeds.

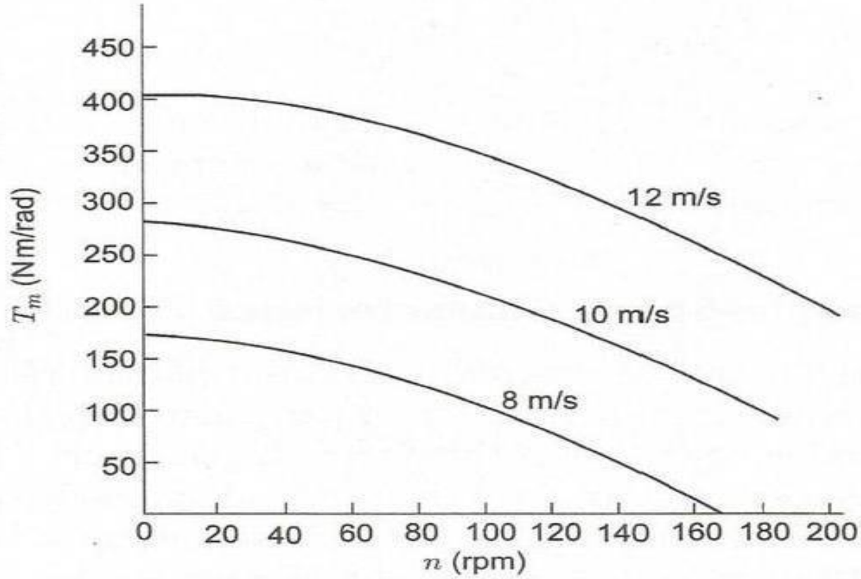
Consequently the machine would fail to speed up above a very low value. If the constant K is lower than the optimumvalue the machine may overspeed at the rated wind speed activating the speed limiting mechanism. Thus the proportionality constant of the load needs to be selected from a rather narrow range , about 10-20% of the optimum power curve. Note that the point of maximum torque is not the same as that of maximum power.

As the power output is the product of torque and speed , it also has a maxima that vary as the cube of the rotational speed. The matching characteristics of the load can make the load curve pass through the maximum power points at all wind speeds. For generators that feed power to the Grid the T-S characteristics are tuned using power electronics controls.

In terms of the power coefficient CP(λ,α) , the aerodynamic torque becomes :

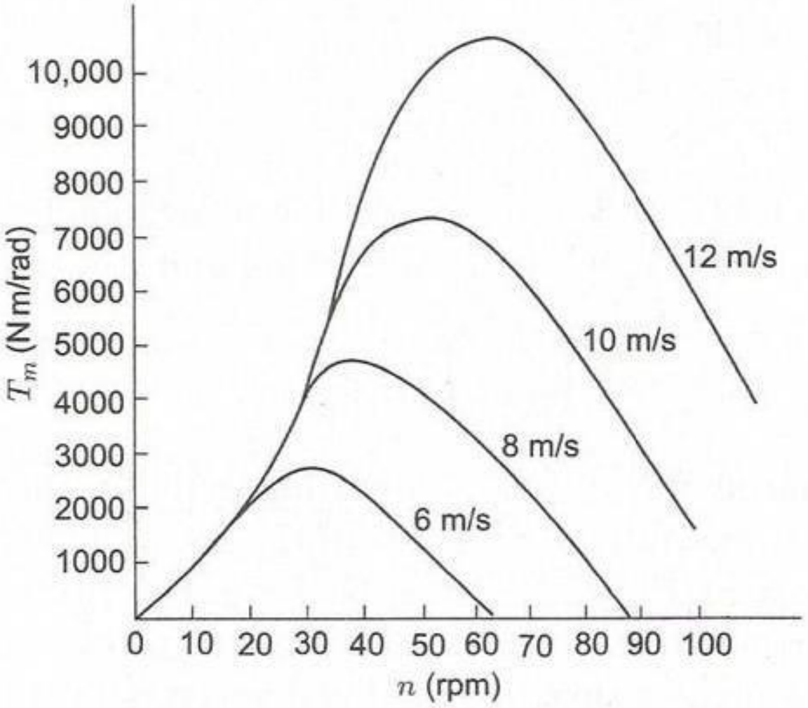
$$T_m = \frac{1}{2}\rho C_T \pi R^3 V_\infty^2$$

Where $C_T = C_P/\lambda$ is called the ***Torque Coefficient***



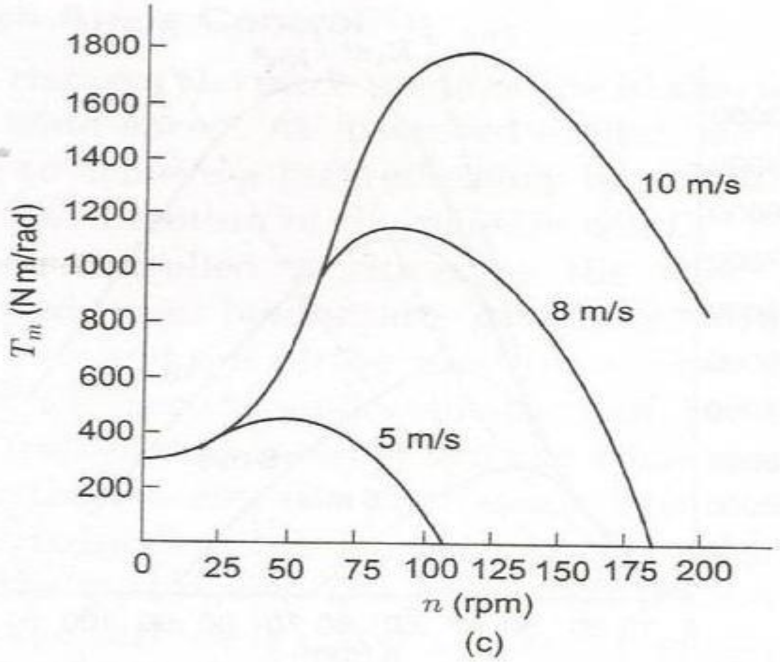
450
400
350
300
250
200
150
100
50
T_m (Nm/rad)
12 m/s
10 m/s
8 m/s
0
20
40
60
80
100
120
140
160
180
200
n (rpm)

(a)



10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
T_m (N m/rad)
12 m/s
10 m/s
8 m/s
6 m/s
0
10
20
30
40
50
60
70
80
90
100
n (rpm)

(b)



(c)

The torque–speed characteristics of various types of wind machines: (a) the Savonius rotor, (b) the Darrieus rotor, (c) the two-blade propeller-type rotor

3.25 Wind Turbine Control Systems

Wind turbines require certain control systems. Horizontal-axis wind turbines have to be oriented to face the wind. In high winds it is desirable to reduce the drive train loads and protect the generator and the power electronics equipment from overloading, by limiting the turbine power to the rated value up to the furling speed. At gust speeds, the machine has to be stalled. At low and moderate wind speeds, the aim should be to capture power as efficiently as possible

Along with many operating characteristics, the technical data sheet of a turbine mentions its output at particular wind speed, generally known as the rated wind speed. This is the minimum wind speed at which the wind turbine produces its designated output power. For most turbines, this speed is normally between 9 and 16 m/s. The choice of the rated wind speed depends on the factors related to the wind speed characteristics of a given site, which are discussed in the next chapter. The Generator rating is chosen so as to best utilize the mechanical output of the turbine at the rated wind speed.

Wind turbines can have four different types of control mechanisms, as discussed in the following.sss

3.26 Pitch Angle Control

This system changes the pitch angle of the blades according to the variation of wind speed. As discussed earlier, with pitch control, it is possible to achieve a high efficiency by continuously aligning the blade in the direction of the relative wind.

On a pitch-controlled machine, as the wind speed exceeds its rated speed, the blades are gradually turned about the longitudinal axis and out of the wind to increase the pitch angle. This reduces the aerodynamic efficiency of the rotor, and the rotor output power decreases. When the wind speed exceeds the safe limits for the systems, the pitch angle Is so changed that the power output reduces to zero and the machine shifts to the ‘stall’ mode. After the gust passes, the pitch angle is reset to the normal position and the turbine is restarted. At normal wind speeds, the blade pitch angle should ideally settle to a value at which the output power equals the rated power.

The Pitch angle control principle is explained in the figure below (1.21). The input variable to the pitch controller is the error signal arising from the difference between the output electrical power and the reference power. The pitch controller operates the blade actuator to alter the pitch angle. During operation below the rated speed, the control system endeavors to pitch the blade at an angle that maximizes the rotor efficiency. The generator must be able to absorb the mechanical power output and deliver to the load. Hence, the generator output power needs to be simultaneously adjusted.

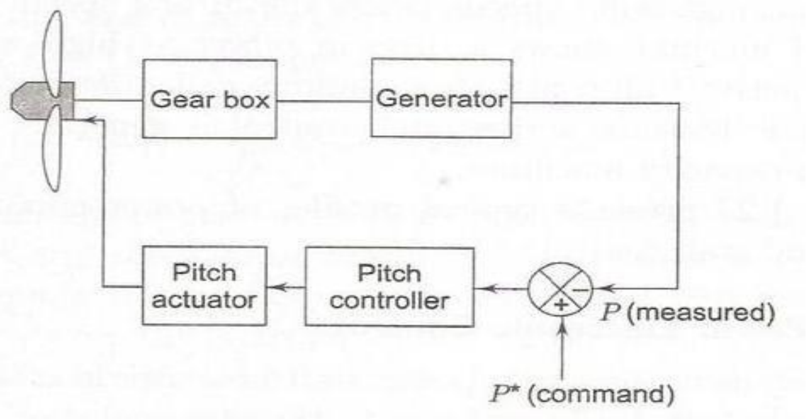


Fig. 1.21 The feedback loop for pitch angle control

Cotinuous pitch control is relatively expensive to incorporate and the cost- benfit trade-off does not justify its use in small wind machines. However, the stalling mechansiam must be incorporated to prevent damage of the turbine during turbulent weather conditions.

3.27 Stall control

Generally stall control to limit the power output at high winds is appiled to constant-pitch turbines driving induction generators connected to the network. The rotor speed is fixed by the network, allowing only 1-4% variation. As the wind speed increases, the angle of attack also increases for a blade running at a near constant speed. Beyond a particular angle of attack, the lift force decreases, causing the rotor efficeincy to drop. This is an intrinsic property and dispenses with the need for a complex control system and moving parts. The lift force can be furthur reduced to restrict the power output at high winds by properly shaping the rotor blade profile to create turbulence on the rotor blade side not facing the wind.

3.28 Active stall control

In this method of control, at high wind speeds the blade is rotated by a few degrees in the direction opposite to that in a pitch-controlled machine. This increases the angle of attack, which can be controlled to keep the output power at its rated value at all high wind speeds below the furling speed. A passive controlled machine shows a drop in power at high winds. The action of active stall control is sometimes called deep stall. Owing to economic reasons, active pitch control is generally used only with high-capacity machines.

Figure below (1.22) presents typical profiles of power curve for pitch control and stall control.

3.29 Power Electronic Control

In a system incorporating a power electronic interface between the generator and the load (or the grid), the electrical power delivered by the generator to the load can be dynamically controlled.

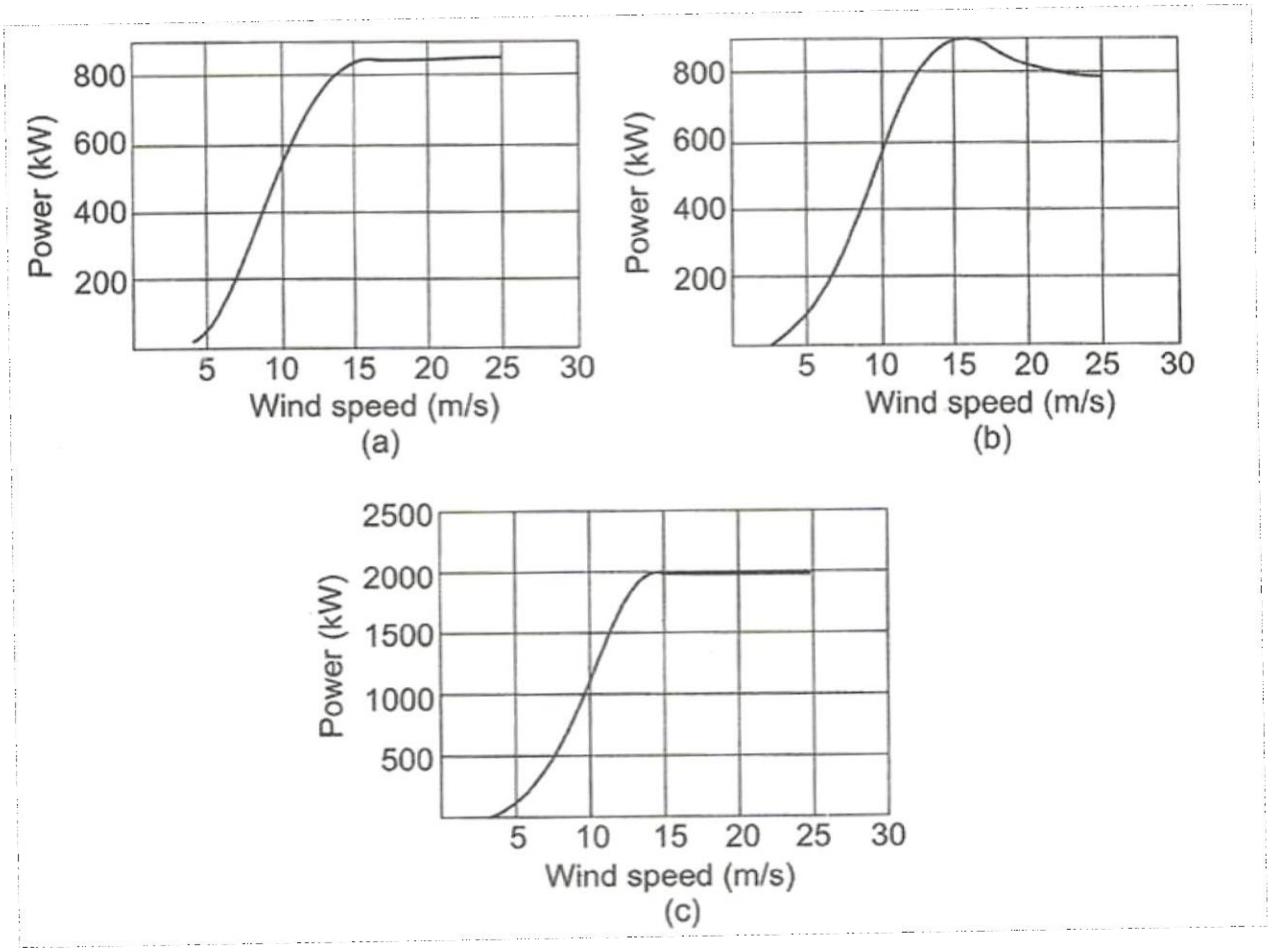


Fig.1.22Typicalpowerprofile:(a)pitchcontrol(b)passivestallcontrol (c) active stall control

The advantage of this method of speed control is that it does not involve any mechanical action and is smooth in operation. A disadvantage is that fast variation of speed requires a large difference between the input power and output power, which scales as the moment of inertia of the rotor. This results in a large torque and hence increases stress on the blades. Moreover, continuous control of the rotor speed by this method implies continuous fluctuation of the power output to the grid, which is usually undesirable for the power system.

3.30 Yaw Control

This control orients the turbine continuously along the direction of wind flow. In small turbines this is achieved with a tail-vane. In large machines this can be achieved using motorized control systems activated either by a fan-tail (a small turbine mounted perpendicular instrument to the main turbine) or, in case of wind farms, by a centralized instrument for the detection of the wind direction. It is also possible to achieve yaw control without any additional mechanism, simply by mounting the turbine downwind so that the thrust force automatically pushes the turbine in the direction of the wind.

The yaw control mechanism can also be used for speed control- the rotor is made to face away from the wind direction at high wind speeds, thereby reducing the mechanical power. However, this method is seldom used where pitch control is available, because of the stresses it produces on the rotor blades. Yawing often produces loud noise, and it is desirable to restrict the yawing rate in large machines to reduce the noise.

3.31 Control Strategy

For every wind turbine, there are five different ranges of wind speed, which require different speed control strategies.

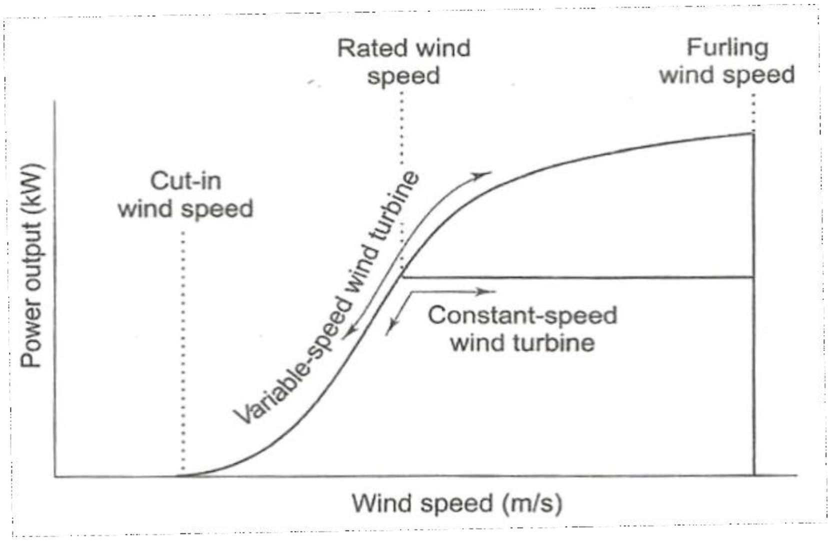
Below a cut-in speed, the machine does not produce power. If the rotor has a sufficient starting torque, it may start rotating below this wind speed. However, no power is extracted and the rotor rotates freely. In many modern designs the aerodynamic torque produced at the standstill condition is quite low and the rotor has to be started (by working the generator in the motor mode) at the cut-in wind speed.

At normal wind speeds, maximum power is extracted from wind. We have seen earlier that the maximum power point is achieved at a specific (constant) value of the TSR. Therefore, to track the maximum power point, the rotational speed has to be changed continuously in proportion to the wind speed.

At high winds, the rotor speed is limited to a maximum value depending on the design limit of the mechanical components. In this region, the Cp is lower than the maximum, and the power output is not proportional to the cube of the wind speed.

At even higher wind speeds, the power output is kept constant at the maximum value allowed by the electrical components.

At a certain cut-out or furling wind speed, the power generation is shut down and the rotation stopped in order to protect the system components.



Typical Power versus wind speed characteristics of variable speed wind machines

The last three control regimes can be realized with yaw control, pitch angle control (if these are installed), and eddy-current or mechanical brakes.

In the intermediate-speed range, the control strategy depends on the type of electrical power generating system used, and can be divided into two basic categories.

The constant-speed generation scheme, and

The variable-speed generation scheme.

The constant-speed generation scheme is necessary if the electrical system involves a grid-connected synchronous generator (the details are given in subsequent chapter). In the case of grid-connected squirrel cage induction generators, the allowable range of speed variation is very small, requiring an almost constant rotational speed.

However, constant-speed generation systems cannot maximize the extraction of the power contained in wind. We can see from Fig.1.12 that the power coefficient reaches a maximum at a specific value of TSR for evey type of wind turbine. Therefore, to extract the maximum amount of power from the wind, the turbine should opearate at a constant TSR, which means that the rotational speed should be proportional to the wind speed. Hence the extraction of maximum power requires a variable-speed generation system with the speed control aimed at keeping a constant TSR.

Such systems can yield 20-30% more power than constant-speed generation systems. With the development of induction generators and power electronic converters, designers are favouring variable-speed generation systems. We will, therefore, discuss the control strategies for such systems in greater detail.

The constant-TSR region, which encompasses the largest range of wind speeds, is generally achieved by regulating the mechanical power input through pitch control or the electrical power output by power electronics control. In many cases a combination of both is employed.

The control scheme generally takes two possible forms. In the first case, the value of the TSR for maximum Cp is stored in a microprocessor. The operating TSR is obtained from the measured values of the wind speed and rotational speed. An error signal is generated whenever the operating TSR deviates from the optimum TSR. If the current value of the TSR deviates from the optimum TSR, the power electronic converted increases the power output so that the rotational speed is reduced to the desired value. The oppsite action is performed if the optimal value exceeds the current TSR.

This scheme has a few disdavantages. First, the wind speed measured in the neighbourhood of a wind turbine (or a wind farm) is not a reliable indicator of V∞ because of the shadowing effects. Second, it is difficult to determine the value of TSR for maximum Cp. Third, this value changes during the lifetime of a wind turbine due to the changes in the smoothness of the blade surface, necessitating alterations in the refrence setting.

A second control scheme is devised to continousaly track the maximum power point (MPP) using the property that the CP versus TSR curve has a single smooth maximum point. This means that if we operate ata the maximum point, small fluctuations in the rotational speed do not significantly change the power output, i.e., the MPP is characterized by $dP/d\omega = 0$. To implement this scheme, the speed is varied in small steps, the power output is measured, and $\Delta P/\Delta\omega$ is evaluated. If this ratio is positive, more mechanical power can be obtained by increasing the speed. Hence the electrical power output is decreased temporarily by power electronic control so that the speed increases. This increases the mechanical power, and the electrical power output is again raised to a higher value. The process continues untill the optimum speed is reached, when mechanical power becomes insensitive to speed fluctuations. When the wind speed changes, this mechanism readjusts the speed at the optimum value.

While controlling the rotaional speed, it should be remembered that a large difference between mechanical power and electrical power results in large torque and, hence, a large stress on the rotor components (especially on the joints between the blades and the shaft). To avoid fatigue and failure, it is necessary to limit the acceleration and deceleration rates to values dictated by the structual strength of the mechanical parts.

3.32 The use of brakes

In the event of load tripping or accidental disconnection of the electrical load, the rotor speed may increase dangerously. This may even lead to the mechanical destruction of the rotor. Moreover, at very high wind speeds, the electrical power throughput has to be kept within limits to protect the generator and the power electronic converter. This can be done by reducing the rotational speed. However, this speed control cannot be achived by power electronic control as discussed above, because that would call for an increase in the electrical power output which is exactly the opposite of what was desired.

In these situations it is advisable to use brakes. Either an eddy-current or a mechanical brake (or a combination of these) is installed in most wind turbines. A mechanical brake is also necessary for stalling these turbines in gustly winds.

Wind speed measurements

- Robinson cup anemometer
- Pressure tube anemometer
- Hot wire anemometer
- Wind speed statistics
- Statistical wind speed distributions
- Site and turbine selection.

3.34 Wind Site Analysis and Selection:

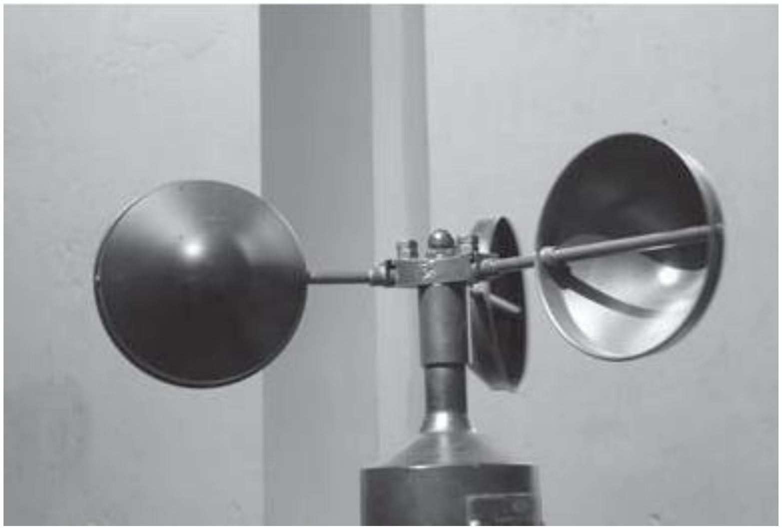
It follows from common sense that a site suitable for the installation of wind turbines should be ‘windy’. However, the windiness of a site needs to be specified in quantitative terms. In order to do so, one needs to first obtain data on wind speeds and directions by installing measuring instruments at potential sites. Since wind speed and direction vary continuously, estimation of the power generation potential requires some statistical analysis. Finally, one has to obtain a proper match between the characteristics of the wind turbine and those of the site. We will take up these issues in this chapter.

Wind Speed Measurements

The device used for wind speed measurement is called an anemometer. There are three different techniques for wind speed measurement. In general, any measurable phenomenon that has strong dependence on wind velocity can be used for wind speed measurement. Experience has shown that thrust, pressure, and the cooling effect, are the three most convenient parameters using which wind speed can be directly measured.

Robinson Cup Anemometer

The Robinson cup anemometer consists of a vertical shaft carrying three or four horizontal arms, at the ends of which there are hemispherical cups of thin sheet metal. The circular rims of the cups are in vertical planes passing through the common axis of rotation. The thrust of wind is greater on the concave sides than on the convex ones, thereby leading to the rotation of the vertical shaft (Fig. 2.1).



The Robinson cup anemometer

As this is a vertical-axis device, there is no problem of orientation along the wind direction. The wind velocity has a linear relationship with the speed of rotation, which is measured by a photocell-operated digital counter. The display can be precalibrated to give the wind speed directly. Modern devices have facilities for continuous data logging and storage, from which data can be retrieved later for analysis.

At very low wind speeds, the readings of the cup anemometer can be erroneous due to the friction of the bearings. During fast variations of wind speed, the inertia effect may be significant; e.g., when the wind speed drops quickly, the anemometer tends to rotate faster and takes time to slow down. In spite of these minor drawbacks, the Robinson cup anemometer is the most extensively used instrument for wind speed measurement.

Pressure Tube Anemometer

The pressure tube anemometer a simple mechanical device suitable for stand- alone application in remote windy locations.

Structure-wise, it has two distinct parts. The head, which is usually mounted on a mast at the desired height, consists of a horizontal tube, bent at one end and supported by two concentric vertical tubes. The horizontal end is connected to the inner tube.

At the other side of the outer tube, there are a few holes a little below the horizontal tube. The entire head is free to rotate, which is turned to face the wind by a vane.

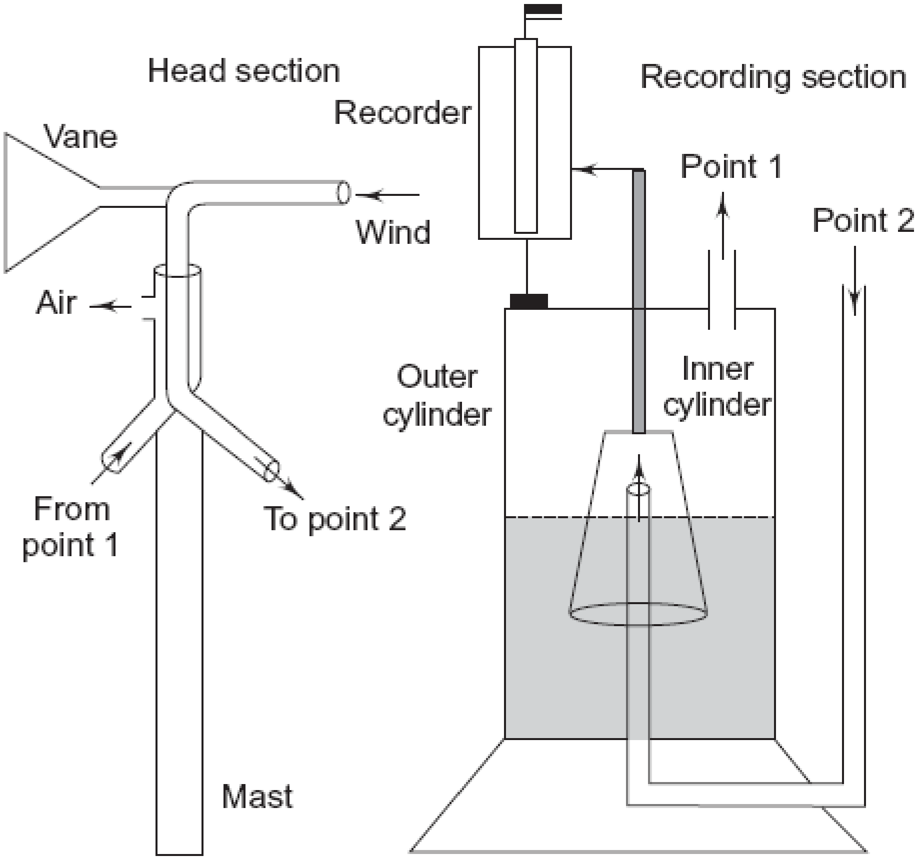


Figure 2.2: **Pressure tube Anemometer**

The wind blowing into the horizontal tube creates pressure, which is communicated through a flexible tube to a recorder. Again, the wind blowing over the small holes in the concentric tube creates a suction effect, which is also communicated to the recorder through a second flexible tube. In the recording apparatus, a copper vessel, closed at one end, floats inverted in a cylindrical metal container partly filled with water and sealed from the outside air. The wind pressure from the horizontal tube of the head is transmitted to the space inside the float, causing it to rise as wind blows. This is assisted by the suction that is applied to the space above the float. Thus, as the wind speed rises and falls, the float also rises and falls, and its motion is transferred to a pen tracing a record on a sheet of paper by means of a rod passing through an airtight passage at the top of the cylinder. If the paper movement is spring operated, the device does not need any electrical supply.

The float can be so shaped, in accordance with the law relating pressure to wind velocity, that the velocity scale on the chart is linear. Most pressure tube anemometers also have wind direction recorders taking signals from the tail-vane, so that both the speed and direction of wind are recorded.

Hot Wire Anemometer

A hot wire anemometer uses the cooling effect of wind on an electrically heated platinum or tungsten wire to measure wind velocities. The wire is heated by a constant-current source. With the variation of wind speed, the wire temperature varies, which varies the resistance of the wire. Naturally, in order to find the wind speed, it suffices to measure the resistance of the wire using any standard method. The calibration has to take into account the resistance–temperature characteristics of the wire and the ambient temperature of air.

In a hot wire anemometer, the temperature difference between the wire and the ambient air is inversely proportional to the square root of the wind velocity:

$$Tw - Ta \propto 1 / \sqrt{v} \quad (2.1)$$

Because of this relation, this anemometer is useful especially for measuring small wind velocities.

Wind Speed Statistics:

Since the power contained in wind varies with the cube of the wind speed, the average wind speed available at a particular site is the first criterion to be considered in site selection. During the site identification process, the measuring instruments described in the previous section are installed at the site. The annual average wind speed is calculated according to the equation

$$\overline{v} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} v \, dt$$

where v is the annual average wind speed (m/s), v is the instantaneous wind speed (m/s) and $t2 - t1$ is the duration of one year (8760 hrs).

In the case of a digital data logger recording wind speed data at regular intervals, the average wind speed can be calculated as

$$\overline{v} = \frac{1}{n}\sum_{i=1}^{n} v_i$$

where vi is the wind speed at the ith observation and n is the number of observations. At any given site, the wind speed varies with the height from the ground level. It is generally not possible to install measuring instruments at all heights, but an empirical formula can be used to find the mean wind speed at a certain height using the observed mean wind speed at 10 m:

$$\overline{v}_H = \overline{v}_{10}\left(\frac{H}{10}\right)^x$$

where vH is the annual average wind speed at height H (m/s), v10 is the annual average wind speed at 10 m (m/s), and x is an exponent that depends on the roughness of the ground. The values of x are given in the Table below

Description of land	Exponent x
Smooth land with very few obstacles (e.g., sea, coast, desert, snow)	0.10–0.13
Moderately rough, (e.g., agricultural fields with very few trees, grasslands, rural areas)	0.13–0.20
Land with uniformly distributed obstacles 10–15 m high (e.g., forests, small towns, agricultural fields with tree plantations)	0.20–0.28
Land with big and non-uniform obstacles (e.g., big cities, plateaus)	0.28–0.40

The measuring instruments record the wind speed continuously against time. If the data are collected throughout a year, the resulting chart would look like a long wavy line, as shown in the figure (2.3)below.

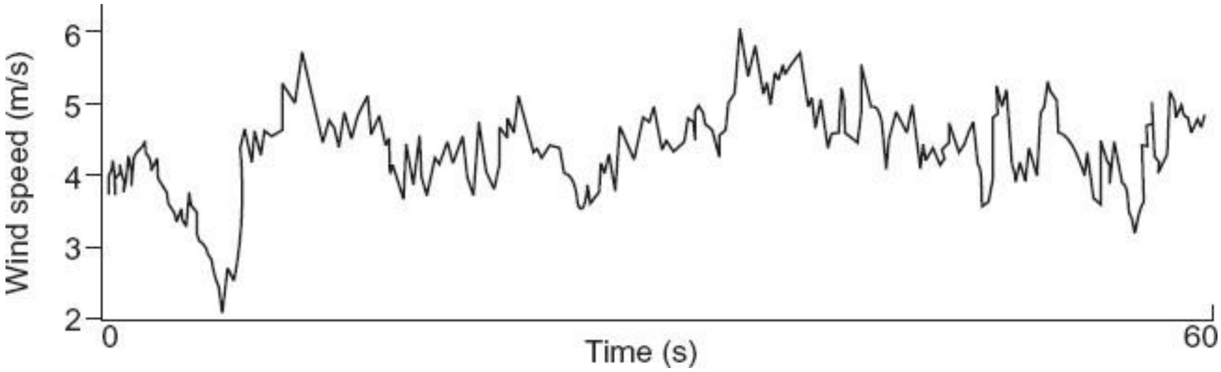


Fig. 2.3 Typical anemometer recording of wind speed versus time

It is clear that this plot is too wavy and irregular for us to obtain any useful information from it. The next step is to obtain, from Fig. 2.3, the plot of wind speed v versus the total time during a year for which the wind speed is v (Fig. 2.4), called the wind speed distribution curve. Of course, the period of time for which the wind speed assumes an exact value is infinitely small. So, the vertical axis actually gives the annual duration for which the wind speed falls within certain limits, for instance 0.5 m/s below and above v. The y-axis of the wind speed distribution curve should be given in hours per annum per metres per second. Thus the integral of the function (or the area under the curve) will always be 8760 hrs, corresponding to the number of hours in a year.

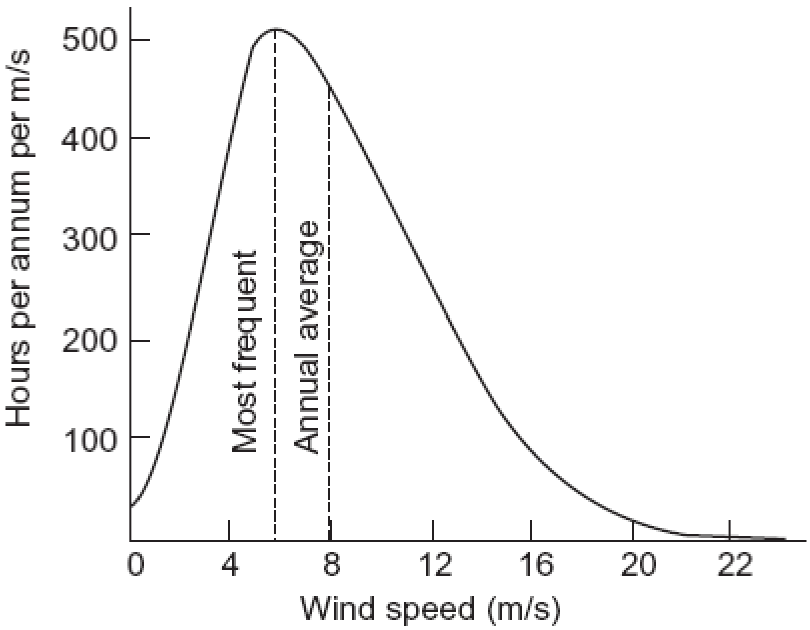


Fig.2.4: Plot with wind speed on the *x*-axis and the duration in a year for which wind assumes that speed on the *y*-axis

It is easy to plot the energy distribution curve for a site—the energy available at a particular wind speed is the power contained in the wind (proportional to v3, the value of the proportionality constant is unimportant for our purpose) multiplied by the duration for which wind blows at that speed. This curve, shown in Fig. 2.5, below gives the value of the wind speed at which the maximum energy is available—it is the wind speed at which the wind turbine should normally be rated. Note that the wind speed for maximum energy is different from and higher than the most frequent wind speed.

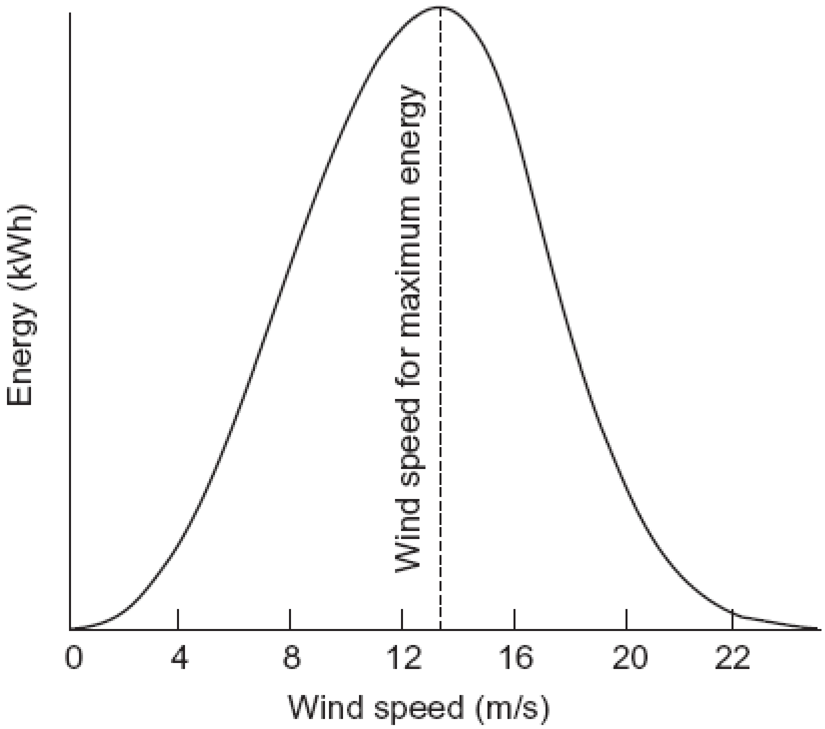


Figure 2.5: The Energy Distribution Curve

Statistical Wind Speed Distributions:

In certain cases, the total data of wind speeds against time over a year may not be available, but the yearly average wind speed may be known. In such cases, the wind speed distribution curves can be obtained approximately from the magnitude of the average wind speed, by using a standard statistical distribution function, such as the Rayleigh distribution function. It is observed that the wind speed distributions of different sites have certain similarities and can be approximated by the Rayleigh distribution function.

where t is the time (hours per year), v is the wind speed (m/s), and v is the annual average

$$t = 8760 \frac{\pi}{2} \frac{v}{\overline{v}^2} \exp\left(\frac{-\pi v^2}{4\overline{v}^2} \right)$$

wind speed (m/s). Equation (2.4) predicts the total number of hours per year for which wind will blow at speed *v* at a site with mean wind speed *v*. It can be shown analytically that for a Rayleigh distribution, the most frequent wind speed occurs at vmf = 0.8v and the maximum energy is available at 1.6 v. These relations give a very quick method of finding the wind speed at which the maximum energy is available, that is, the speed at which a wind turbine should be rated. It should be noted, however, that the Rayleigh distribution becomes inappropriate at wind speeds below 10 mph, and therefore should not be used for sites where the mean annual wind speed is below 10 mph.

A more general distribution function is required to obtain a better approximation for wind speed distribution on a daily or a still shorter time scale. In such cases, one may apply the Weibull distribution, given by:

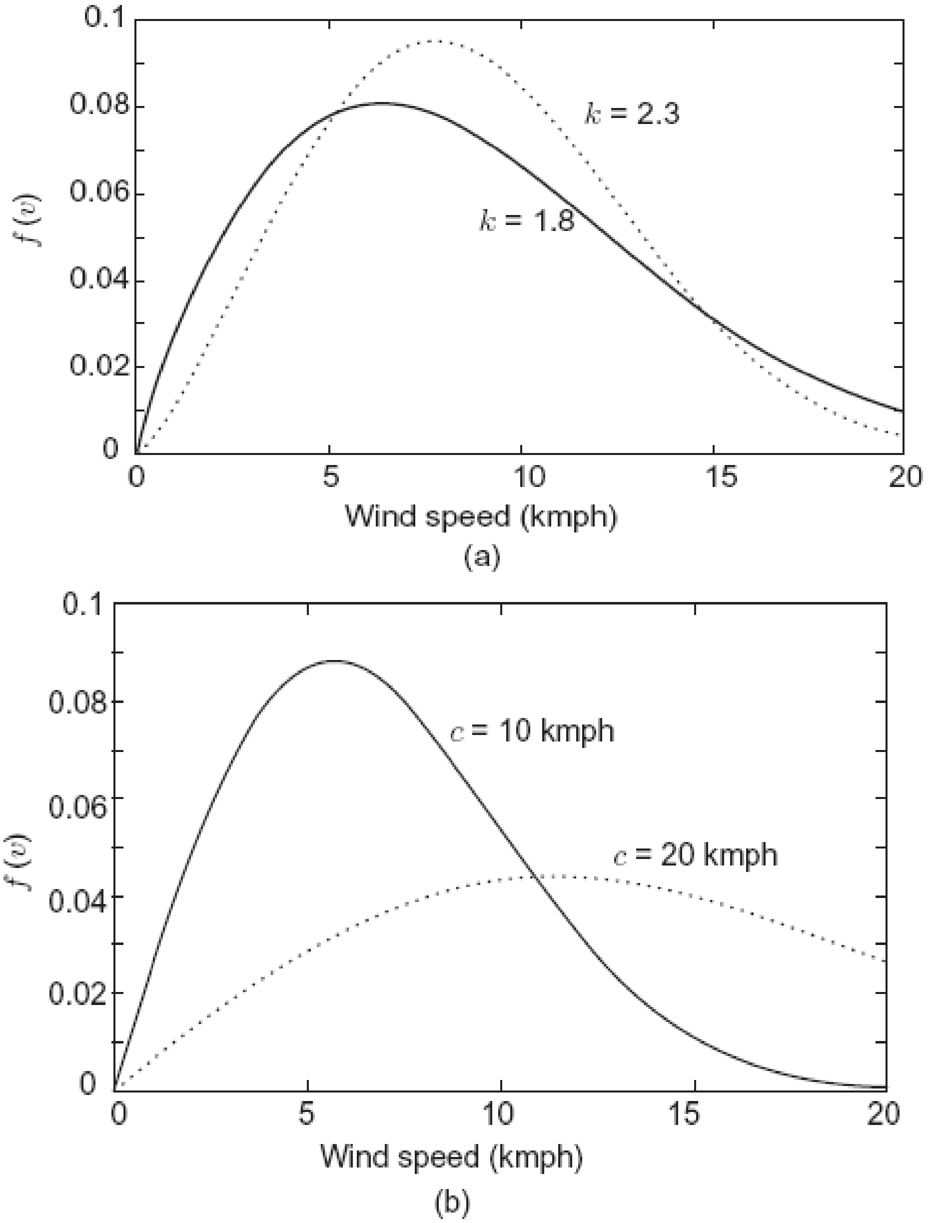
$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$$

where c is a scale factor often taken equal to the mean wind speed calculated at hub height, k is the shape factor, ranging between 1.8 and 2.3, and

$$f(v) = \frac{\text{fraction of time the wind speed is between } v \text{ and } (v + \Delta v)}{\Delta v}$$

The curves calculated using Eqn (2.5) with k = 1.8 and k = 2.3 are shown in Fig. 2.6(a). The value of k is chosen to fit the actual curve in the best way. It may be noted that for k = 2, the Weibull distribution reduces to the Rayleigh distribution when converted into the proper units.

The dependence of the distribution function on the choice of the scale factor c is shown in Fig. 2.6(b). For greater values of c, the curve shifts to the right, to higher wind speeds, which implies that high wind speeds are experienced for a greater number of days. As stated earlier, a good choice of c for a particular site is the annual average wind speed v.



The Weibull distribution for (a) $k = 1.8$ and 2.3, with c set at mean wind speed $v = 10$ kmph, and (b) $c = 10$ and 20 kmph, with k set at 2

We can get an idea about the energy potential of a site from the root mean cube (rmc) speed, which is given by:

$$V_{\mathrm{rmc}} = \left(\frac{1}{8760} \int_0^\infty f(v) v^3 dv \right)^{1/3}$$

In terms of discrete observations of anemometer readings, the rmc wind speed can be calculated using the formula

$$\overline{v} = \left(\frac{\sum_{j=1}^{N} V_j^3}{N} \right)^{1/3}$$

where Vj is the wind speed at the jth observation and N is the number of wind speed observations. The value of Vrmc is very useful in estimating the annual average power of a site, given by:

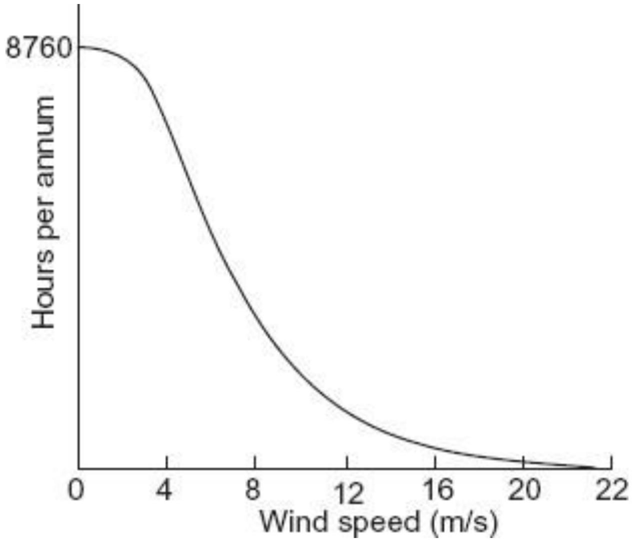
$$P_{\mathrm{rmc}} \approx \frac{1}{4} \rho \, V_{\mathrm{rmc}}^3 \ (\mathrm{W/m^2})$$

We thus obtain, either from direct measurement or by using this statistical distribution formula, the wind speed distribution curve shown in Fig. 2.4.

Site and Turbine Selection:

Site selection involves not only the choice of the geographical location for a wind turbine or a wind farm, but also the model of the turbine that is best suited to a particular site.

For the final selection process, that is, while choosing the wind turbine that is best suited for a particular site, a modification of the curve shown in Fig. 2.4 is necessary. At this stage, we plot the speed–duration curve—the graph of v versus the total duration for which the wind speed exceeds or equals v (Fig. 2.7). Naturally, the largest coordinate on the y-axis is the number of hours in a year (8760), when the wind speed exceeds zero. If the wind speed is measured using a digital recorder with data logging facility, the wind speed distribution and duration curves can be obtained directly or generated by a computer later using the stored data.



wind speed along the *X-axis* and the duration for which the wind speed equals or exceeds that speed along the *y*-axis

The productivity of any wind generator at a particular site depends on the characteristics of the site (given by Fig. 2.7) and those of the wind machine. The latter are given as the power versus wind speed characteristics (such as that shown in Fig. 2.8), which are generally available for all commercially produced wind machines.

Every wind turbine model has a specific cut-in speed, a rated speed, a furling speed, and power versus wind speed characteristics within the wind speed range between the cut-in speed and the furling speed. At the cut-in speed the wind generator starts generating power. As the wind speed increases, the power output increases in proportion with the power contained in the wind.

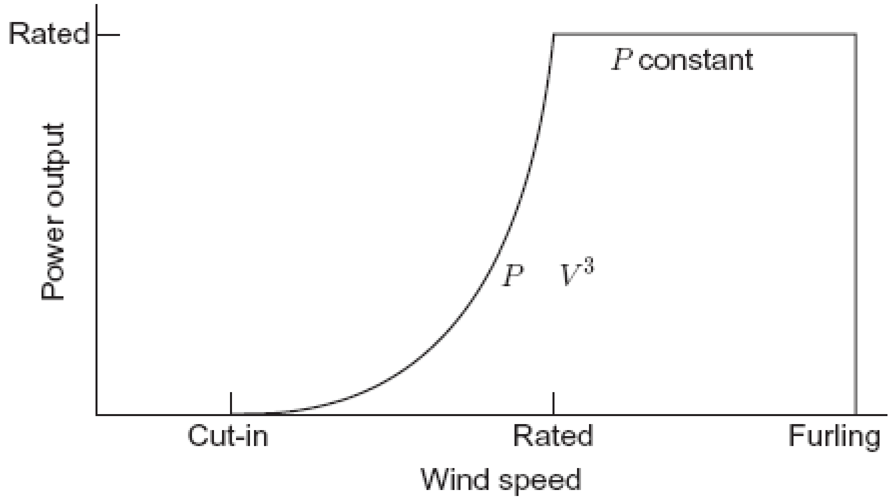


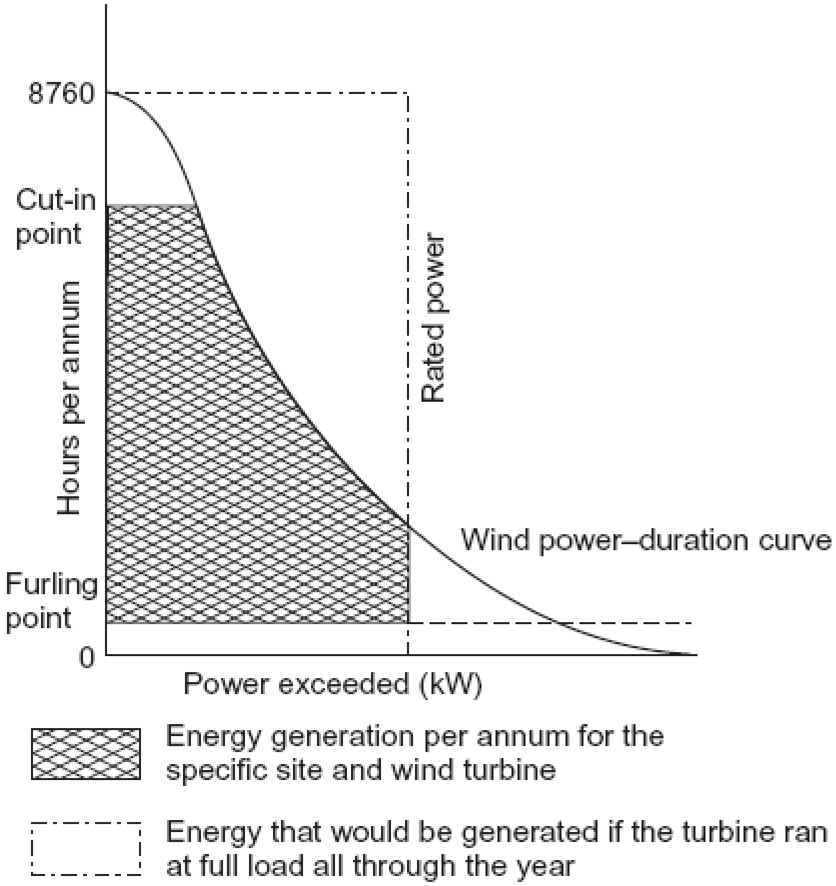
Fig. 2.8: **Typical power versus wind speed characteristics of constant-speed wind machines**

After the rated speed is reached, the speed-regulating mechanism comes into action, and there is a region of constant speed. Beyond a certain wind speed, the maximum power handling capacity of the generator is reached, and thereafter the system works in the constant-power output mode. In some machines the constant speed region is small (or negligible) and the speed-regulating mechanism works only in constant-power mode. In such cases the characteristics can be approximately expressed as:

$$P(v) \approx \begin{cases} 0.5\eta_v C_p \rho A v^3 & \text{for } V_c \leq v < V_r \\ 0.5\eta_v C_p \rho A V_r^3 & \text{for } V_r \leq v < V_f \end{cases}$$

where Vc is the cut-in speed, Vr is the rated speed, Vf is the furling speed, ηv is the efficiency of generator and mechanical transmission, Cp is the wind turbine coefficient of performance, ρ is the density of air, A is the blade swept area, and v is the wind speed. At the furling wind speed, the plant is shut down to avoid damage.

From Figs 2.8 and 2.7, the wind generator’s characteristics, as weighted by the site’s wind speed–duration curve, yield the power–duration characteristics. For each value of wind speed shown in Fig. 2.7, the corresponding value of the output power is obtained from Fig. 2.8. The typical output power–duration curve for a wind turbine is shown in Fig. 2.9. To illustrate, we have also shown the wind power–duration curve (obtained by the relation $0.5\eta vCp\rho Av3$), so that the energy loss due to cut-in and furling becomes clear.



The output power–duration characteristics of a wind generator at a given site

The area under the output power–duration curve measures the energy output of a particular machine at a given site. By plotting similar curves for different machines at a particular site, one can choose the appropriate machine. One generally chooses the model that gives the maximum output for a specific rated power at a particular site.

Capacity Factor

Wind power plants differ in a variety of ways from power plants that burn fuel. In spite of the downtime in a year, a coal plant can be run day and night at almost its rated capacity during any season of the year. In contrast, the wind speed varies with the time of the day and with the season. At times the wind speed may even be insufficient to drive the turbine. Consequently, a wind turbine cannot operate 24 hrs a day, 365 days a year at full power. A wind farm generally runs 65–80% of the time in a year with variation in output power. Because wind farms get paid for the total energy production, the annual energy output is a more relevant measure for evaluating a wind turbine than its rated power at a certain speed.

The term capacity factor refers to the capability of a wind turbine to produce energy in a year. It is defined as the ratio of the actual energy output to the energy that would be produced if it operated at rated power throughout the year. Capacity factor=(Annual energy output)/ (Rated power × Time in a year)

Thus, the capacity factor is the ratio of the average output power, computed over a year, to the rated power. The capacity factor is influenced by the same factors that affect the production of electricity by a wind turbine. These factors include the mean wind speeds at different hours of the day, the type and characteristics of the turbine (such as the cut-in, rated, and furling speeds), and the nature of the variation of output power between the cut-in speed and the rated speed.

The average power output from a wind turbine is obtained from the product of the power produced at each wind speed and the fraction of time for which this speed prevails, integrated over all possible wind speeds. In terms of the probability distribution f(v) of the wind speed–duration curve, the average power is given by :

$$P_{\text{avg}} = \int_0^\infty P(v)f(v)\,dv$$

When the total data of wind speeds over a year are not available but the yearly average wind speed at a particular site is known, the Weibull distribution function given by Eqn (2.5) may be used instead of f(v). The equation describing the variation in output power between the cut-in and furling speeds is given by Eqn (2.18). Substituting P(v) from Eqn (2.18) into Eqn (2.19) and dividing the result by the rated power, we get the capacity factor (CF):

$$\mathrm{CF} = \frac{1}{V_r^3}\int_{V_c}^{V_r} v^3 f(v)dv \, + \int_{V_r}^{V_f} f(v)dv$$

If a closed form expression cannot be obtained after integration, numerical integration will be required. Capacity factors of successful wind farms usually lie in the range 0.20–0.35, which is quite low compared to the capacity factors of 0.5–0.75 for fossil fuel plants.

Summary:

This chapter introduces the various techniques of wind speed measurement. Of these techniques, the Robinson cup anemometer is most popular, because the output is obtained in the form of an electrical signal. Data loggers can then be used to keep a record of the wind speeds occurring at short time intervals, which can later be loaded into a computer for further analysis.

The chapter also introduces the techniques of analyzing the mass of data that is obtained from direct measurement at any given site. Statistical techniques to obtain the approximate wind speed distribution curve at any site are presented.

A major problem faced by wind system planners is to choose a wind turbine that will suit the specific characteristics of a particular site. The technique to achieve this matching has also been introduced.

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UNIT – IV – HYDROGEN PRODUCTION AND STORAGE – SEEA3010

UNIT-IV

Hydrogen Production

Hydrogen holds great promise as a fuel, especially in connection with fuel cells. It could play an important role in powering land vehicles, sea vehicles, as well as large air- and spacecraft, and in serving industrial and domestic heat and electricity generation needs. Hydrogen also offers opportunities as a mean for transporting large quantities of energy over long distances. In this chapter, we look into different approaches of hydrogen production namely

chemical,

electrolytic,

thermolytic,

photolytic,

and photobiologic.

Hydrogen is, at best, an excellent vector of energy. It holds great promise as:

1. fuel for land and sea vehicles, especially when used in high efficiency fuel cells,

2. fuel for large air- and spacecraft owing to its high energy-to-weight ratio when in cryogenic form,

3. industrial and domestic fuel for generation of heat and electricity,

4. a means for transporting large quantities of energy over long distances.

The advantages of hydrogen include:

1. **Low pollution.** Hydrogen burns cleanly, producing only water. It is true that depending on the flame temperature when burned in air, small amounts of nitrogen oxides may also be generated. Pollution, however, may be associated with some hydrogen production processes.

2. **Controllability.** At ambient temperatures, hydrogen reacts extremely slowly with oxygen. Catalysts permit adjusting the reaction speed over a large range from very low temperature flames to intense ones.

3. **Safety.** Hydrogen’s reputation as a dangerous gas stems mostly from the spectacular 1937 explosion of the Hindenburg in Lakehurst, New Jersey, when 36 people were killed. Yet, a good case can be made that the explosion actually proved how safe the gas is. Indeed, the Hindenburg carried 200,000 cubic meters of hydrogen, equivalent to 2.5 × 1012 joules of energy. An energetically equivalent amount of gasoline would correspond to over 80 cubic meters, which could form a pool of fiery liquid covering the area of some 15 football fields.

a. Being the lightest of all gases, it quickly rises and disperses, while liquid fuels form pools that spread the fire.

b. The smallness of the hydrogen molecule causes this gas to leak easily through tiny cracks and holes, making it difficult to accumulate in explosive concentrations.

c. Owing to its low density, a given volume of hydrogen contains little energy and thus represents a much smaller hazard than natural gas or gasoline (the vapor of the latter contains 20 times the energy of H2 on the same volume basis).

d. At 1 atm, the autoignition temperature for hydrogen is about 580◦C, whereas that for gasoline is as low as 260◦C. The likelihood of accidentally starting a fire is much higher with the latter fuel.

e. Hydrogen-air mixtures with less than 4.1% fuel (in volume) will not catch fire, while the flammability limit for gasoline is 1%. f. A pure hydrogen flame radiates little energy, allowing firemen to approach much more closely the site of a fire.

g. Hydrogen is totally nontoxic and can be breathed in high concentration (of course, it can asphyxiate you and can also cause you to explode if hydrogen-filled lungs are accidentally ignited).

Hydrogen production can fall into one of several categories, among which one can list:

1. Production of hydrogen in massive amounts at stationary plants as, for instance, in the production of ammonia.

2. Production of hydrogen in small amounts by compact on-board plants for use in fuel cell vehicles. This last application is only now being developed and promises to become of significant economic interest.

3. Production of hydrogen in modest amounts for the food industry and other small consumers. Frequently, electrolytic processes discussed later on are employed because they yield purer gas.

4. Production of hydrogen for use in compact residential or local electricity (and hot water) generation.

4.1 Chemical Production of Hydrogen

Hydrogen balloons were introduced surprisingly early—on December 1, 1783, only 10 days after the first manned hot-air flight, Jaques-Alexandre-César Charles and one of the Robert brothersc made their ascent. The test was a little too successful; after a short trip, Robert disembarked to salute the onlookers, causing the lightened balloon to rise quickly to 2700 m, carrying the flustered Charles, who, eventually, opened a valve dumping some hydrogen and returning safely to the ground. Charles is the physicist celebrated in “Charles’s law” (1787), which states that the volume of a fixed amount of gas at constant pressure is proportional to the temperature. This is, of course, a part of the ideal gas law.

Early on, hydrogen was produced by passing steam over red-hot iron filings. The iron combines with oxygen in the water, liberating hydrogen

$$3Fe + 4H_2O \rightleftharpoons Fe_3O_4 + 4H_2.$$

The gas was then washed by bubbling it through water. The iron oxide formed is the ferrosoferric oxide in which iron appears in two different states of oxidation—ferrous" (iron II), usually forming pale green salts, and "ferric" (iron III), usually forming yellow-orange-brownish salts. The mineral magnetite is naturally occurring Fe3O4, a compound that is also used in ferrites employed in some electronic devices. After 1850, hydrogen for balloons was frequently produced from the reaction of iron with sulfuric acid. The high price of the latter led to costly hydrogen.

The hydrogen production by chemical means can be done by

- Metal water hydrogen production
- Large scale hydrogen production

The large scale hydrogen production can be done by

- Partial Oxidation
- Steam Reforming
- Thermal Decomposition
- compact fuel processor.

In the above method of hydrogen production impurities are generated. The generated impurities can be used for producing the fuel for the chemical reaction. These methods are called

- Syngas
- Shift Reaction
- Methanation
- Methanol
- Syncrude

The device that is used to produce the hydrogen gas was invented by IdaTechcompany in USA. The device name is called as compact fuel processor.

4.1.1 Metal-Water Hydrogen Production

Small amounts of hydrogen are produced even now by making aluminum chips react with caustic soda (NaOH). This is sometimes the source of the gas used in meteorological balloons:

$$2Al + 2NaOH + 2H_2O \rightarrow Na_2Al_2O_4 + 3H_2.$$

Alternatively, one could react the aluminum with KOH:

$$2Al + 2KOH + 6H_2O \rightarrow 2KAl(OH)_4 + 3H_2.$$

Jerry Woodall of Purdue University proposes the production of hydrogen by decomposition of water using aluminum's affinity for oxygen. The basic reaction is

$$2Al + 3H_2O \rightarrow 3H_2 + Al_2O_3.$$

This reaction is strongly exothermic—it causes an enthalpy change of 812 MJ per kilomol of alumina produced, and there is a strong thermodynamic driving force (the G change due to the reaction is −864 MJ/kmol). Nevertheless, aluminum appears perfectly stable in water as attested by its common use in cooking utensils. The reason is the passivation that results from the very quick formation of a tough layer of oxide that isolates the metal from contact with the oxygen in the air. The oxide— alumina—is very hard (it is the abrasive corundume) and quite refractory (it melts at about 2330 K). It adheres strongly to the aluminum surface. Aluminum is combustible, burning with an intense flame. Fortunately, because of passivation, it is hard to ignite. Aluminum aircraft are usually safe from fire, but if the metal is ignited, they will burn spectacularly. There are substances in which aluminum can be dissolved. It makes sense that when dissolved, the aluminum, having no fixed surface which can be passivated, should react with water, producing hydrogen. Indeed, this is what happens when aluminum is dissolved in gallium—one of the few metals (together with cesium, rubidium, francium, and mercury) that are liquid at room temperature.f An alloy containing, by weight, 2.5% aluminum and 97.5% gallium remains liquid down to below 50◦C. Pouring water on this liquid causes an abundant evolution of hydrogen, consuming aluminum but leaving the gallium untouched.

The other reactions are possible between aluminum and water. In general, they can form compounds of the form AlxOyHz. In the reaction shown

$$2Al + 3H_2O \rightarrow 3H_2 + Al_2O_3.$$

in Eq. (10.4), all the hydrogen in the water becomes hydrogen gas and thus z = 0 in the aluminum compound that is formed. Petrovic and Thomas (2008) considered, in addition to the above reactions

$$2Al + 6H_2O \rightarrow 3H_2 + 2Al(OH)_3$$

and

$$2Al + 4H_2O \rightarrow 3H_2 + 2AlOOH.$$

4.1.2 Large-Scale Hydrogen Production

The bulk of the hydrogen produced in the world is made from fossil fuels. Oil, naphtha, and natural gas are still the main materials used. Owing to their growing scarcity, some effort is being made to use the more abundant coal, although the high sulfur content of many coals leads to serious ecological concerns. Hydrocarbons and alcohols, among other substances, can yield hydrogen when noncatalytically submitted to partial oxidation, steam reforming, or thermal decomposition. These processes lead to a mixture of CO and H2 called syngas. When any of the above reactions is used in a fuel processor to feed fuel cells with pure hydrogen, the efficiency, η, can be defined as

$$\eta \equiv \frac{\text{LHV of the hydrogen delivered to the fuel cell}}{\text{HHV of feedstock + HHV of fuel used for heat}}.$$

4.1.2.1 Partial Oxidation

Partial oxidation can be carried out noncatalytically (POX) or catalytically (autothermal reaction [ATR]). Partial oxidation is preferred when the raw material is a heavier fraction of petroleum, while steam reforming is more convenient for lighter ones. However, small fuel processors for automotive use based on partial oxidation of methanol are being seriously considered.

In the partial oxidation process, air is used as oxidant and this results in nitrogen being mixed with the hydrogen produced, reducing the partial pressure of the latter and, consequently, lowering the fuel cell output. Partial oxidation is accomplished by reacting a fuel with a restricted amount of oxygen:

$$C_nH_m + \frac{n}{2}O_2 \rightarrow nCO + \frac{m}{2}H_2.$$

Thus, for the case of methane,

$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2.$$

4.1.2.2 Steam Reforming

In steam reforming, the fuel reacts with water that adds its hydrogen to that from the fuel and does not introduce any nitrogen into the reformate. This contrasts with the partial oxidation process. Steam reforming of a generalized hydrocarbon proceeds according to

$$C_nH_m + nH_2O \rightarrow nCO + \left(\frac{m+2n}{2}\right)H_2.$$

This reaction is also known as the carbon-steam reaction.

4.1.2.3 Thermal Decomposition

Compounds containing hydrogen can be thermally broken down in a process known as thermal decomposition. This process to extract hydrogen is illustrated in the following example.

$$CH_3OH \rightarrow CO + 2H_2$$

$$C_2H_5OH \rightarrow CO + H_2 + CH_4.$$

4.1.2.4 Syngas

Syngas, the mixture of CO and H2 that results from all the reactions discussed so far, can be used directly as fuel. It can even be directly used in molten carbonate and ceramic fuel cells, but, owing to the presence of the carbon monoxide, it is totally incompatible with low temperature fuel cells such as SPFCs. Syngas has been used as domestic and industrial fuel, but its low energy per unit volume makes it unattractive if it has to be pumped to a distant consumer. For such application, the gas can be enriched by transforming it into methane (see Eq. (10.20)). This is the basis of many coal gasification processes. Observe that the preceding syngas is dangerously poisonous owing to the carbon monoxide it contains. An important use of syngas is as a feedstock for the production of an amazing number of chemicals. Many of these have an H:C ratio substantially larger than that of syngas. For this reason, and for its use in low temperature fuel cells, a hydrogen enriching step may be needed. This is known as a shift reaction.

4.1.2.5 Shift Reaction

The shift reaction promotes the combination of carbon monoxide with water. The result is carbon dioxide and more hydrogen:

$$CO + H_2O \rightarrow CO_2 + H_2.$$

By using the shift reaction, it is possible to adjust the H:C ratio of syngas over a wide range of values. For fuel cells, the shift reaction is used to (nearly) eliminate all the CO.

In fixed installations, the heat necessary for the reaction to proceed comes, usually, from the combustion of hydrocarbons

$$C_nH_m + (n + \frac{m}{4})O_2 \rightarrow nCO_2 + \frac{1}{2}mH_2O.$$

In the more compact automotive and residential uses, the heat may conveniently come from the combustion of part of the hydrogen in the reformate

4.1.2.6 Methanation

The transformation of syngas into methane, part of the process of transforming any fossil fuel into the (usually) more valuable "natural gas," is called methanation. Besides being of great industrial importance, methanation is of interest to us in this text because it provides a technique for eliminating most of the CO impurity from the stream of hydrogen produced from carbon-bearing fuels. The methanation reaction is

$$CO + 3H_2 \rightarrow H_2O + CH_4.$$

This is the reverse of steam reforming of methane (Eq. (10.12)). Incidentally, carbon dioxide can also be transformed into methane:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O.$$

4.1.2.7 Methanol

Methanol may become the fuel of choice for fuel cell cars. It can be produced from syngas:

$$CO + 2H_2 \rightarrow CH_3OH.$$

This reaction, discovered in 1902 by Sabatier and Sedersens, is the base of the Fischer–Tropsch process that attained such fame in Germany during World War II, generating liquid fuels from coal. The plant that produces methanol bears a strong resemblance to an ammonia plant. The difference lies in the type of syngas and in the catalysts used in the reactor

It should be pointed out that the end product of syngas-based products is controlled by adjusting temperatures and pressures and by the choice of catalysts. Methanol can also be produced directly from biomass such as wood.

4.1.2.8 Syncrude

Syncrude is the term that describes the liquid products resulting from coal liquefaction. Liquefaction is a more efficient process of converting coal than gasification. It requires little water and can use all

sorts of coal, including bituminous coals that tend to cake when submitted to gasification. There are essentially four syncrude processes:

1. The Fischer–Tropsch process similar to that used for production of methanol. Here, however, selectivity is not desired: Instead of pure methanol, the process yields a complex mixture of hydrocarbons.

2. Pyrolysis, the destructive diluent distillation of coal in the absence of air, results in gases, liquids, and solids (char). Coal is flash-heated because prolonged heating will cause the liquid fraction to crack, forming gases.

3. Direct hydrogenation of coal.

4. Solvent extraction of liquids. The solvents used are produced in a preliminary direct hydrogenation step.

4.2 Compact Fuel Processors

Compact fuel processors for use in automobiles or for residential applications are vigorously being developed at the moment. Much of the work has been concentrated on adapting the classical industrial hydrogen production techniques to the much miniaturized requirements of the in situ hydrogen generators for automotive uses.

$$CH_3OH \rightarrow CO + 2H_2.$$

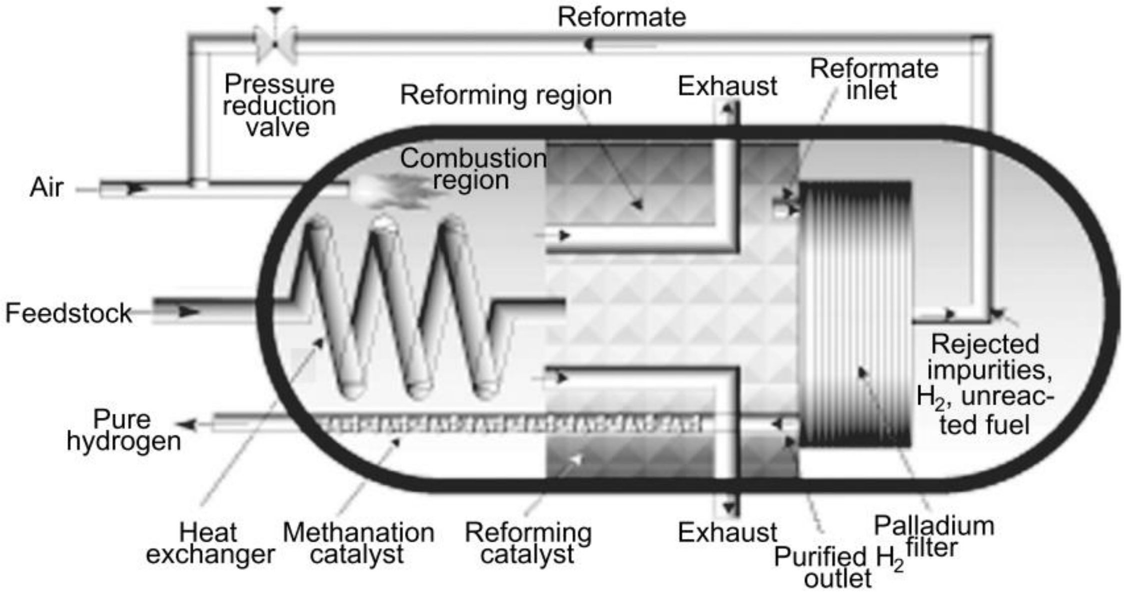
If the methanol were evaporated and burned, it would yield (see Table 10.1) 676.34 MJ per kilomol of water vapor being produced. If the alcohol is first decomposed, then the resulting 2 kilomols of hydrogen would yield 2 × 241.82 = 483.64 MJ, while the carbon monoxide would yield an additional 282.99 MJ, for a total of 766.63 MJ.

It is important to get rid of much of the CO and to extract additional H2. This can be accomplished by employing a shift reaction,

$$CO + H_2O \rightarrow CO_2 + H_2.$$

The overall reaction is

$$CH_3OH + H_2O \rightarrow CO_2 + 3H_2,$$



Fuel processor diagram

IdaTech (of Bend, Oregon) has developed a series of processors that work in the lines of the above example. They can handle different fuels, such as methanol, methane, and others. Refer to the above. An equimolar pressurized methanol-water mixture, or equivalent feedstock, is forced into the reforming region having first been heated and vaporized in a coil-type heat exchanger exposed to the high temperature of the combustion region. In the reforming region, the methanol is converted to H2 and CO. The latter is water gas shifted into CO2 and more hydrogen. However, considerable amounts of impurities are left. To separate the hydrogen from these impurities, part of the gas is allowed to pass through a palladium filter that is selectively permeable to H2. A small part of the hydrogen produced in the reforming region (mixed with the rest of reformate leftover gases), instead of going through the palladium membrane, is forced out into the combustion region, where it burns, combining with air introduced into the apparatus by means of a blower.i A spark igniter, not shown in the figure, starts the combustion. This hydrogen (part of the nonpurified reformate) provides the energy necessary to drive the reforming reaction. No external source of heat is needed, except during start-up. At start-up, a small electric heater raises the temperature of the reforming region to initiate the reaction. Start-up times as short as 3 minutes have been demonstrated.

4.3 Hydrogen Purification

Hydrogen derived from electrolysis comes close to being acceptably pure when leaving the electrolyzer. On the other hand, when hydrogen is derived from fossil fuels, it is accompanied by many impurities, including massive amounts of CO2, objectionable traces of CO, and, in some processes, large amounts of nitrogen. In addition, the feedstock itself may contain undesirable components, such as sulfur, which must be removed prior to processing.

The impurities in hydrogen gas are sulphur, CO2, and CO(carbon Manoxide). Hence this impurities have to be removed.

4.3.1 Desulfurization

If the feedstock is in gaseous form, sulfur can be removed by spraying it with a calcium-based (limestone, for instance) slurry. The SO2 in the gas reacts with the slurry, producing sulfites or sulfates which are then removed. Molybdenum disulfide catalysts containing small amounts of cobalt or nickel can be used to convert sulfur-bearing molecules in heavy crude into H2S gas. A number of other desulfurization processes exist.

4.3.2 CO_2 Removal

Syngas and biogas (see Chapter 13) contain large percentages of carbon dioxide which, at best, acts as a diluent. In the presence of water, a destructive acid is formed that can damage equipment and pipelines. Removal of CO2 is a technique central to sequestering schemes aimed at reducing CO2 emissions. The removal can be accomplished by a number of processes, including:

1. Chemical methods that use, for example, calcium hydroxide to absorb the carbon dioxide, forming calcium carbonate. In a later step, the carbonate is regenerated to hydroxide.

2. Physical processes called temperature swing adsorption (TSA) that take advantage of the solubility variation of CO2 with temperature. The solvents may be water, methanol, or one of the three ethanol amines (mono- [MEA], di- [DEA], and tri- [TEA]).

3. Currently, the most popular technique is pressure swing adsorption (PSA), which employs the ability of certain substances such as some zeolites to selectively adsorb carbon dioxide (or some other substances) at high pressure and then desorb them when the pressure is lowered. In an effort to design better adsorbers, organic molecules are being investigated.

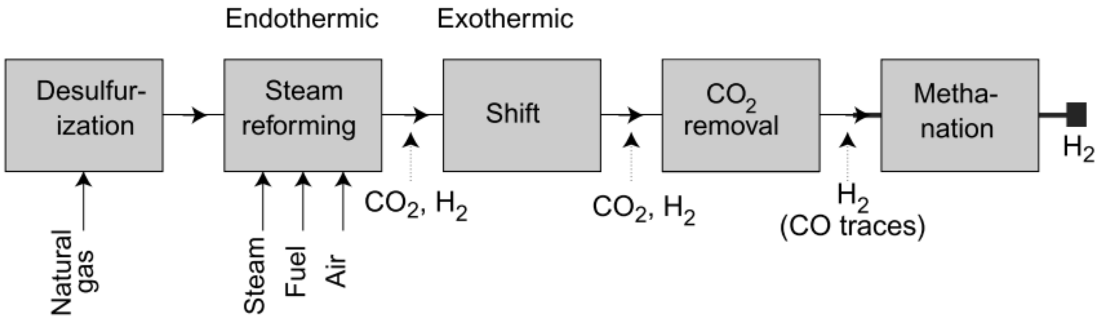
4. Special membranes (cellulose acetate, for example) displaying higher permeability to carbon dioxide than to other molecules perform partial removal of CO2. This selectivity cannot be due to pore sizes because CO2 is a relatively large molecule. The membranes do not act as filters—they are nonporous. Carbon dioxide dissolves into the membrane, diffuses through it, and emerges on the other side. Some of the useful gas is lost in the process: 85% can be recovered if 3% CO2 is tolerated in the exhaust, and 90% to 92% is recovered if 8% CO2 in the exhaust is acceptable.

4.3.3 CO Removal and Hydrogen Extraction

Hydrogen extraction (with the removal of most of the CO) can be achieved by means of metallic membranes that allow the passage of H2 but not of other gases. Again, although known as “filters,” they are nonporous and depend on the dissociation of H2 into H, which then forms a hydride (see Chapter 11) that diffuses rapidly through the sheet and reconstitutes the molecular hydrogen on the other side. This is a two step mechanism: the dissociation and the hydridization and diffusion. Tantalum allows the second step to proceed efficiently but is a poor catalyst for the dissociation. Palladium performs both steps very well but is expensive. One possible solution is the use of tantalum with a very thin palladium plating. Since hydrogen tends to embrittle the palladium, the latter is alloyed with gold, silver, or copper.

Sizable flow rates through the membrane without excessive pressure differentials demand small thicknesses. This economizes palladium but can result in very fragile sheets which may have imperfections in the form of minute pinholes. Unwanted gases seeping through such pinholes destroy the selectivity of the “filter.” Deposition of very thin but very uniform layers of palladium on top of a high porosity substrate may solve the problem. The degree of undesirable porosity of the membrane can be inferred from a measurement of a helium flux through it. Helium, unlike hydrogen, can only cross the membrane by passing through the pinholes.

4.4 Hydrogen Production Plants

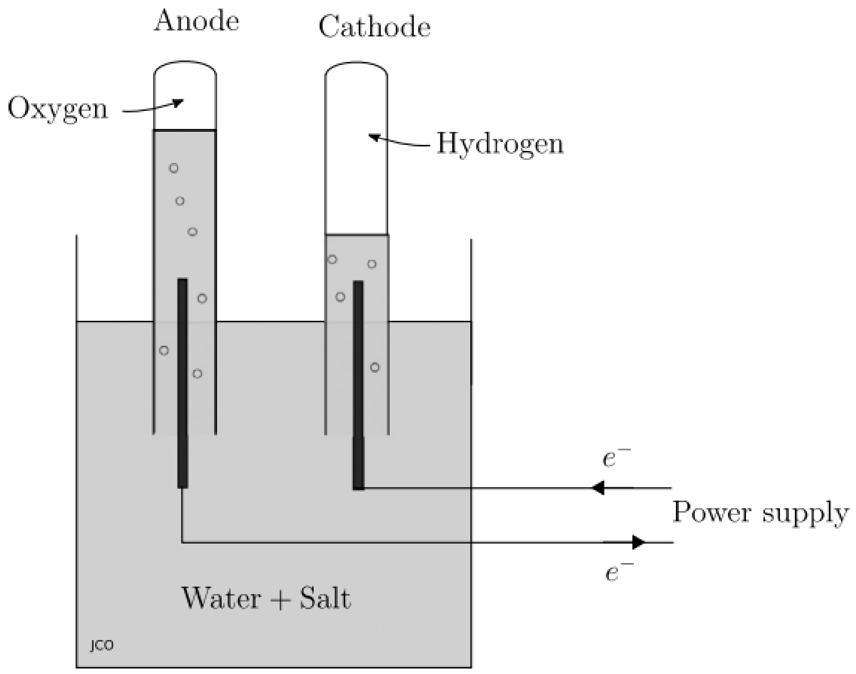


Large-scale hydrogen production starting from fossil fuels (frequently, for the production of ammonia) is a mature technology. A typical setup is shown above. The first step in the process is frequently the desulfurization of the feedstock because sulfur tends to poison the catalysts required in some of the subsequent steps. Next, syngas is produced by steam reforming. This is, as pointed out previously, an endothermic reaction that requires heat input. The shift reaction that eliminates most of the CO releases substantially less heat than that needed to drive the reforming (or decomposition) reaction. The shift reaction, being exothermic, profits from operation at low temperatures owing to equilibrium considerations. However, this influences unfavorably the kinetics of the reaction. Consequently, attention has been given to the development of good catalysts. Early catalysts based on nickel, cobalt, or iron oxide required temperatures above 700 K. Modern copper-based catalysts allow operation at temperatures as low as 520 K. After the shift reaction, the gas contains large amounts of carbon dioxide mixed with hydrogen. This requires a CO2 removal step. The final step in the hydrogen production sequence is the elimination of residual CO, which, otherwise, would alter the catalyst in the ammonia synthesis process.

4.2 Electrolytic Hydrogen

Production of hydrogen by electrolysis is a relatively old art that has found industrial application in the food industry and in other activities which need only a moderate amount of the gas. Hydrogen produced by electrolysis has the advantage of being easily purified, whereas that produced from fossil fuels tends to contain several hard to remove contaminants.

One important coming application of electrolyzers is in hydrogen gas stations for refueling of fuel cell vehicles.



Above figure illustrates a tabletop setup that can be used to demonstrate water electrolysis. A dilute salt (e.g., sodium chloride) solution is placed in a container in which inverted tubes are placed over two electrodes. These tubes will help collect the hydrogen gas produced. A power supply pumps electrons to the cathode, triggering the cathode reaction:

$$4e^- + 4H_2O(l) \rightarrow 2H_2(g) + 4OH^-(aq).$$

The dissolved ions allow current conduction to the anode, where the anode reaction takes place:

$$2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-.$$

The description above does not necessarily represent the actual sequence as the reactions may occur in steps. If we add the above equation we obtain the overall reaction:

$$6H_2O(l) \rightarrow 2H_2(g) + O_2(g) + 4H^+(aq) + 4OH^-(aq).$$

The H2 and OH− are formed at the cathode and O2 and H+ at the anode. The hydrogen ions and the hydroxide ions combine to form water:

$$H^+ + OH^- \rightarrow H_2O,$$

which would bring the overall reaction to

$$2H_2O \rightarrow \underset{Cathode}{2H_2} + \underset{Anode}{O_2}.$$

4.2.1 Electrolyzer Configurations

Electrodes must be chosen to fulfill the following requirements:

1. corrosion resistance,
2. catalytic action,
3. large surface.

In KOH electrolytes, the cathode (H2 electrode) can be made of iron because catalysis problems are minor and iron is cheap and stable in alkaline solutions. The anode is usually nickel—in general, nickel plated iron. The plating is made spongy to increase the effective surface. KOH cells present the disadvantage of being very bulky.

The different type of Electrolysers are

- Solid polymer electrolysers (SPEs)
- Ceramic Electrolyte Electrolysers
- High Efficiency Steam Electrolysers
- Concentration-Differential Electrolysers

Solid Polymer Electrolyte Electrolyzers

Solid polymer electrolyzers (SPEs) are dramatically more compact than KOH ones and do not require electrolyte controls. They can operate at much higher current densities than liquid electrolyte devices. They have the disadvantage of requiring deionized water and of producing wet gases. Ion exchange membranes are close to ideal electrolytes. Their advantages include:

1. The electrolyte can be made extremely thin, leading not only to great compactness but also to reduced series resistance owing to the short path between electrodes. Electrolyte thicknesses as small as 0.1 mm are used.
2. No diaphragm is needed: The ion exchange membrane allows the motion of ions but not of gases.
3. The electrolyte cannot move. It has constant composition, and no electrolyte concentration controls are needed.
4. There are no corrosives in the cells or in the gases produced.
5. Notwithstanding its thinness, the membrane can be strong enough to allow large pressure differentials between the H2 and the O2 sides. Differentials as large as 3 MPa (30 atm) are permitted in some cells.
6. Large current densities are possible.
7. Extremely long life (20 years?) seems possible without maintenance.

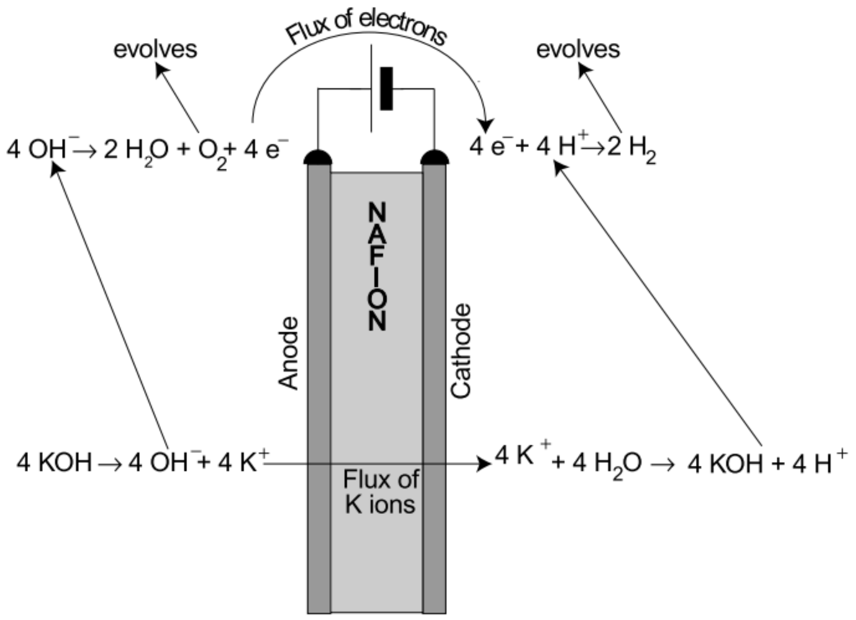
Ceramic Electrolyte Electrolyzers

ceramic fuel cells using the anion conductor yttria-stabilized zirconia as electrolyte. Cation conducting ceramics have been proposed for use in electrolyzers. They work at temperatures between 450◦C and 800◦C and use steam as feedstock but produce pure, dry hydrogen. High temperatures improve the kinetics of the reaction.
SrCe0.95Yb0.05O2.975 is an example of the material used as electrolyte.

High Efficiency Steam Electrolyzers

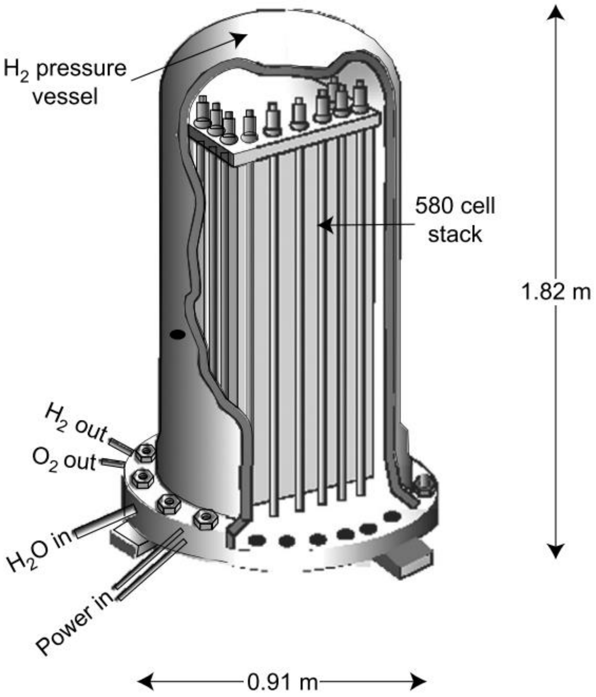
the theoretical efficiency of electrolyzers increases the hotter the device gets. For instance, at 300◦C, ηtheory = 1.20, while at 1000◦C, it is nearly 1.40. Also, there are catalysis problems that reduce the efficiency of the process. But, here too, the higher temperature helps, because catalysis improves substantially as the temperature increases. Thus, there are two important effects that suggest the use of higher temperatures in electrolysis: One is thermodynamical, and the other has to do with chemical kinetics. But there are additional advantages. Usually, the produced oxygen is simply released into the air, notwithstanding its commercial value. If this oxygen can be used in situ, the economics of the system improve. Finally, the heat exhausted from the cathode can be employed to preheat the feed water, increasing the thermal efficiency of the process. An analysis of the overall efficiency of high temperature steam electrolysis (HTSE) combined with a high temperature gas reactor (HTGR)

Concentration-Differential Electrolyzers



In a normal electrolyzer, the minimum amount of electric energy required is equal to the free energy change, G, necessary to separate water into its constituent molecules. In concentration-differential electrolyzers, part of this minimum energy can come from nonelectric sources. Consider the device shown in above Figure. It is a common ion exchange membrane electrolyzer except that the anode is in a concentrated KOH solution, while the cathode is in distilled water. As indicated in the figure, the KOH dissociates into K+ and OH−. The membrane, permeable to positive ions but not to negative ions nor to electrons, allows the migration of K+ to the cathode, where it reacts with water, regenerates KOH, and forms H+ ions. The hydroxyl ion at the anode has its negative charge removed by the external power supply and decays into water, oxygen, and electrons. The oxygen is one of the outputs of the system. The electrons, pumped by the power supply to the cathode, recombine with the protons to form hydrogen—the other output of the system.

Electrolytic Hydrogen Compression



For many applications, such as ammonia production or delivery of hydrogen to fuel cell cars, hydrogen must be available at high pressure. Thus, frequently a hydrogen plant must include a compressor. An electrolyzer can produce gases at pressures above that of the environment provided its outlets are throttled, as is the case of the Lurgi, Teledyne, and GE equipment. This, however, limits the maximum pressure to values well below those necessary in some applications. Alternatively, the pressure of the environment itself can be raised by housing the electrolyzer in a pressure vessel. For economic reasons, one needs compact equipment; otherwise, the cost of the pressure vessel becomes prohibitive.

The great advantage of electrolytic compression is the simplicity and economy in maintenance since there are no moving parts in the system.

4.3 Thermolytic Hydrogen

Thermolytic hydrogen indicates the production of hydrogen gas by using the heat energy. The thermolytic hydrogen production can be done by three methods namely

- Direct Dissociation of Water
- Chemical Dissociation of Water
- **Sulphur-Iodine Cycle**

4.3.1 Direct Dissociation of Water

Because water vapor, at high temperatures, dissociates into hydrogen and oxygen, one could, in principle, separate the gases by using something like the palladium filter discussed in the section on CO removal. Although at first glance this scheme may seem attractive, its implementation is difficult. As an experiment, introduce 1 kilomol of water vapor (and nothing else) into a cylindrical container equipped with a piston weighed down so as to maintain a constant pressure of 1 atm. The water is then heated to 3000 K. Pressure and temperature have been chosen arbitrarily to serve as an example. If all the molecules remained as H2O, one could look up their free energy by consulting an appropriate table. However, at least some of the water vapor will dissociate into its components, hydrogen and oxygen, according to

$$H_2O \leftrightarrow H_2 + \frac{1}{2}O_2,$$

and the mixture, containing H_2O, H_2, and O_2, will have a different free energy.

If the dissociation were complete, the gases in the container would consist of 1 kilomol of hydrogen and 0.5 kilomols of oxygen. The free energy of this gas (still at 1 atm and 3000 K) will be found to be larger than that of the pure H2O vapor.

4.3.2 Chemical Dissociation of Water

To circumvent the difficulties encountered with the direct dissociation of water, several chemical reactions have been proposed. In all of them, the intermediate products are regenerated so that, at least theoretically, there is no consumption of materials other than water itself. The temperatures required for these reactions must be sufficiently low to permit practical implementation of the process. In particular, it is desirable that the temperatures be low enough so that the process can be driven by some types of nuclear fission reactors. To be sure, almost all of the world’s current reactors are Generation II, III, or III+ reactors.

The chemical dissociation of water can be done by three methods namely

- Mercury-Hydrobromic Acid Cycle
- Barium Chromate Cycle
- Sulfur-Iodine Cycle

4.3.2.1 Mercury-Hydrobromic Acid Cycle

The highest temperature step operates at 730°C. Overall efficiency is 50%. The major disadvantage is the use of corrosive hydrobromic acid. Partial reactions are

$$
\begin{aligned}
&Hg + 2HBr \rightarrow HgBr_2 + H_2,\\
&HgBr_2 + Ca(OH)_2 \rightarrow CaBr_2 + HgO + H_2O,\\
&HgO \rightarrow Hg + \frac{1}{2}O_2,\\
&CaBr_2 + 2H_2O \rightarrow Ca(OH)_2 + 2HBr.
\end{aligned}
$$

The overall reaction is

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2.$$

4.3.2.2 Barium Chromate Cycle

Another, more complicated, chain of reactions for the thermolytic production of hydrogen is

Reaction 1

$$Cr_2O_3(s) + 4Ba(OH)_2(\ell) \xrightarrow{600^\circ C} 2Ba_2CrO_4(s) + 3H_2O\ (g) + H_2\ (g),$$

Reaction 2

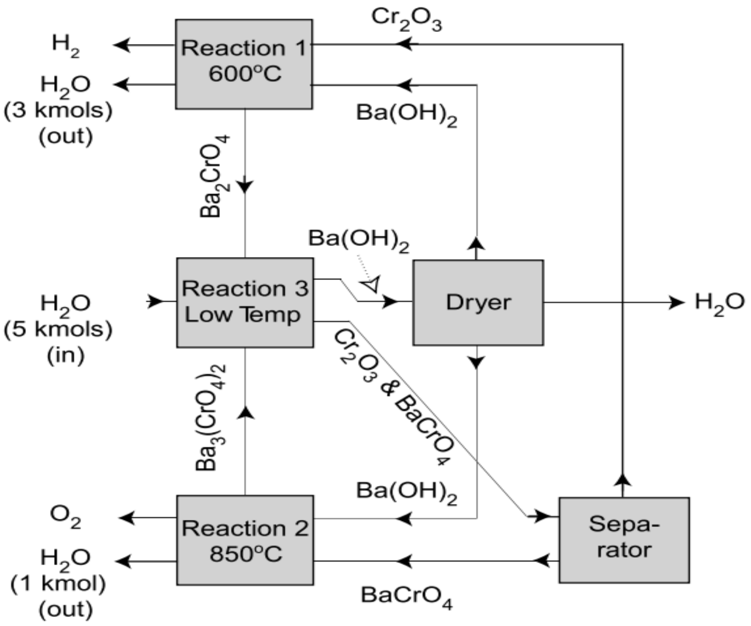
$$2BaCrO_4(s) + Ba(OH)_2(\ell) \xrightarrow{850^\circ C} Ba_3(CrO_4)_2(s) + H_2O\ (g) + \frac{1}{2}O_2\ (g)\,.$$

Note that since hydrogen evolves from Reaction 1 and oxygen from Reaction 2, which occur in different parts of the equipment, it is easy to separate these gases. Input reactants are Cr2O3 and BaCrO4. Products (besides H2 and O2) are Ba2CrO4 and Ba3(CrO4)2. To recover the reactants, the last two chromates are made to react with water at low temperature

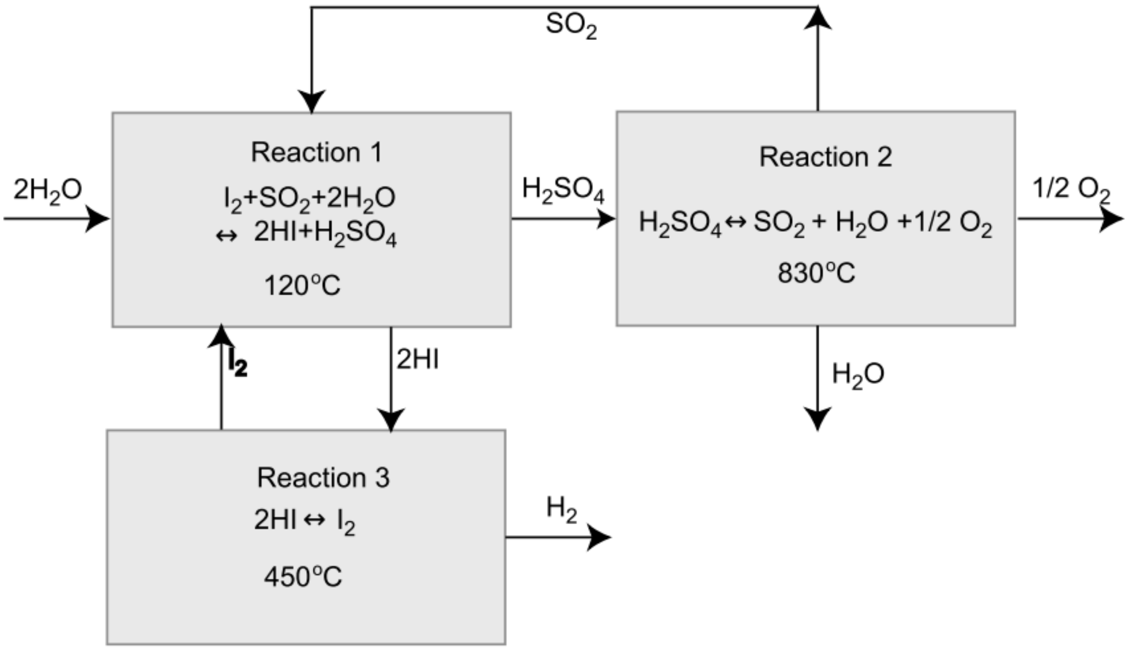
Reaction 3

$$2Ba_2CrO_4(s) + Ba_3(CrO_4)_2 + 5H_2O \rightarrow Cr_2O_3(s) + 2BaCrO_4(s) + 5Ba(OH)_2(d).$$

With the possibility of the development of advanced nuclear reactors, the cycle below has been looked at with interest.



4.3.2.3 Sulfur-Iodine Cycle



Invented in the 1970s, the sulfur-iodine cycle is being developed right now in the hope of applying it to the hydrogen production with Generation IV reactors. It consists of three reactions.

The first reaction combines iodine with sulfur dioxide and water to form hydrogen iodide and sulfuric acid. The hydrogen iodide is distilled and sent to Reaction 3 while the sulfuric acid goes to Reaction 2, where, at the high temperature of 830◦C, the acid is dissociated into sulfur dioxide (fed to Reaction 1), water (in exactly half the amount taken in by the reaction to which it is returned), and oxygen, one of the two useful outputs of the process. Meanwhile, the hydrogen iodide which found its way to Reaction 3 is thermally dissociated into iodine (returned to Reaction 1), liberating hydrogen, the main product of the system. The problem with this process is the same as other processes proposed. We are dealing with corrosives at a high temperature, which mean a requirement of special superalloys.

4.4 Photolytic Hydrogen Production

The technology for using solar light energy to produce hydrogen is well established. One certainly can produce this gas through entirely nonpolluting processes by using photovoltaic converters whose output drives electrolyzers. The main effort here is to develop processes that can accomplish this transformation more economically.

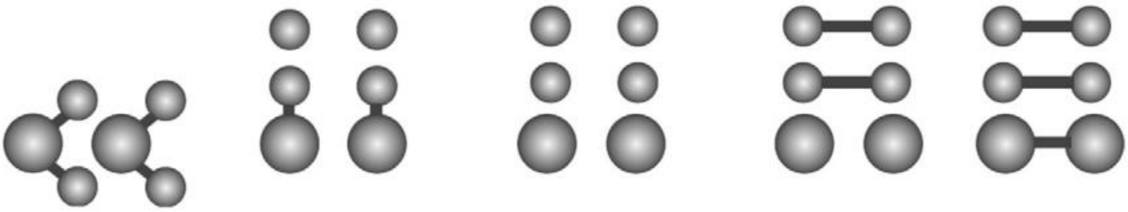
Water can be decomposed (and synthesized) according to

$$2H_2O \rightleftharpoons 2H_2 + O_2.$$

Although simple looking, the reaction is the result of a chain of events that leads through the formation of several intermediate substances and can follow different paths depending on the circumstances and the catalysts. The structural formula of water, H–O–H, suggests that the first step in the dissociation must be the breaking of the H–O bond so that H and OH (or the corresponding ions) are formed. Next, the OH is dissociated into O and another H; then these atoms coalesce into diatomic molecules. If no ionized species take part in the reactions, the different energies involved are given in Table 10.3.

Table 10.3 Dissociation energies.

	eV/molecule	MJ/kmol
$H_2O \rightarrow H + OH$	5.15	496.2
$OH \rightarrow H + O$	4.40	423.9
$H + H \rightarrow H_2$	−4.48	−431.7
$O + O \rightarrow O_2$	−5.12	−493.3
$H_2O \rightarrow H_2 + \frac{1}{2}O_2$	2.51	241.8



$$2\,H_2O \longrightarrow 2\,H + 2\,OH \longrightarrow 4\,H + 2\,O \longrightarrow 2\,H_2 + 2\,O \longrightarrow 2\,H_2 + O_2$$

$$\uparrow \qquad \uparrow \qquad \uparrow \qquad \uparrow$$

$$2 \times 5.15\text{ eV} + 2 \times 4.40\text{ eV} - 2 \times 4.48\text{ eV} - 5.12\text{ eV}$$

For direct lysis, the input energy must be 5.15 + 4.40 = 9.55 eV per molecule of water. The result is a hydrogen-oxygen mixture with 2.51 eV more energy than the initial water. The efficiency of this “fuel” production is 2.51/9.55 = 0.263. The rest of the input energy will appear as heat as the result of the back-reaction of the activated intermediate species.

4.4 Solar Photolysis

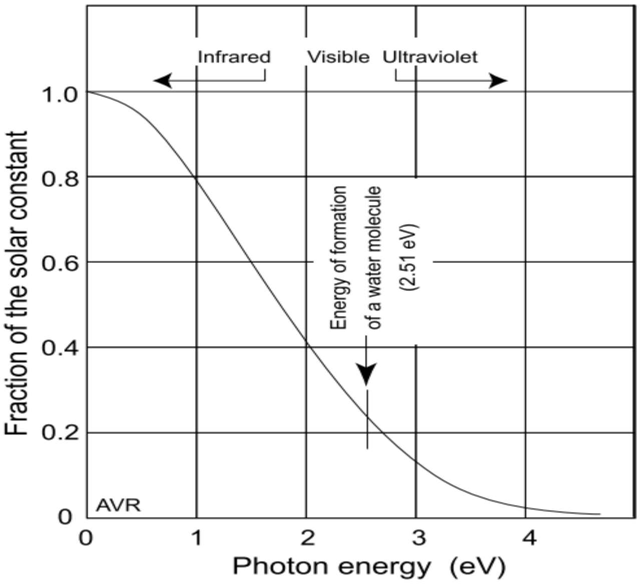


FIGURE 4.6 Cumulative energy distribution in the solar spectrum.

Fig. 4.6 shows the cumulative energy distribution in the solar spectrum. It can be seen that about 22% of the energy is associated with photons having more than 2.51 eV, the energy necessary to dissociate water. However, as was discussed in the preceding section, without catalysts, photons with more than 5.15 eV are necessary to initiate the reaction. Thus, practical photolytic hydrogen production depends on the development of appropriate catalysts.

A catalyst, X, may, for instance, be oxidized in the presence of water under the influence of light:

$$X + H_2O \rightarrow X^+ + H + OH^-,$$

$$X^+ + \frac{1}{2}H_2O \rightarrow X + H^+ + \frac{1}{4}O_2,$$

$$H^+ + OH^- \rightarrow H_2O.$$

The threshold energy for this reaction is 3.8 eV, somewhat less than the 5.15 eV necessary in the absence of catalysts. The reaction would use only 3% of the solar energy, and, of that, a great deal would be lost in the $H^+ + OH^- \rightarrow H_2O$ back-reaction. Actually, for a ground-based system, the available energy is considerably less than 3% because the higher frequencies of the solar spectrum are selectively absorbed by the atmosphere.

A somewhat more favourable reaction is one in which the catalyst, Y, is reduced:

$$
\begin{aligned}
&Y + H_2O \rightarrow Y^- + H^+ + OH,\\
&Y^- + H_2O \rightarrow Y + OH^- + \frac{1}{2}H_2,\\
&OH^- + H^+ \rightarrow H_2O,\\
&\frac{1}{2}OH + \frac{1}{2}OH \rightarrow \frac{1}{2}H_2O + \frac{1}{4}O_2.
\end{aligned}
$$

A third reaction avoids intermediate species that will back-react:

$$
\begin{aligned}
&Z + H_2O \rightarrow ZO + H_2,\\
&ZO \rightarrow Z + \frac{1}{2}O.
\end{aligned}
$$

The threshold for this reaction is 2.9 eV, and it could use 13% of the solar energy. However, its realizability is uncertain. The above energy considerations paint a dubious picture of the possibilities of using direct sunlight for the production of hydrogen. But, as usual, there many other aspects to be considered. Direct photolysis of water runs into a fundamental difficulty: Water is transparent to most of the sunlight. Only frequencies above some 1600 THz are absorbed, and this represents less than 0.01% of the solar radiation in space, and much less of the solar radiation that reaches the surface of the Earth Nevertheless, these analyses have not discouraged investigators from trying to find economical ways of harvesting solar energy transforming it into chemical energy. If a plant leaf can do it, so should we. Only by 1972 was it possible to demonstrate the dissociation of water by direct absorption of light without the help of an externally applied bias. Fujishima and Honda (1972) used an n-TiO_2 single crystal and a platinum counterelectrode in the arrangement depicted in Fig. 10.17. Titanium dioxideq was used because of its stability in liquid environments. However, it is a white pigment used in common paints. This means that it reflects all of the incident visible light, absorbing only ultraviolet of frequencies larger than 1580 THz (190 nm). This is due to its large band-gap (3 eV). Thus, titania uses only a small part of the energy available in the solar spectrum, one of the causes of the low efficiency of the Fujishima and Honda cell (<1%)

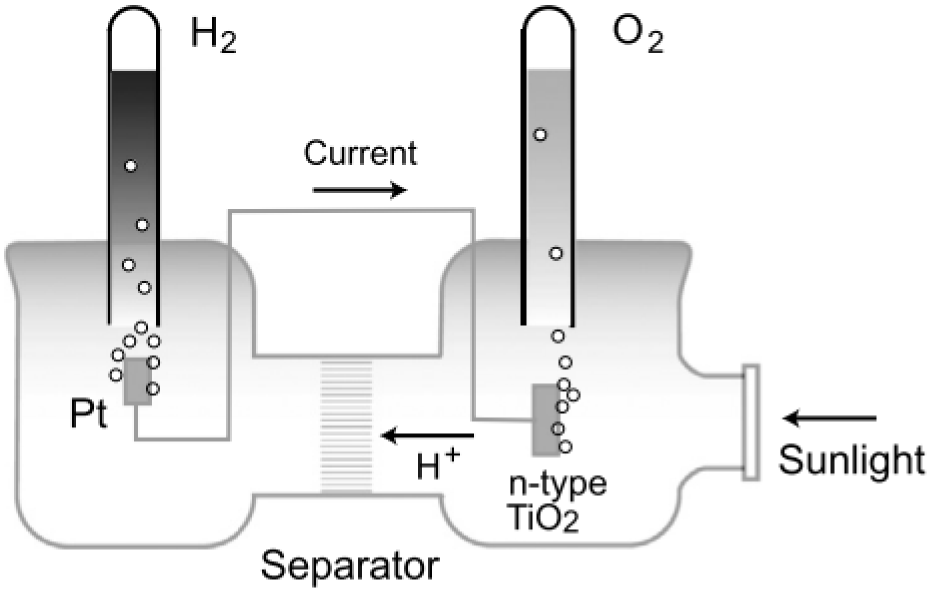


FIGURE Sunlight was used to produce hydrogen and oxygen in a 1972 experiment by Fujishima and Honda.

Titania, or any other material, dipped in an electrolyte will develop a contact potential. A transition layer in which the potential changes from that of the semiconductor to that of the electrolyte is formed on the surface. This layer is thin (a few tenths of nanometers) so the electric fields are intense. In the case of n-type titania, the direction of the field is such that the electron created by the incident photon is driven deeper into the semiconductor while the corresponding hole is injected into the electrolyte. A charge separation occurs even though there is no p-n junction. The hole injected into the (aqueous) electrolyte oxidizes the water.

$$2p^+ + H_2O \rightarrow \frac{1}{2}O_2 + 2H^+,$$

causing oxygen to evolve at the photoelectrode. Meanwhile, the proton from the above reaction migrates through the electrolyte to the platinum electrode, where it combines with the electron (that came from the TiO2 via the external connection) and is reduced to H and eventually associates to form H2, evolving at the metal electrode:

$$2e^- + 2H^+ \rightarrow H_2.$$

These results are encouraging but, owing to the low efficiency, are hardly practical.

4.5 Photobiologic Hydrogen Production

The majority of living organisms must respire—consume oxygen and release carbon dioxide—to fuel their anabolism. This is true of plants. These, however, under the influence of light, also perform photosynthesis, the opposite to respiration: They fix atmospheric carbon dioxide and release oxygen. Thus, when exposed to light, plants tend to be net oxygen producers and, in the dark, net oxygen consumers. In principle, some plants could generate the oxygen needed for their respiration by extracting it from water and releasing hydrogen. This occurs, for instance, with certain algae. Since in darkness the plant is almost dormant, the amount of hydrogen released is small. An enzyme—hydrogenase—promotes such release. Hydrogenase is inhibited by the presence of oxygen and, thus, does not work when photosynthesis is active. Sulfur deprivation reversibly inactivates photosynthesis, allowing the production of hydrogen in larger amounts when the plant is exposed to light

It has been demonstrated a photobiological hydrogen production system using the alga hlamydomonas reinhardtii. The processes proceed in two stages:

1. Algae are grown normally and build up their store of carbon compounds.
2. Sulfur is withdrawn from the system and the algae, still exposed to light, release hydrogen, consuming some of the accumulated carbon.

After Stage 2 has depleted much of the carbon, Stage 1 is reinitiated and the plant is again “refattened.” At present, it appears that substantially more research is required not only to perfect the parameters of the system but also to develop more efficient strains or algae. The overall sunlight-to-hydrogen gas efficiency will be modest because photosynthesis is less than 8% efficient (see Chapter 13) and light is needed not only for photosynthesis but also for the hydrogen release. Nevertheless, what really counts from the practical point of view is the cost of the gas produced and not the efficiency of the system. It remains to be seen if the proposed Melis system will be economically attractive.

4.6 Fuel Cells

Although fuel cells date back to 1839, when Sir William Groves demonstrated his “gaseous voltaic battery,” until recently they remained in their technological infancy. NASA revived fuel cell research: Both Gemini and Apollo used fuel cells, and so did the space shuttle. Their most important applications in the near future are as power sources for buses and automobiles, as central utility power plants, as dispersed (including residential) power suppliers, and as power sources for cell phones and other small electronic devices. In this chapter, we go over the principles behind these electrochemical energy conversion devices.

Mechanical heat engines generally use the heat released by the reaction of a chemical substance (fuel) with oxygen (usually from air). The heat is then upgraded to mechanical energy by means of rather complicated machinery. This scheme is inherently inefficient and cumbersome. It is the final outcome of our millenarian struggle to control and use fire. Converting chemical energy directly into electricity is more straightforward, especially in view of the electric nature of the chemical bond that holds atoms in a molecule. Devices that convert chemical energy directly into electricity are called voltaic cells,a a subgroup of electrochemical cells which also include devices that use an electric current to promote a chemical reaction. Such devices are called electrolytic cells or electrolyzers.

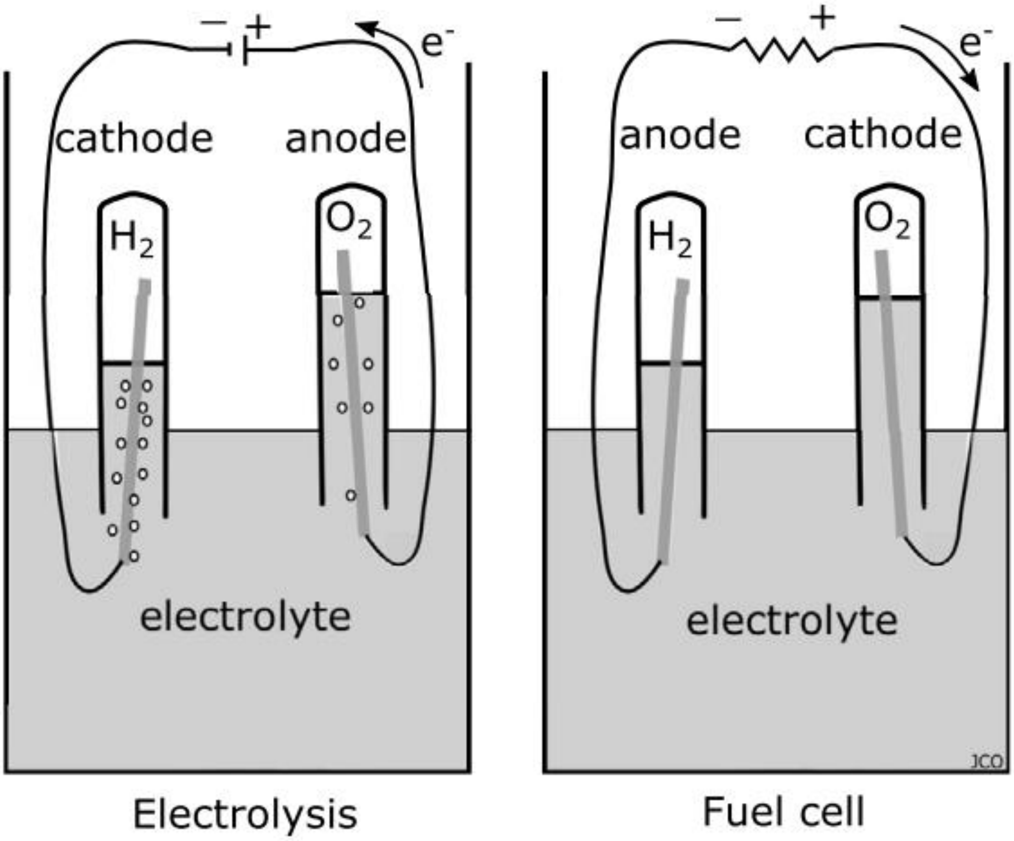


FIGURE 5.11 An electrolytic cell (left) and a fuel cell (right).

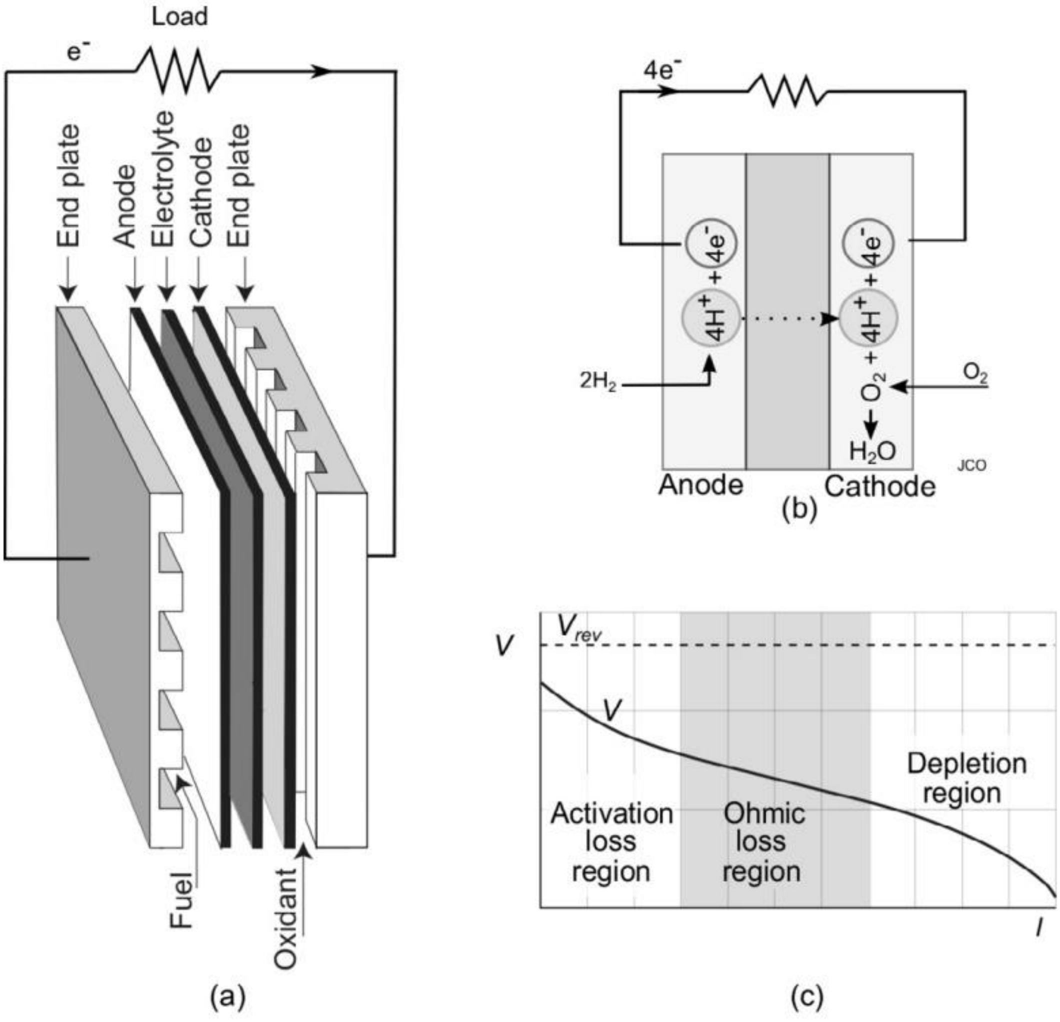
Flashlight batteries, automobile batteries, and fuel cells are examples of voltaic cells. Because voltaic cells transform chemical energy directly into electricity without requiring an intermediate degradation into heat, they are not limited by the Carnot efficiency.

The words “cell” and “battery” are, in modern parlance, interchangeable. “Cell” suggests one single unit (although “fuel cell” most frequently consists of a number of series-connected units). “Battery” suggests a number of units, but a single 1.5 V flashlight cell is commonly called a battery. If the battery is not worth preserving after its first discharge, it is an expendable (also called primary) battery. If the device is reusable after discharge, it may fall into one of two categories: 1. Rechargeable (also called secondary) devices, in which the activity is restored by means of an electric charging current, as is the case of automobile batteries. 2. Refuelable devices (fuel cells), which deliver a sustained output because their consumables are replenished. To facilitate such replenishment, these consumables are usually fluids, although some fuel cells use solid consumables, as is the case of zinc-air cells, described later in this chapter.

$$\text{Voltaic cells}\begin{cases}\text{Expendable}\\ \text{Nonexpendable}\begin{cases}\text{Rechargeable}\\ \text{Refuelable}\end{cases}\end{cases}$$

In simple terms, one can think of a fuel cell as a battery that has a continuous supply of its consumables: fuel and oxidant.

Fig. 9.2 summarizes key aspects of fuel cells that we will explore along this chapter. Fig. 9.2(a) shows a typical fuel cell planar configuration in which an electrolyte is sandwiched between two electrodes (the cathode and anode). Fuel and oxidant are replenished through channels that are part of the end plates and electrons circulate externally through the load. Fig. 9.2(b) illustrates the reactions in a hydrogen fuel cell. In this case, the fuel is hydrogen, the oxidant is oxygen, and the products are electricity and water. In this cell, the positive ions go across the electrolyte. Fig. 9.2(c) illustrates a typical fuel cell V -I response. Three regions can be identified, a region where activation losses dominate (at low currents); a region dominated by ohmic losses (at intermediate currents); and finally, at large currents, where the cell is depleted, a region dominated by concentration losses. In Fig. 9.2(c), the distance between the dashed line, representing a “no-loss” voltage, and the solid line, representing the actual cell voltage, can be interpreted as losses (e.g., see Fig. 9.32 or Fig. 9.40). In the literature, these losses are referred as overvoltages, overpotentials, polarizations, irreversibilities, voltage drops, or just losses.



(a) Basic fuel cell configuration. (b) Reactions, electrons, and ion flows in a hydrogen fuel cell. (c) Fuel cell V -I response.

Voltaic Cells

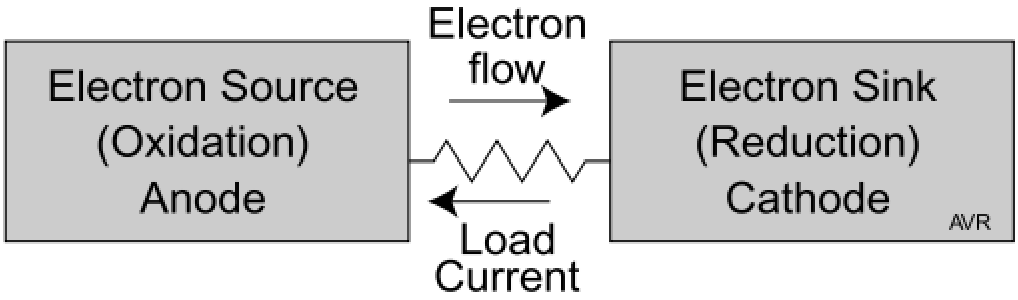
The purpose of voltaic cells is to provide a flow of electrons in an external circuit where useful work can be done. To this end, the cells must consist of a source and a sink of electrons.

The reactions used in electrochemical cells are called reduction-oxidation (redox) reactions, because the buzz word for releasing electrons is oxidation and for capturing electrons is reduction.

Oxidation and reduction

Chemical reactions occur with a change in an atomic oxidation number (redox reactions) or without such a change (metathesis reaction). A neutral element has an oxidation number or oxidation state of zero. As it undergoes a redox reaction, the element will either lose or gain one or more electrons. Loss of electrons is called oxidation, while gain is called reduction. If you heat up mercury, Hg, to some 350◦C in the presence of oxygen, O2, you will obtain a yellow/red solid, HgO. The mercury is oxidized; it loses two electrons that become attached to the oxygen, and thus acquires an oxidation state of 2. This is why the oxide, called mercuric oxide, is also known as mercury(II) oxide. If you want to reduce the oxide back to its original metallic form, you must cause the Hg2+ ion to grab back the two electrons it had lost. This can easily be accomplished by exposing HgO to concentrated sunlight. Elements that are easily oxidized furnish the electrons needed to reduce other particles—they are reductants, whereas elements that have affinity to electrons provide a way to dispose of electrons from easily oxidizable elements and are called oxidants. Oxygen is, of course, a prototypical oxidant. The word "oxygen" stems from oxús = acid or sharp, and means generator of acids, a name that appears in de Morveau and Lavoisier's "Nomenclature Chimique" from 1787, when chemists were under the wrong impression that oxygen was an essential element in acids. Actually, it is hydrogen that is essential. When an acid is dissolved in water, some of its hydrogen atoms lose their electron—the water becomes acidic; the hydrogen is oxidized. By extension, any reaction that involves the loss of electrons is called, as we explained, oxidation. The reverse reaction—gaining electrons—is called reduction.

In electrochemical cells, the full reaction is broken down into two half-cell reactions or half-reactions that occur in physically separate regions of the device. These regions are interconnected by an electrolyte that conducts ions but not electrons. The latter, having (in voltaic cells) been released by the oxidizing half-reaction, can move to the reduction side only via an external circuit, establishing the external current that is the purpose of the cell. The conventional direction of this external current is from the reduction to the oxidizing side—the current exits the device from the reduction side (cathode) and enters the device at the oxidizing side (anode), as indicated below



A voltaic cell must consist of a source and a sink of electrons.

As in any source of electricity, the cathode is the positive electrode and the anode the negative one, the opposite of what happens in sinks of electricity (loads). See the Introduction to Chapter 6 for a discussion of the words "anode" and "cathode." As an example of an electrochemical cell, consider a membrane capable of acting as an electrolyte. Put hydrogen in contact with one side of this membrane. At ambient conditions, most of the gas will be in the form of H2 molecules; however, a small amount will dissociate:

$$H_2 \rightarrow 2H,$$

and some of the resulting H will oxidize (ionize)—that is, lose an electron:

$$H \rightarrow H^{+} + e^{-}.$$

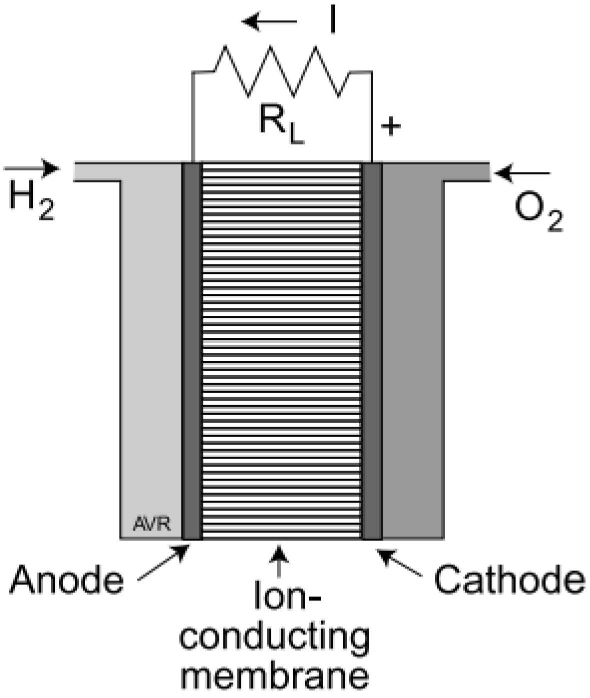
Since the membrane does not conduct electrons, the electrons will remain on its surface while the positive ions will diffuse through it and arrive at the other side. Because the ions carry a positive charge, the hydrogen side becomes negative owing to the excess electrons that remain on it and the opposite side becomes positive owing to the positive ions that arrived there. The resulting electric field causes some of the positive ions to drift back to the hydrogen side. A dynamic equilibrium is established when the diffusion exactly equals the returning drift. It is easy to calculate the potential developed (Chapter 7, Section 7.1). Now sprinkle a conducting powder on both sides of the membrane so as to create two porous electron-conducting layers (i.e., two electrodes). Interconnect the electrodes externally through a load resistance, RL. Ions cannot flow through this external connection, but electrons can and, when they do, they flow from the hydrogen side, where they are abundant, to the opposite side, establishing an electric current, as indicated in Fig. 9.4. The reaction of interest that occurs at the hydrogen electrode is

$$\underline{\text{Anode reaction}}: \qquad 2\,H_2 \rightarrow 4\,H^{+} + 4\,e^{-}.$$

The difficulty with this picture is that it contradicts the First Law of Thermodynamics in that it causes an I 2RL amount of heat to be generated in the load, while, at the cathode, the incoming electrons will combine with the H+ that diffused through the membrane regenerating the hydrogen atom, H, eventually recreating the H2 gas used as “fuel.” We would generate heat without using any fuel. The external circuit creates a path for the electrons but cannot by itself force a current to circulate, just as a pipe with one end dipped into a lake cannot cause water to flow up inside it. For the water to flow, the open end of the pipe must be lower than the surface level of the lake. Similarly, to have an external current, it is necessary to lower the (thermodynamic) potential on the cathode side. This can conveniently be done by introducing oxygen so that, combined with the electrons and the H+, water is formed

$$\underline{\text{Cathode reaction}}: \qquad 4\,e^{-} + 4\,H^{+} + O_2 \rightarrow 2\,H_2O.$$

This reaction is strongly exothermic—that is, it releases energy (not mostly as heat, as in the case of the combustion of hydrogen, but mainly as electricity). This is, of course, the energy that powers the fuel cell. The electrochemical cell just described is shown in Fig. 9.4. Under STP conditions (273.15 K, 1 atm), the degree of hydrogen dissociation at the anode is small. It can be increased somewhat by altering physical conditions (e.g., increasing the temperature). Remember Le Chatelier’s principle. It also can be increased by the action of catalysts.



The overall cell reaction is

$$2\,H_2\,(g) + O_2\,(g) \rightarrow 2\,H_2O\,(g).$$

Clearly, a voltage appears across the terminals of our fuel cell. All voltaic cells rely on the potential difference that develops when an electrode is put in contact with an electrolyte. In the text box titled “Cell potential,” we discuss this phenomenon in a simple qualitative fashion, and also point to the mechanisms that cause oxidation and reduction.

Fuel cells can be classified according to several criteria; among them are the temperature of operation, the state of the electrolyte, the type of fuel, and the chemical nature of the electrolyte. As in many technical areas, there is here a proliferation of acronyms capable of driving the uninitiated to distraction. We will use a few:

- AFC alkaline fuel cell,
- DMFC direct methanol fuel cell,
- MCFC molten carbonate fuel cell,
- PAFC phosphoric acid fuel cell,

- PEM proton exchange membrane fuel cell,
- SAFC solid acid fuel cell,
- SOFC solid oxide fuel cell (ceramic),
- SPFC solid polymer fuel cell.

4. 10 Hydrogen Storage

Hydrogen can be stored as an element or it can be extracted, as needed, from some hydrogen-rich substance using an on-board extraction process: –

Processes that alter the state or the phase of hydrogen (hydrogen only systems):

– compression of the gas, or a combination of compression and refrigeration;

– liquefaction of the element owing to its low critical temperature, hydrogen must be cooled to some 20 K to remain liquid in nonpressurized vessels.

– Processes that associate hydrogen to other substances:

– adsorption of the gas on some appropriate substrate such as activated carbon;

– chemical combination of hydrogen so as to create a hydrogen-rich compound—such compounds can be:

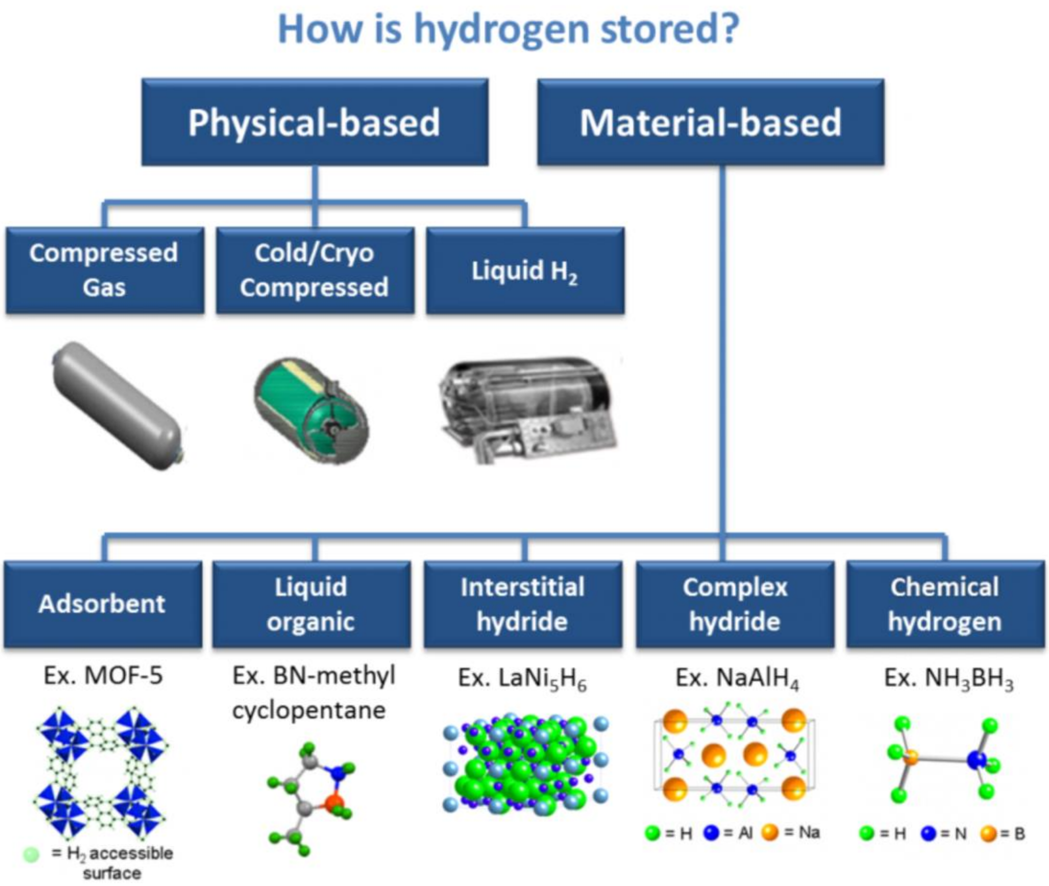
– compounds in which H2 is tightly bound, requiring a relatively complex chemical process – for the recovery of the gas (included are, for instance, substances like methanol , ethanol, ammonia, and water itself that can be thought of as “carriers” of hydrogen);

– compounds that can be reversibly transformed into another substance with a higher (or lower) hydrogen content; – metal hydrides, which are metal-hydrogen compounds that can release and absorb hydrogen reversibly by a simple change of temperature.

A number of characteristics have to be considered when evaluating hydrogen storage systems. They include:

1. Gravimetric concentration. This is the ratio of the mass of the stored hydrogen to the overall mass of the (loaded) storage and retrieval system. The dimensions are kilograms per kilogram—that is, it is a dimensionless parameter.
2. Volumetric concentration. This is the ratio of the mass of the stored hydrogen to the total volume of the storage and retrieval systems. The dimensions are kilograms per cubic meter (ML–3).
3. Turnaround efficiency. This can be the ratio of the retrieved hydrogen to the amount of input hydrogen, or the ratio of the energy retrieved to the input energy.
4. Dormancy. The ability of the system to retain its hydrogen over a long period of time.

DOE Targets for Automotive Hydrogen Storage



The different methods of hydrogen storage are shown below

Compressed Gas

Cryogenic Hydrogen Storage

Storage of Hydrogen by Adsorption

Storage of Hydrogen in Chemical Compounds

Metal Hydrides

4.10.1 Compressed Gas

For compressed gas containers, the main quantity of interest is the gravimetric concentration

- gravimetric concentration: the ratio of the mass of the maximum amount of gas that can be stored to the mass, Mcont , of the container, where the maximum amount of gas corresponds to gas at just under the burst pressure.
- This ratio is proportional to the performance factor (PF) of the container:

$$PF \equiv \frac{p_{burst} V}{M_{cont}}.$$

joules per kilogram

PF is to use better materials and better technology in the construction

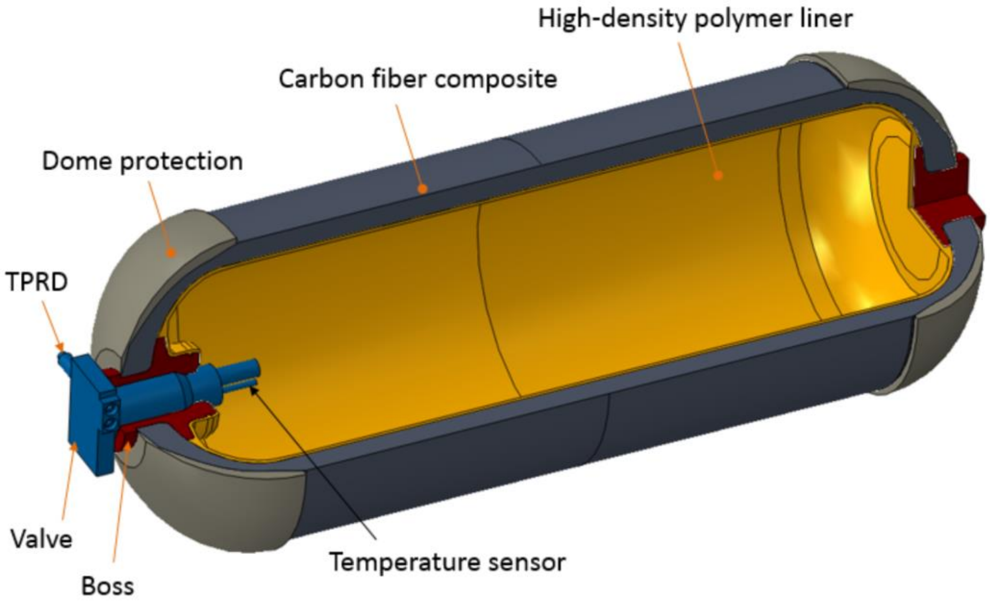
- The mass of the container is proportional to the pressure so that the ratio of stored gas mass to the mass of the container is independent of the storage pressure.
- To improve the PF is to use better materials and better technology in the construction.
- Small quantities of hydrogen, as used in chemical laboratories, can be conveniently stored in simple steel pressure cylinders, usually at 150 atm
- For fuel cell vehicles (FCVs), compressed hydrogen may be a practical way to carry the necessary fuel.

Compressed gas Storage can be done by

- canister
- underground
- pipes

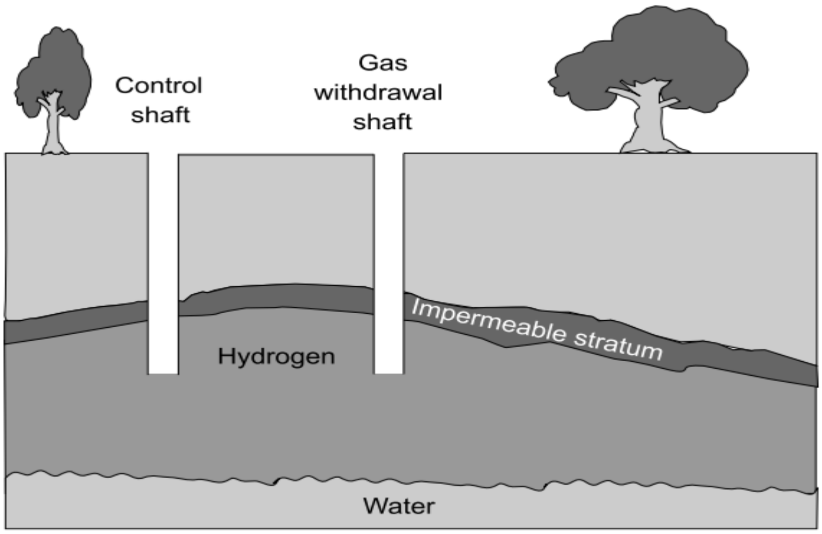
4.10.1.1 Canisters

- Canisters of modern design store the hydrogen in a plastic container that is impermeable to the gas but that, by itself, is unable to resist any significant pressure.
- This resistance is provided by a lining of carbon fiber-epoxy composite, a layer protected by an outer shell resistant to considerable mechanical damage.
- canisters can operate with pressures of up to 700 atm but must a pass burst test of 1650 atm.
- Additionally, they are tested by cycling the pressure 500,000 times.
- Note that even if one plans to use these canisters for 20 years, refueling them every week, only 1000 cycles are used.



- The above canister contains two layers, inner layer polymer liner outer carbon fiber composite. There is also dome protection at the top and bottom of the canister for rough usage of the canister. There is a TPRD (thermally activated pressure relief device) sensor and valve for releasing the hydrogen gas. When the pressure or temperature of the hydrogen gas increases the valve opens and releases the gas. The failure mode of these canisters is relatively less—they do not explode in shrapnel but fail by delamination of the wrapping. They are designed to leak before bursting.

4.10.1.2 Under Ground Storage



- In underground formations, such as porous rocks, old mines, caves, aquifers, and exhausted natural gas deposits.
- Results of the helium storage in Amarillo, Texas, suggest that there will be little difficulty with this technology.
- depicts an arrangement for keeping large amounts of gas in an aquifer, provided an impermeable layer of rocks forms an

  adequate roof over the structure.
- In Amarillo, 8.5 × 108 m3 of helium is stored without problems. It should be noted that helium has leakage characteristics similar to those of hydrogen.
- At STP, 8.5 ×108 m3 of hydrogen corresponds to 10,000 TJ of stored energy.

4.10.1.3 Pipeline Storage

- Pipelines used for transporting the gas. A typical trunk pipeline for natural gas can be over 1000 km long. It may have a 1.2 m diameter and operate at 6 MPa (60 atm). The hydrogen stored in such a pipeline would correspond to an energy of 1000 TJ, nearly 20 times the capacity of the Ludington reservoir.

4.10.2 Cryogenic Hydrogen Storage

Cryogenic means materials stored at low temperature below -150 degree centigrade. Cryogenic hydrogen storage indicates hydrogen stored extremely low temperature. Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8°C. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption).

- hydrogen was first liquefied in 1898
- The largest storage unit in existence is one at Cape Canaveral(Florida usa), with a capacity of 3375 m3.
- Since the density of liquid hydrogen is 71 kg m−3, the facility can accumulate 240,000 kg of liquid hydrogen, or 34 TJ, just a little less than the capacity of the Ludington reservoir we have been using for comparison
- There are two different species of hydrogen molecules: para- and ortho-hydrogen. In the first, the spin in the two atoms that constitute the molecule are in opposite directions, while in the second, the spins are in the same direction.
- The equilibrium at STP corresponds to 25% p-H2 and 75% o-H2, whereas at 20.4 K, the equilibrium shifts to 99.79% p-H2. Owing to the slow kinetics of the reaction, freshly cooled hydrogen tends to have an excess of the ortho variety and its transformation into the para variety results in the release of heat causing the liquid to boil even though no external heat is supplied.

- Freshly condensed hydrogen, even if kept in a perfectly adiabatic container, will lose 1% of its mass during the first hour and 50% during the first week. To minimize such losses, o-H2 is catalytically converted to p-H2 during the liquefaction process. Levels of 95% p-H2 are desirable
- Liquid hydrogen has been considered as a fuel for aircraft. Lockheed investigated the performance of a supersonic airplane designed to carry 234 passengers 7800 km at Mach 2.7. A kerosene powered plane with such a capability would have a gross weight of 232 tons, of which 72 tons would be fuel. A hydrogen plane with equivalent performance would have a gross weight of only 169 tons, of which less than 22 tons would be fuel. One of the problems of high speeds while inside the atmosphere is the high temperatures generated. The stagnation temperature of a body moving through a gas (the temperature reached by the gas at the point in which its flow speed relative to the body is zero) This means that the heat developed at the leading edges of the fuselage, wings, and control surfaces must be efficiently removed. Part of this can be achieved by radiation and conduction and part by refrigeration. The liquid hydrogen fuel can be used to cool critical regions of the plane prior to being conveyed to the engine in gaseous form.

4.10.3 Storage of Hydrogen by Adsorption

hydrogen molecules and methane can be readily adsorbed on carbon.The gases are held in place by weak Van der Waals forces so that the energy necessary to retrieve the fuel is small. Carbon systems can be combined with other techniques: The gas can be pressurized, and the temperature can be lowered. Typically, an adsorption system using activated carbon requires 20 to 40 atm pressure and a temperature of liquid nitrogen to hold the hydrogen.

Carbon nanotubes promise to take up hydrogen much more effectively. Single wall carbon nanotubes have been reported as yielding gravimetric concentrations of up to 10% when operated at 120 K and 0.4 atm.

graphite nanotubes

All these systems require low temperatures or high pressures

4.10.4 Storage of Hydrogen in Chemical Compounds

The main difficulty encountered in the storage of hydrogen is, as pointed out, the low density of the gas. It is possible to substantially increase the packing density by associating hydrogen with other substances. The storage and retrieval processes consist then of the synthesis of a hydrogen-rich compound, followed, when the gas is needed, by its dissociation.

The requirements of a practical hydrogen storing compound include: 1. High storage capacity. The density of liquid hydrogen is 71 kg m^{-3}. Many hydrogen-rich compounds have packing densities that exceed this value. As an example, consider three common hydrides listed in Table 11.3. To achieve high volumetric storage capacity, the hydride must have a high hydrogen-packing density.

To achieve a high gravimetric storage capacity, the hydride must be of relatively low density.

The different methods of hydrogen storage in chemical compounds are

Hydrogen carriers

Water Plus a Reducing Substance

Formic Acid

4.10.4.1 Hydrogen Carriers

Clearly, one way to store and transport hydrogen is to synthesize a hydrogen-rich substance and then, as needed, generate hydrogen by a chemical “reforming” process. Of great interest for FCVs is the use of methanol, a liquid fuel, which can be reformed with relative ease. Considerable effort is being devoted to the design of simple on-board reformers, but there are difficulties namely efficiency,CO2 emission, Containments and environmental danger.

Efficiency.

Assume natural gas as the feedstock. If hydrogen is produced from this gas in a practical device, ≈ 90% of the heat of combustion of the initial raw material appears in the H2. If natural gas is converted to methanol, only 71% of the heat of combustion of the raw material is available from the alcohol produced. While hydrogen can be used directly by a fuel cell, methanol has to be reformed on-board and only 77% of the heat of combustion of the alcohol becomes available as hydrogen for the cell. Thus, the relative efficiencies are 90% for hydrogen and only 77% of 71% or an overall 55% for methanol.

2. CO2 emission. Again, assume that both methanol and hydrogen are derived from natural gas. Fueling an FCV with methanol results in an overall emission of CO2 1.5 times that resulting from using hydrogen.

3. Contaminants. Fuel cells for automotive use will, most likely, be low temperature SPFCs that are sensitive to the presence of impurities, such as CO, that degrade the catalyst. Such impurities will be present in the hydrogen whether it is produced directly from natural gas or through an intermediate methanol step. The latter requires reforming aboard the vehicle where, plausibly, good purification of the hydrogen will be more difficult and more expensive than at a central hydrogen generating plant.

4. Environmental danger. If the use of methanol ever becomes as widespread as that of gasoline today, there will, unavoidably, be some spills, as happens occasionally with petroleum products. The consequences of methanol spills may, however, be much more serious than those of oil or gasoline. The last two fuels do not mix with water and float on its surface. Methanol mixes with water in any proportion and a major spill may contaminate an aquifer. This will render the water of a given region undrinkable because methanol is quite poisonous, blinding or killing those who ingest a sufficient quantity of it.

4.10.2 Water Plus a Reducing Substance

The iron oxidizes into rust and the water is reduced to hydrogen in a reversible reaction:

$$3\mathrm{Fe} + 4\mathrm{H_2O} \leftrightarrow \mathrm{Fe_3O_4} + 4\mathrm{H_2}.$$

Driving this reaction toward the left constitutes a way of storing hydrogen. There are, however, substantial difficulties in this scheme. Unfortunately, the reaction cannot be driven to completion either in the forward, or hydrogen producing direction or in the reverse direction. The temperatures that must be used are quite high (above 1000◦C). Although iron oxidation is exothermic, the heat released is far less than that needed to boil the required water and superheat the resulting steam.

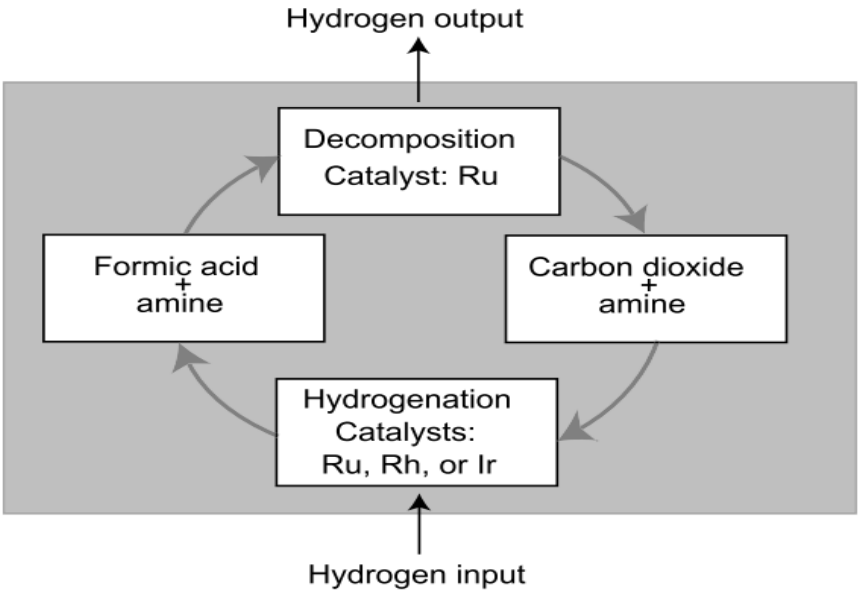
4.10.3 Formic Acid

Photosynthesis operates by hydrogenating carbon dioxide transformation into glucose. A simpler reaction is the direct hydrogenation of CO2, transforming it into formic acid. Formally,

$$CO_2 + H_2 \rightarrow HCOOH.$$

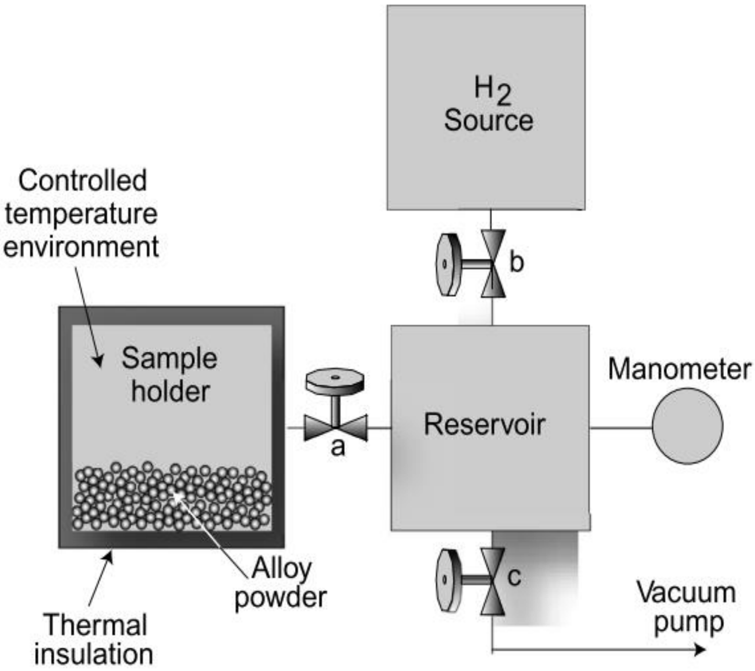
Hydrogenation is an example of an addition reaction in which a substance reacts with a double or triple bond, opening it up and incorporating itself into the product. Hydrogenation of fats or organic oils remove some or all multiple C = C or C ≡ C bonds, reducing the degree of saturation of the original fat or oil. Since carbon dioxide, O = C = O, has two double bonds, it can be hydrogenated twice.

The hydrogenation is accomplished in the presence of an amine and is mediated by a ruthenium, rhodium, or iridium catalyst. The resulting formic acid can be made to release the hydrogen on demand by means of a room temperature decomposition (still in the presence of an amine). CO2 is released and reused during the next storing phase; the system is CO2 neutral.



4.10.4 Metal Hydrides

A number of elements form unstable hydrides (hydrides that can easily be reversed). Magnesium, iron, titanium, zirconium, yttrium, lanthanum, and palladium are examples. Hydrides of elements are called binary. Ternary hydrides—hydrides formed by a combination of hydrogen with a binary compound—are more promising. A typical example are the hydrides of TiFe. The addition of a third element, leading to quaternary hydrides, increases even further the degree of freedom in choosing the characteristics of the system. As can be seen, a large number of combinations are possible. Research in this area has only scratched the surface. The exchange of hydrogen (or any other gas) with a solid is called sorption. If hydrogen is being fixed, the reaction is called absorption; if hydrogen is being released, desorption. Hydride characteristics are best inspected by examining the pressure versus hydrogen concentration isotherms of the material.



A certain amount of activated granules composed, for example, of elements A and B forming an alloy, AB, is placed in the sample holder. The exact number of kilomols of the alloy, μAB, has previously been determined. Valves a and c are open, and valve b is closed. The sample is degassed by heating it to a high temperature and extracting the released vapors by means of a vacuum pump. Valves a and c are then closed and b is opened, filling the reservoir with a known volume of hydrogen at known pressure and temperature—that is, with a known amount of the gas. With b and c closed, a is opened and hydrogen is absorbed. This causes the temperature of the powder to rise because the absorption is exothermic. The system is then returned to the initially selected temperature and the equilibrium pressure is observed.

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UNIT – V – HYBRID RENEWABLE ENERGY SYSTEMS – SEEA3010

Unit-5

Hybrid energy System

Wind and photovoltaic sources are one of the cleaner forms of energy conversion available. One of the advantages offered by the hybridization of different sources is to provide sustainable electricity in areas not served by the conventional power grid. They are very used in many applications, but due to their nonlinearity, hybrid energy systems are proposed to overcome this problem with important improvements. In general, hybridization consists of combining several energy sources and storage units within the same system in order to optimize the production and energy management. In review papers, they can be found under the following names: hybrid renewable energy systems (HRESs) or multi-source multi-storage systems (MSMSSs).

5.1 **Advantages and Disadvantages of an Hybrid System**

Hybrid renewable energy systems (HRESs) are attractive configurations used for different applications and especially in standalone power generation systems as electrification, water pumping and telecommunications. The most advantages of these systems are their simplicity to use and their independent from one energy source, so they can be productive during the day the night. On the other side, the disadvantage is that there are different sources and storage units, so the system is more complex than a single-source system. In this case, an energy management control is necessary to control the power flow, so the global system will be more complex and of course higher cost

5.2 Configuration of Hybrid System

The first and most basic decision that a power system designer is faced is what architecture to be used. This decision will influence every other aspects of the system design including the types and quantities of power converters that will be needed. So two choices must be considered

- Choice of power converters
- Choice of common bus type.

5.2.1 **Choice of Common Bus Type**

The different energy sources can been interconnected through a DC bus or through an AC bus or through DC/AC bus.

5.2.1.1 Architecture of DC Bus

In the hybrid system presented in Fig. 1.1, the power supplied by each source is centralized on a DC bus. Thus, the energy conversion system to provide AC powerat their first rectifier has to be converted then continuously. The generators are connected in series with the inverter to power the load alternatives. The inverter should supply the alternating loads from the DC bus and must follow the set point for the amplitude and frequency. The batteries are sized to supply peak loads. The advantage of this topology is the simplicity of operation, and the load demand is satisfied without interruption even when the generators charge the short-term storage units.

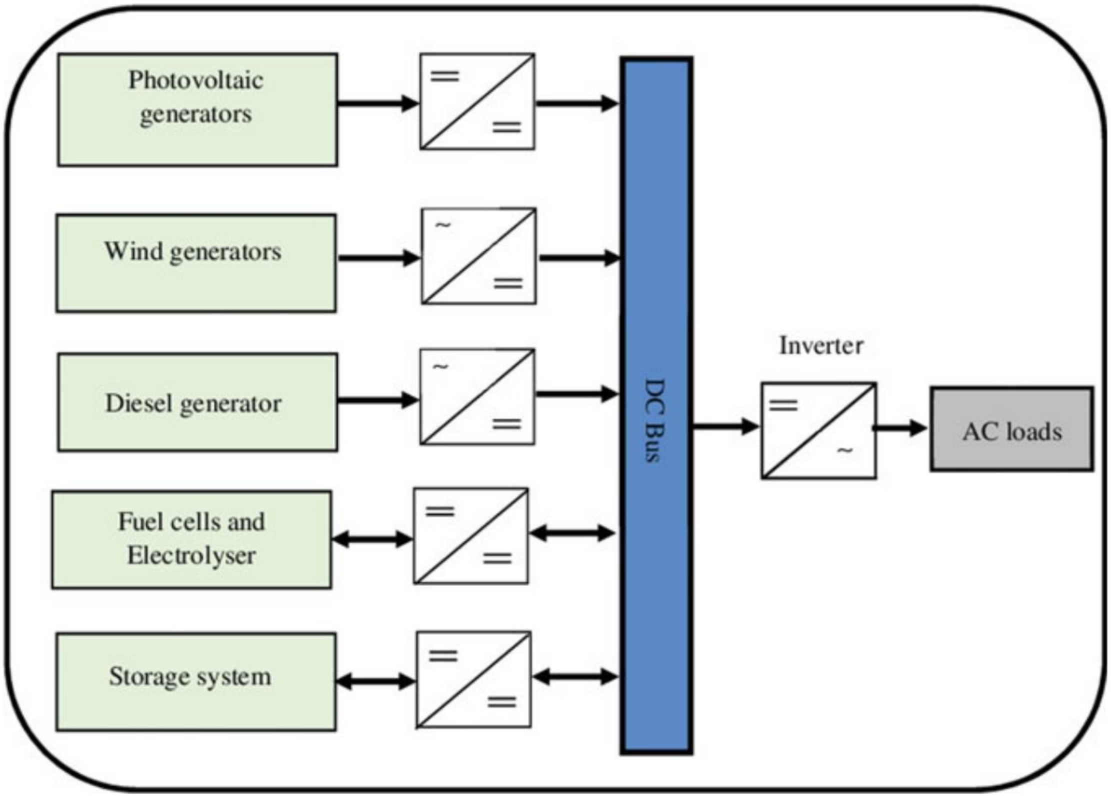


Fig. 1.1 Configuration of the hybrid system with DC bus

5.2.1.2 Architecture of AC Bus

In this topology, all components of the HPS are related to alternating loads, as shown in Fig. 1.2. This configuration provides superior performance compared to the previous configuration, since each converter can be synchronized with the generator so that it can supply the load independently and simultaneously with other converters. This provides flexibility for the energy sources which supply the load demand. In the case of low load demand, all generators and storage systems are stationary except, for example, the photovoltaic generator to cover the load demand. However, during heavy load demands or during peak hours, generators and storage units operate in parallel to cover the load demand. The realization of this system is relatively complicated because of parallel operation, by synchronizing the output voltages with the charge voltages. This topology has several advantages compared to the DC-coupled topology such as higher overall efficiency, smaller sizes of the power conditioning unit while keeping a high level of energy availability, and optimal operation of the diesel generator due to reducing its operating time and consequently its maintenance cost.

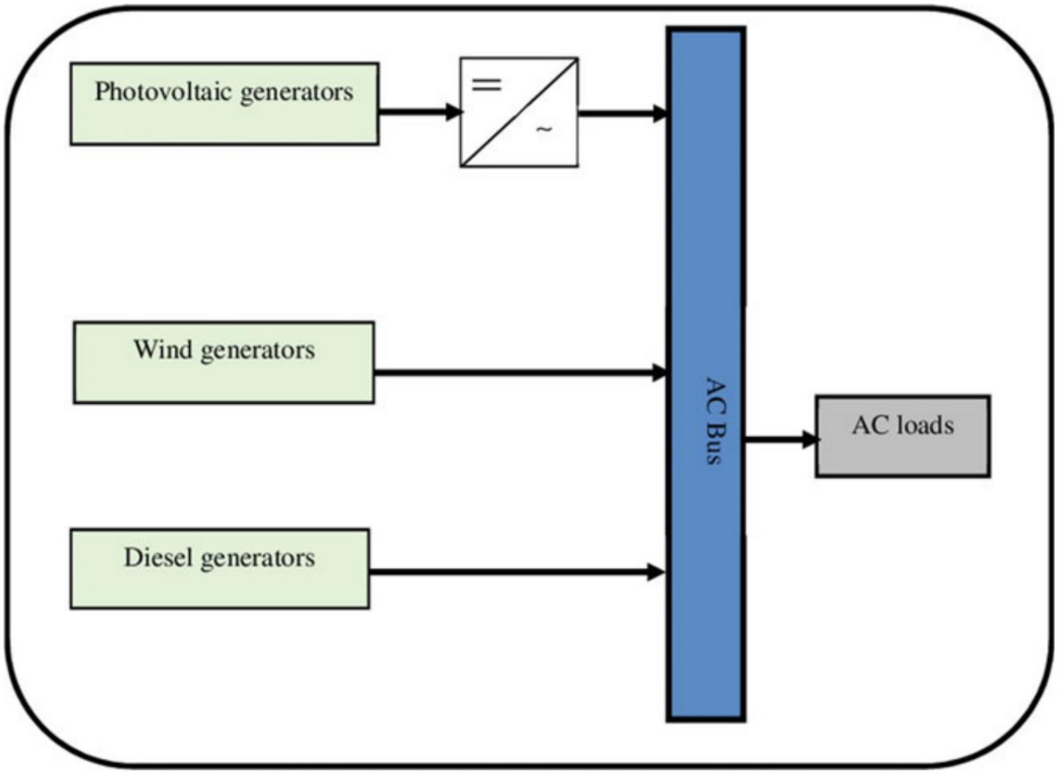


Fig. 1.2 Configuration of the hybrid system with AC bus

5.2.1.3 Architecture of DC/AC Bus

The configuration of DC and AC buses is shown in Fig. 1.3. It has superior performance compared to the previous configurations. In this case, renewable energy and diesel generators can power a portion of the load directly to AC, which can increase system performance and reduce power rating of the diesel generator and the inverter. The diesel generator and the inverter can operate independently or in parallel by synchronizing their output voltages. Converters located between two buses (the rectifier and inverter) can be replaced by a bidirectional converter which, in normal operation, performs the conversion DC/AC (inverter operation). When there is a surplus of energy from the diesel generator, it can also charge batteries (operating as a rectifier). The bidirectional inverter can supply the peak load when the diesel generator is overloaded.

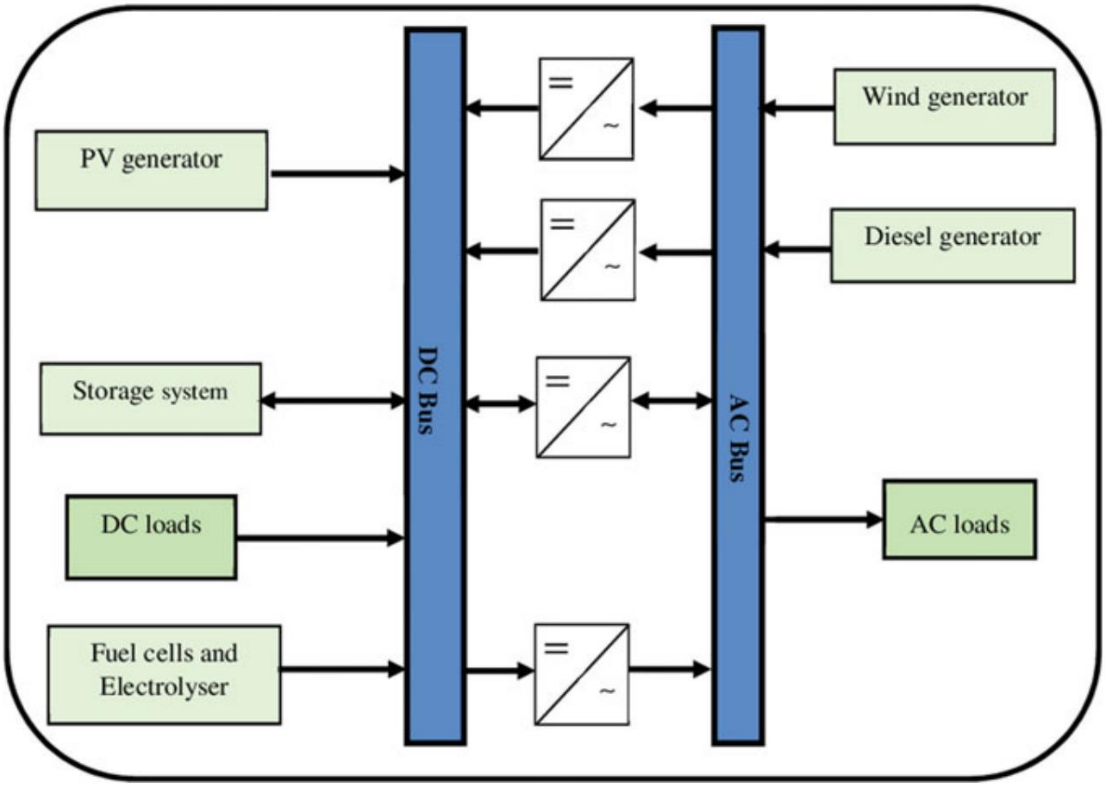


Fig. 1.3 Configuration of the hybrid system with AC bus and DC bus

The advantages of this configuration are:

- The diesel generator and the inverter can operate independently or in parallel. When the load level is low, one or the other can generate the necessary energy. However, both sources can operate in parallel during peak load.

- The possibility of reducing the nominal power of the diesel generator and the inverter without affecting the system's ability to supply peak loads.

The disadvantages of this configuration are:

- The implementation of this system is relatively complicated because of the parallel operation (the inverter should be able to operate autonomously and operate with synchronization of the output voltages with output voltages of diesel generator).

5.2.3 Choice of Converters

A power converter is a system for adapting the source of electrical energy to a given receiver by converting it (Fig. 1.4)

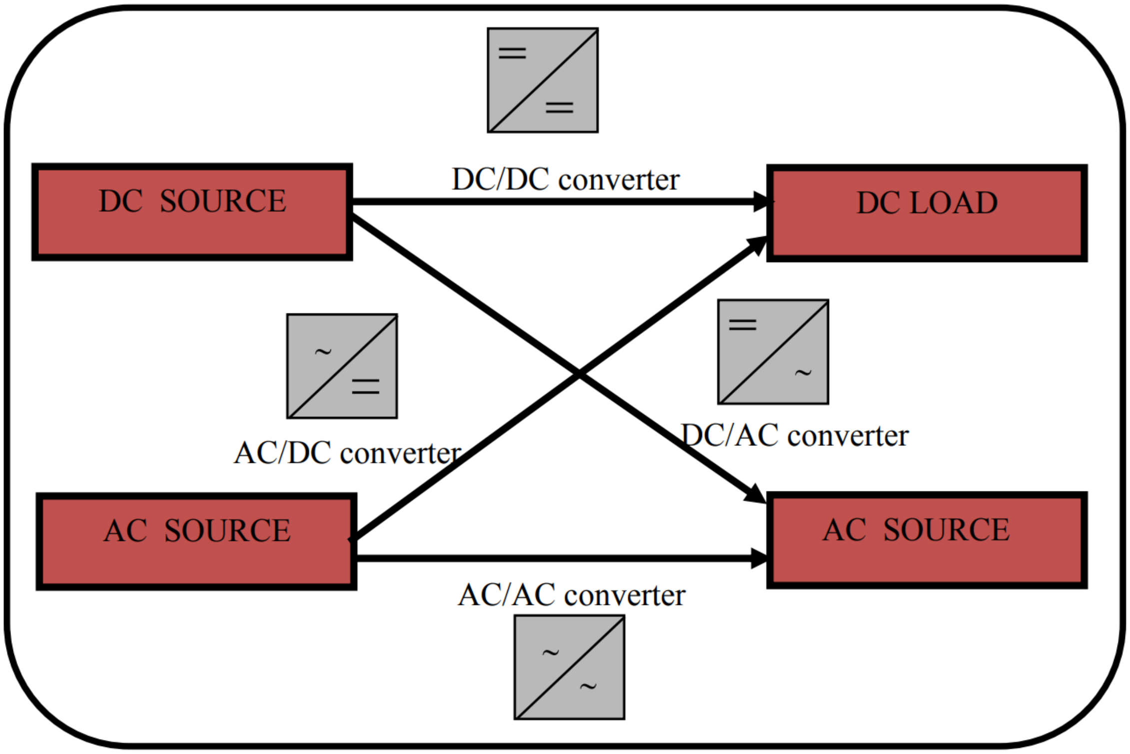
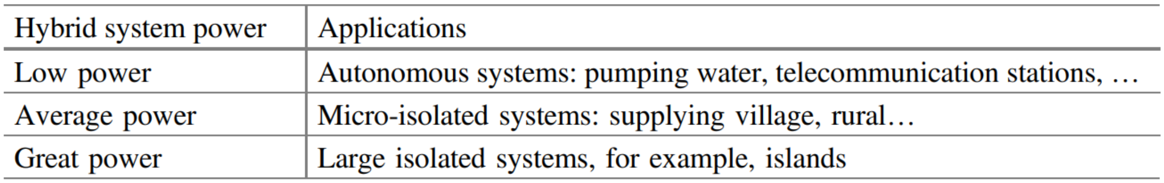


Fig. 1.4 Sources and loads supplied by various static converters

5.4 Classifications of Hybrid Energy Systems

The power delivered by the hybrid system can vary from a few watts for domestic applications up to a few megawatts for systems used in the electrification of small islands. Thus, for hybrid systems with a power below 100 kW, the configuration with AC and DC bus, with battery storage, is the most used. The storage system uses a high number of batteries to be able to cover the average load for several days. This type of hybrid system uses small renewable energy sources connected to the DC bus. Another possibility is to convert the continuous power to an alternative one by using inverters. Hybrid systems used for applications with very low power (below 5 kW) supply generally DC loads (Table 1.1).

Table 1.1 Classification of hybrid systems by power range



Hybrid system power	Applications
Low power	Autonomous systems: pumping water, telecommunication stations, …
Average power	Micro-isolated systems: supplying village, rural…
Great power	Large isolated systems, for example, islands

5 .5 Different Combinations of Hybrid Systems

Mathematically, it can have 2 power n (2n) combinations of hybrid systems. In the following, the most used combinations of hybrid system are presented as follows (Fig. 1.5). Mathematically, it can have the following combinations with one storage. By combining just one element with another, there are about eighteen alternatives. And by considering multiple storages, it can obtain a multiplicity of configurations (about seventy). Some of them have been cited in the literature, others not at all, which may be impossible to do because of the complexity of some combinations. The most important systems are presented, and references of the most cited systems are given to have an overview. The most used hybrid systems can be summarized as shown in Table 1.5.

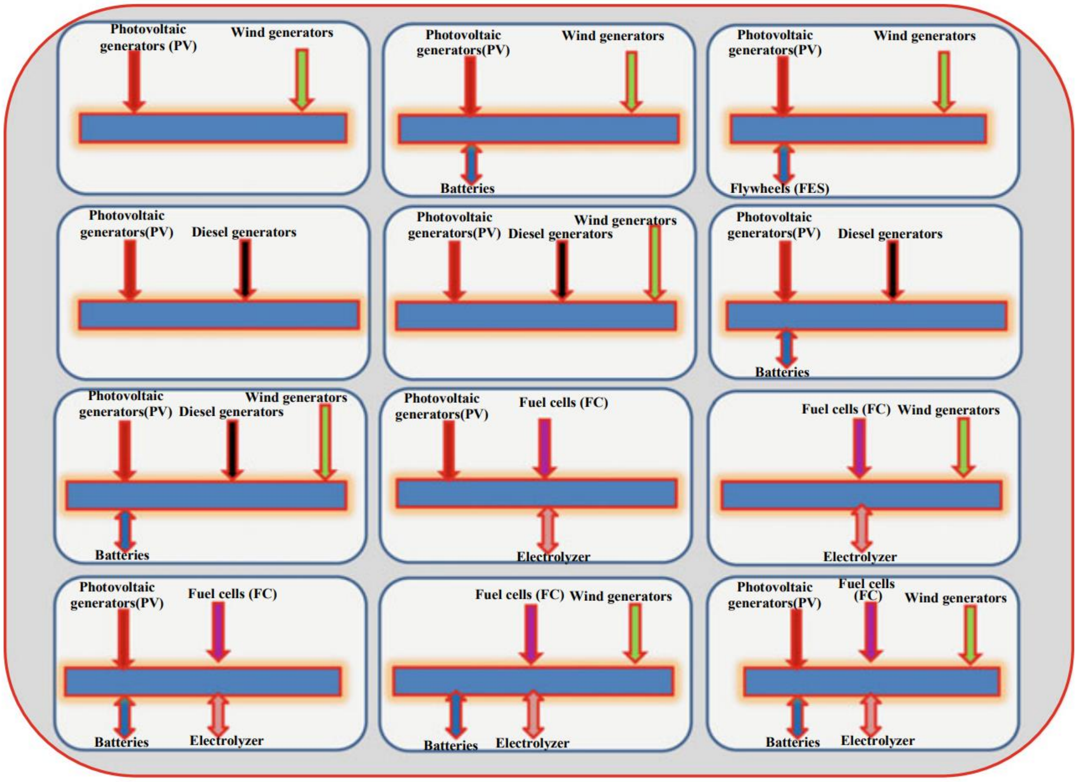


Fig. 1.5 Representation of some used hybrid systems

5.5.1 PV System with Battery Storage

In standalone PV applications, electrical power is required from the system during night or hours of darkness [14, 15]. Thus, the storage must be added to the system. Generally, batteries are used for energy storage (Fig. 1.6). This system can supply DC and AC loads (Fig. 1.7).

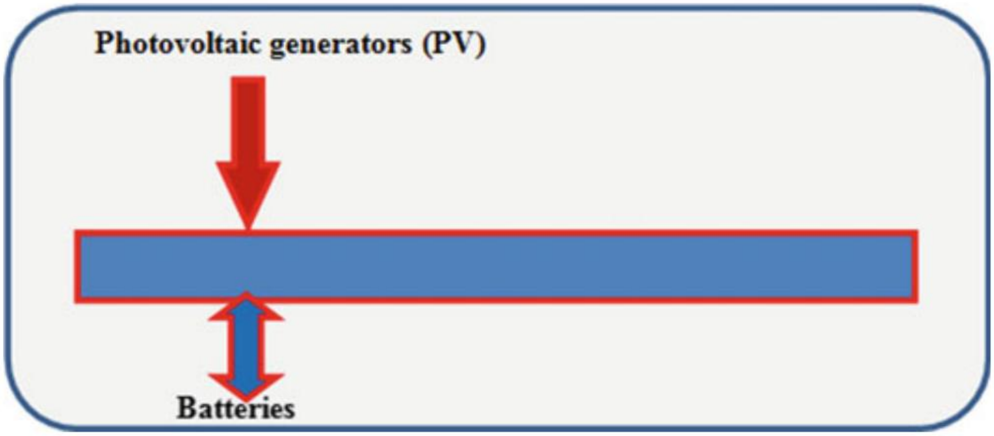


Fig. 1.6 Photovoltaic system with battery storage

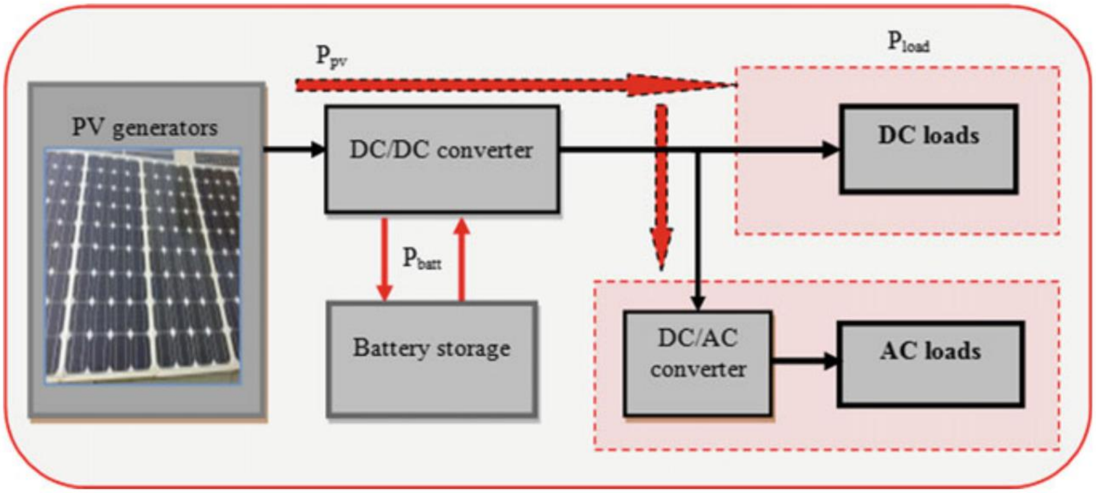


Fig. 1.7 Standalone PV system with battery storage powering DC and AC loads

5.5.2 PV System/Fuel Cells

The role of PV/FCs system is the production of electricity without interruption in remote areas. It consists generally of a photovoltaic generator (PV), an alkaline water electrolyzer, a storage gas tank and a proton exchange membrane fuel cell (PEMFC) (Fig. 1.10)

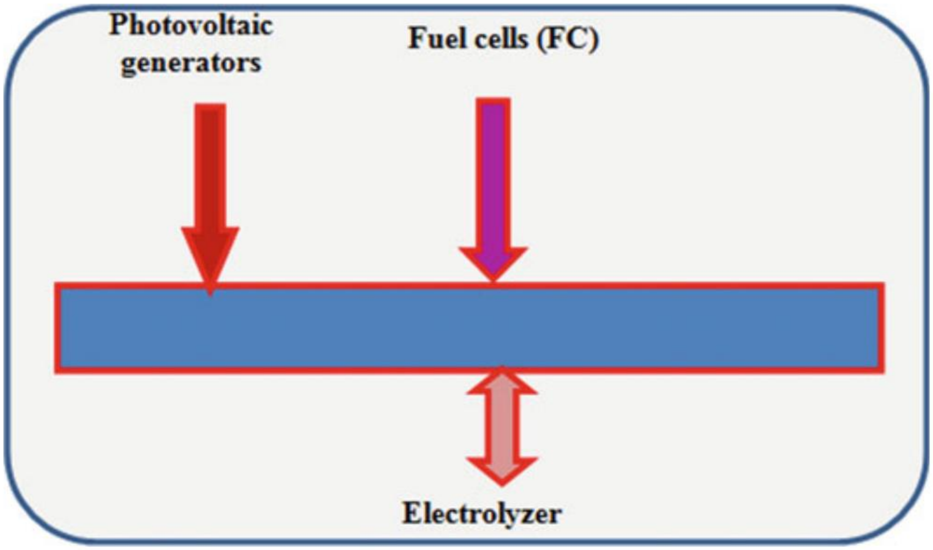


Fig. 1.10 PV system with fuel cells

PV subsystem works as a primary source, converting solar irradiation into electricity that is given to a DC bus (Fig. 1.11). The second working subsystem is the electrolyzer which produces hydrogen and oxygen from water as a result of an electrochemical process. When there is an excess of solar generation available, the electrolyzer is turned on to begin producing hydrogen which is sent to a storage tank. The produced hydrogen is used by the third working subsystem (the fuel cell stack) which produces electrical energy to supply the DC bus

5.5.3 PV System/Fuel Cells with Battery Storage

In this system, PV subsystem always works as a primary source; then, the second working subsystems are the battery storage and the electrolyzer which supplies the fuel cells (Fig. 1.14)

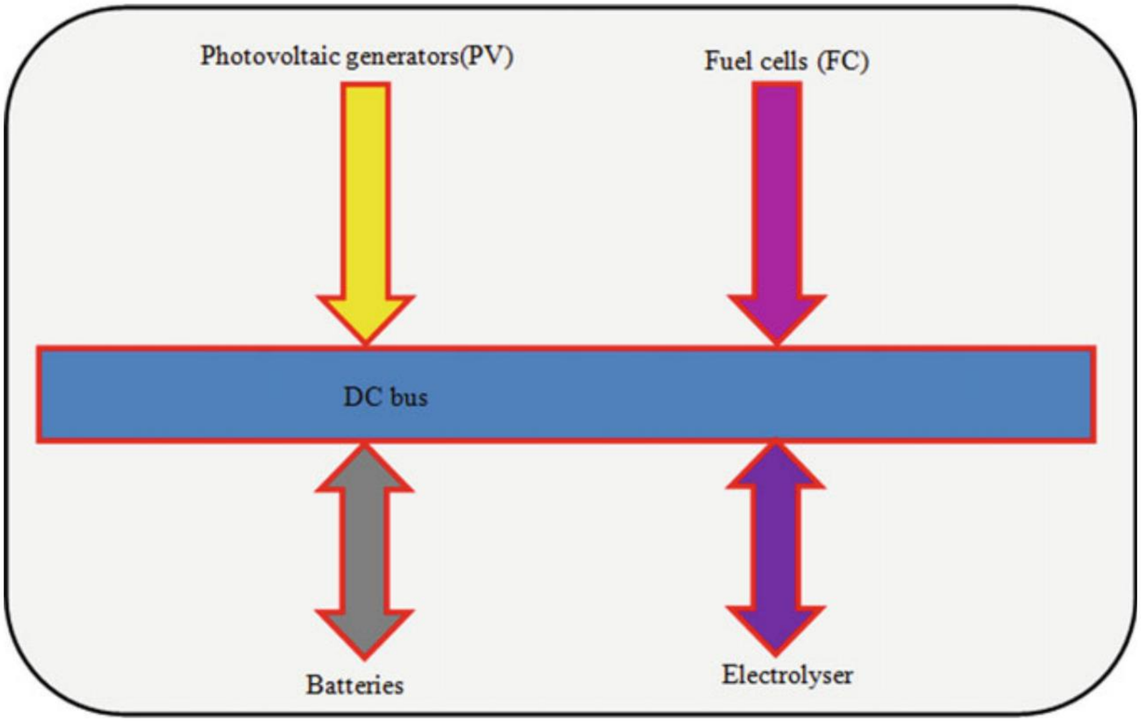


Fig. 1.14 PV/FC system with batteries storage

5.5.4 PV System/FC Multi-storage Batteries/ Super-Capacitors

In this system, it is added a multi-storage to the previous system (Fig. 1.15). It consists of batteries and super-capacitors (Fig. 1.17)

The block diagram representing PV/FC system with multi-storage is given in Fig. 1.18.

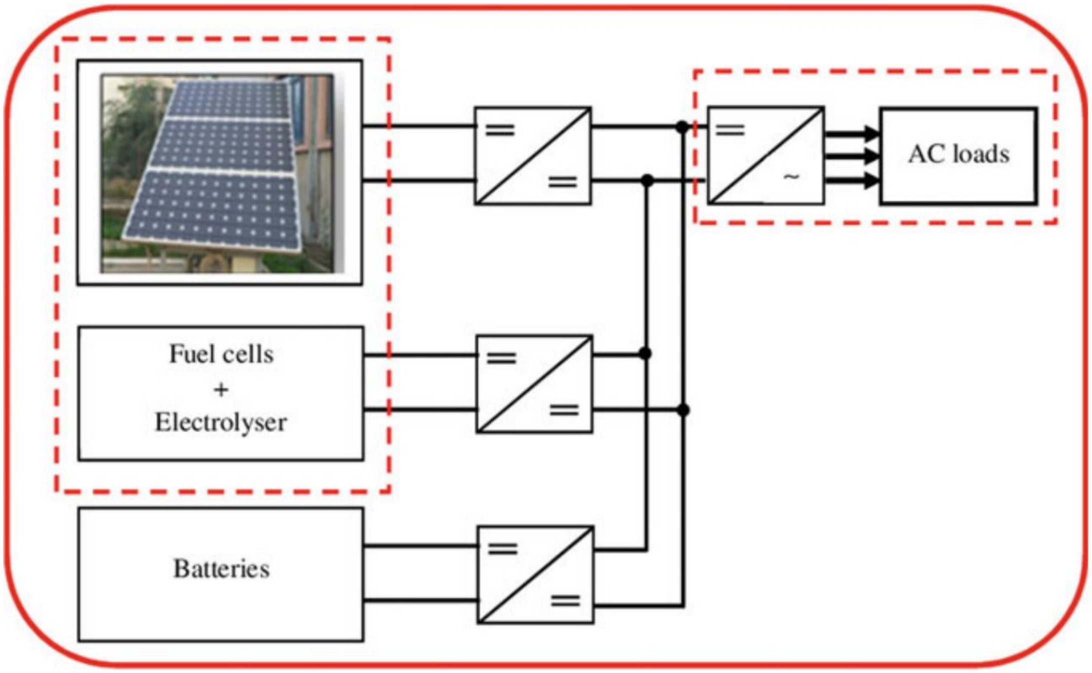


Fig. 1.15 PV/FC system with battery storage block diagram

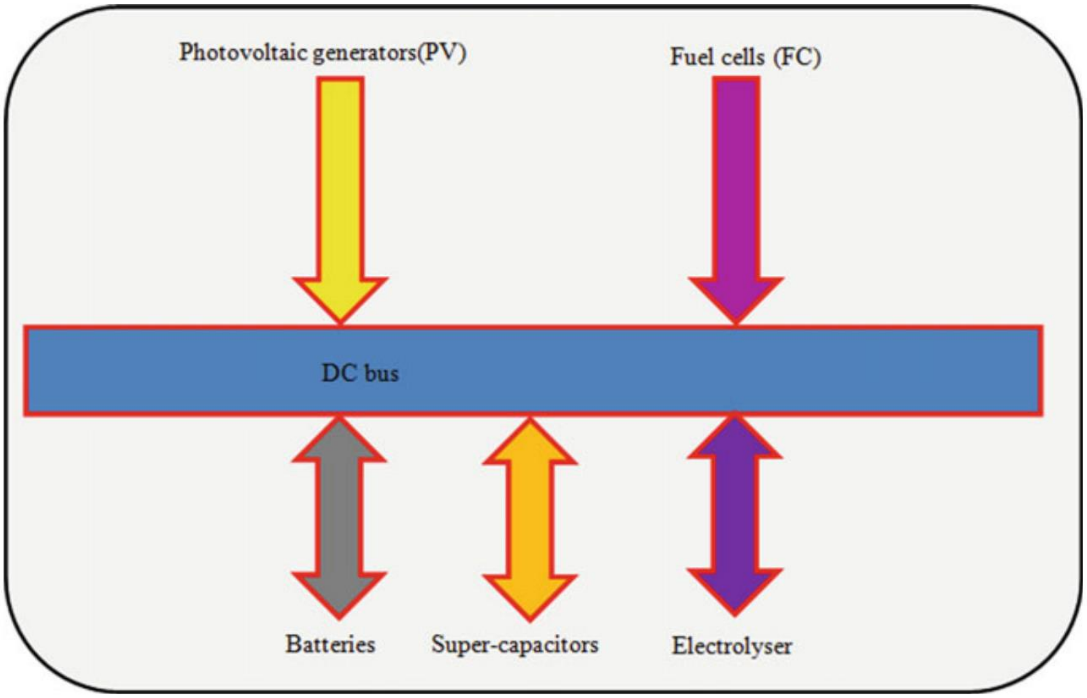


Fig. 1.17 PV/FC system multi-storage batteries/super-capacitors

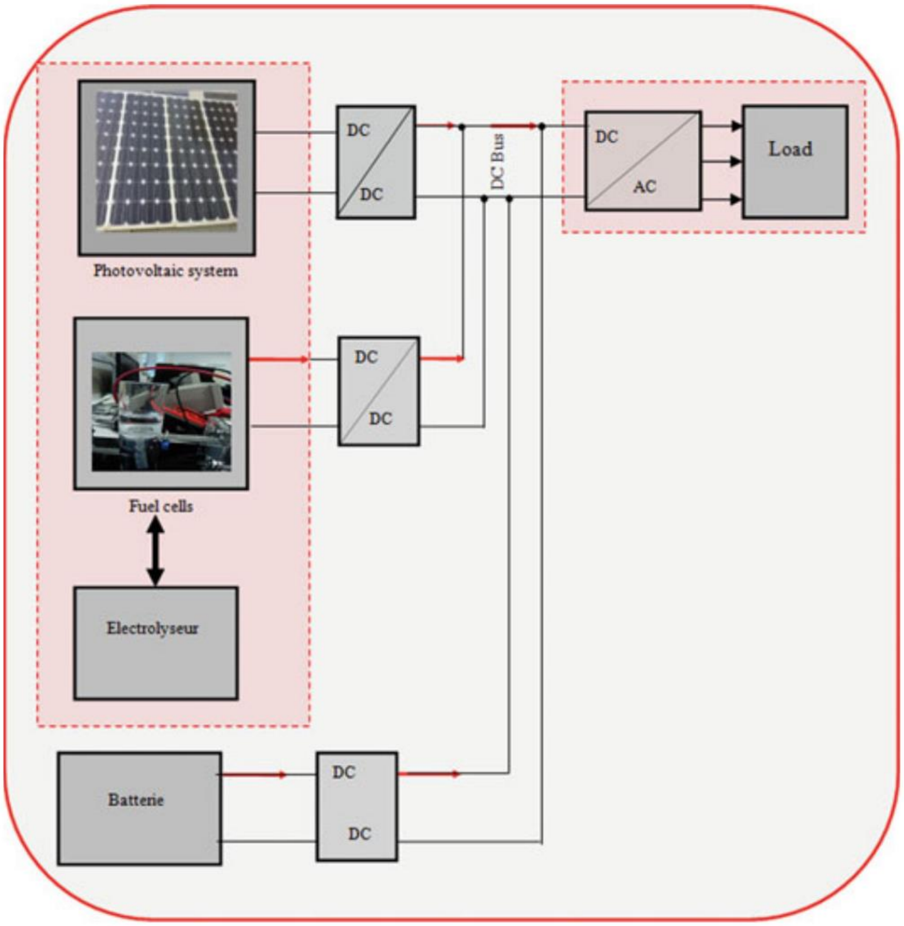


Fig. 1.18 PV/FC system with multi-storage batteries/super-capacitor block diagram

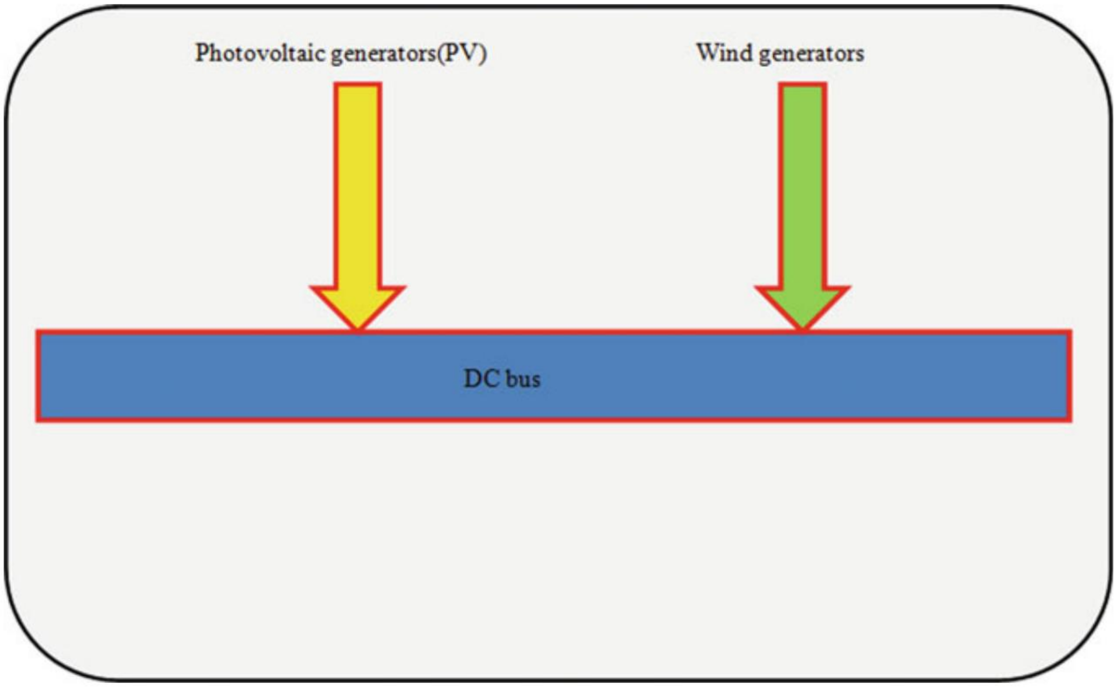


Fig. 1.19 Hybrid wind/photovoltaic system

5.5.5 Hybrid Wind/Photovoltaic System

The advantage of this type of hybrid system depends on the wind, solar radiation and the type of load. It consists of a photovoltaic subsystem, a DC/DC converter and a wind turbine. The two energy sources are connected to a DC bus (Fig. 1.19).

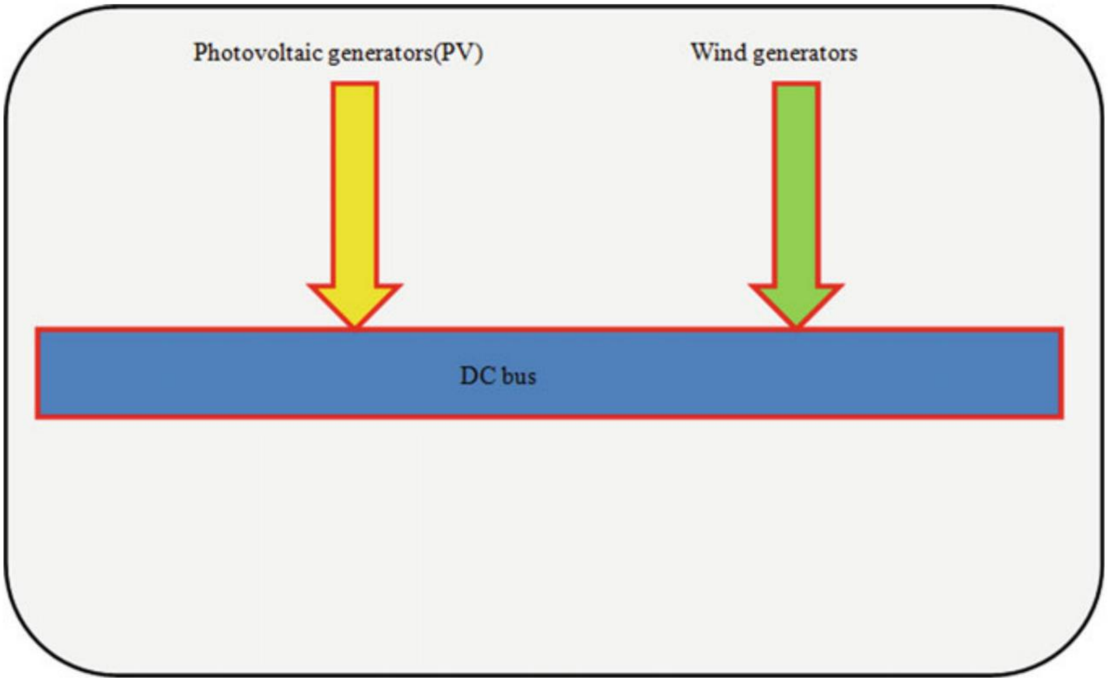


Fig. 1.19 Hybrid wind/photovoltaic system

5.5.6 Hybrid Wind/Photovoltaic System with Battery Storage

Both energy sources are connected to a DC bus, and batteries are added as a storage system (Fig. 1.23).

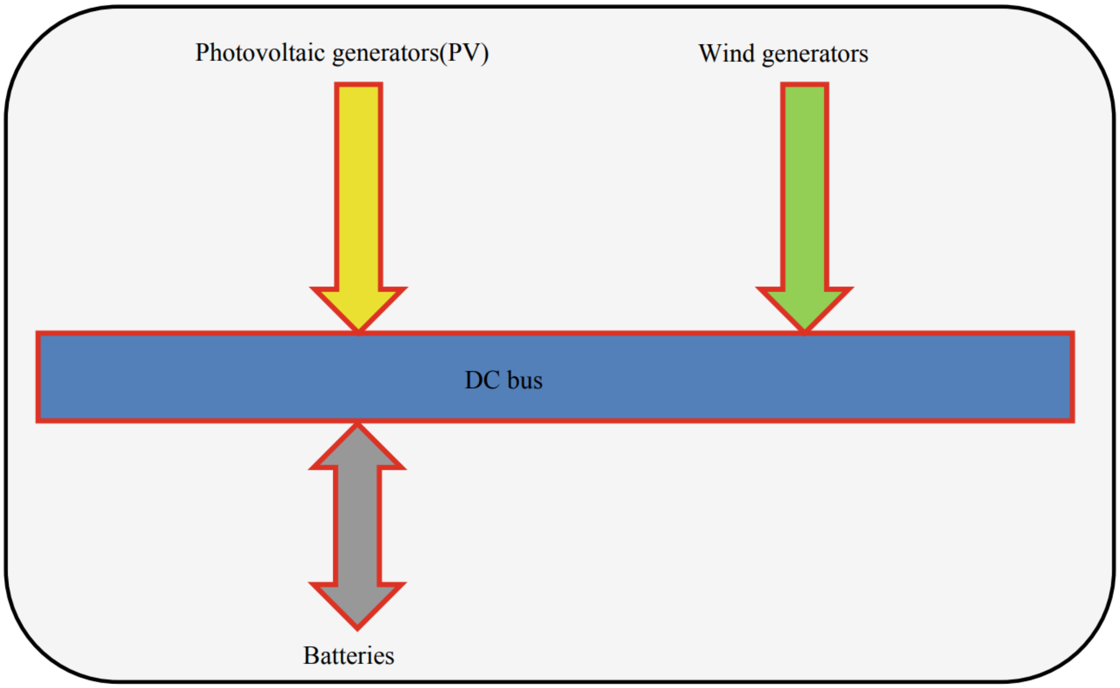


Fig. 1.23 Hybrid wind/photovoltaic system with battery storage

5.5.7 Hybrid Wind/Photovoltaic System with Flywheels Storage

Flywheels energy storage can also be used. FES works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy (Fig. 1.25)

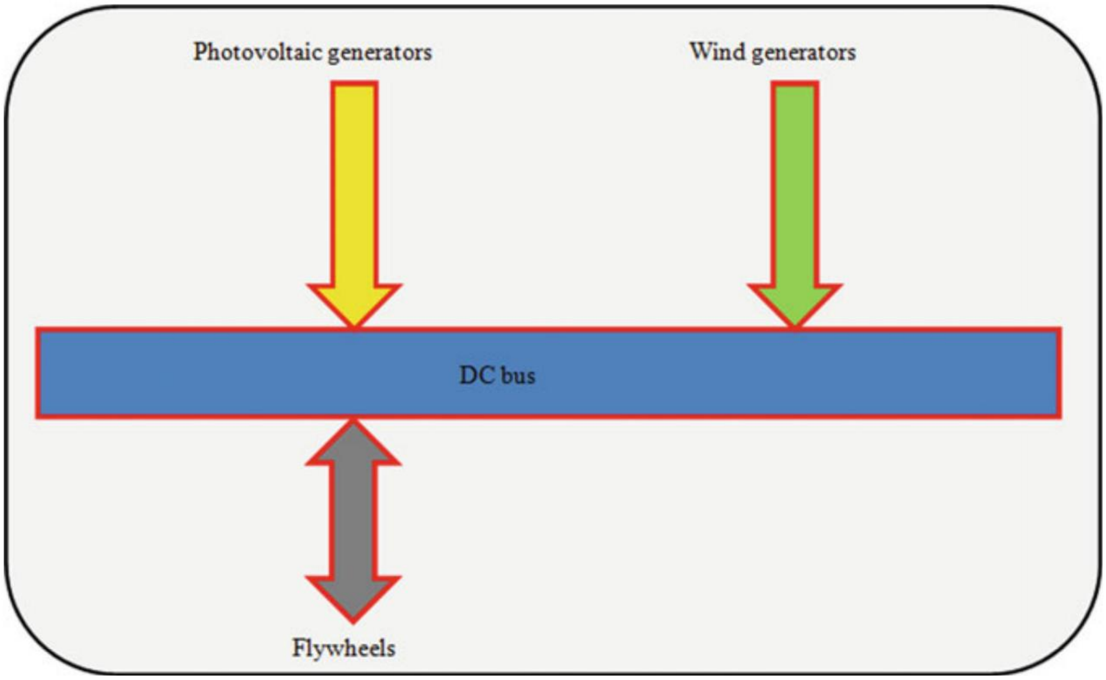


Fig. 1.25 Hybrid wind/photovoltaic system with flywheel storage

5.5.8 Wind Turbine System with Fuel Cells

The system consists of a wind generation system with an electrolyzer to generate hydrogen from surplus wind and a fuel cell for storage. Wind generator turbine provides electricity for electrolyzer, and the excess of energy can be send to generate hydrogen for storage and converted into electricity during peak times (Fig. 1.26).

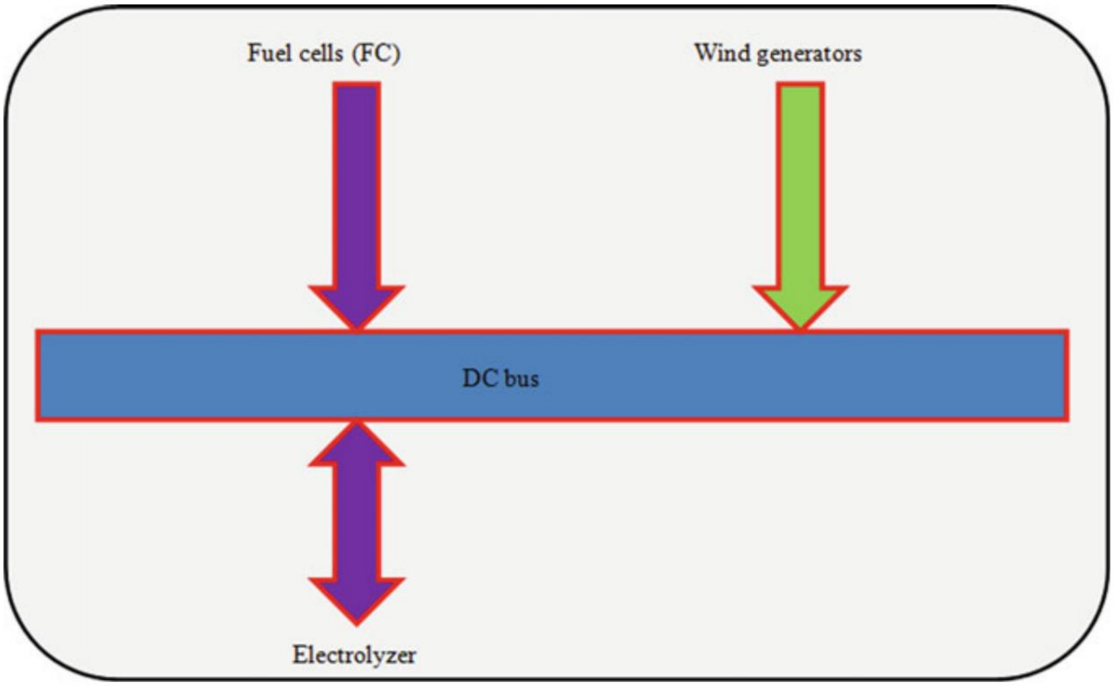


Fig. 1.26 Hybrid wind/photovoltaic system

5.5.9 Wind System/Fuel Cells with Battery Storage

Battery storage can be added to the previous system (Fig. 1.27)

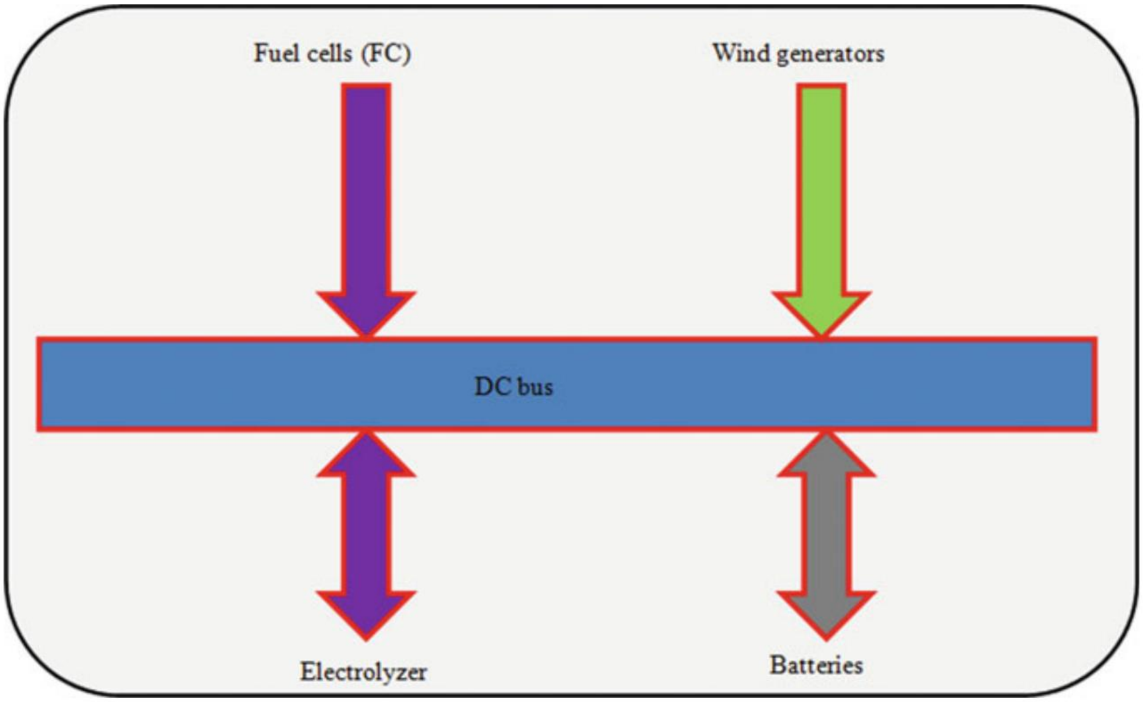


Fig. 1.27 Hybrid wind/fuel cell system with battery storage

5.5.10 Wind System/Fuel Cells with Hybrid Storage Batteries/Super-Capacitors

In this system, it is added a multi-storage. It consists of batteries and supercapacitors (Fig. 1.28)

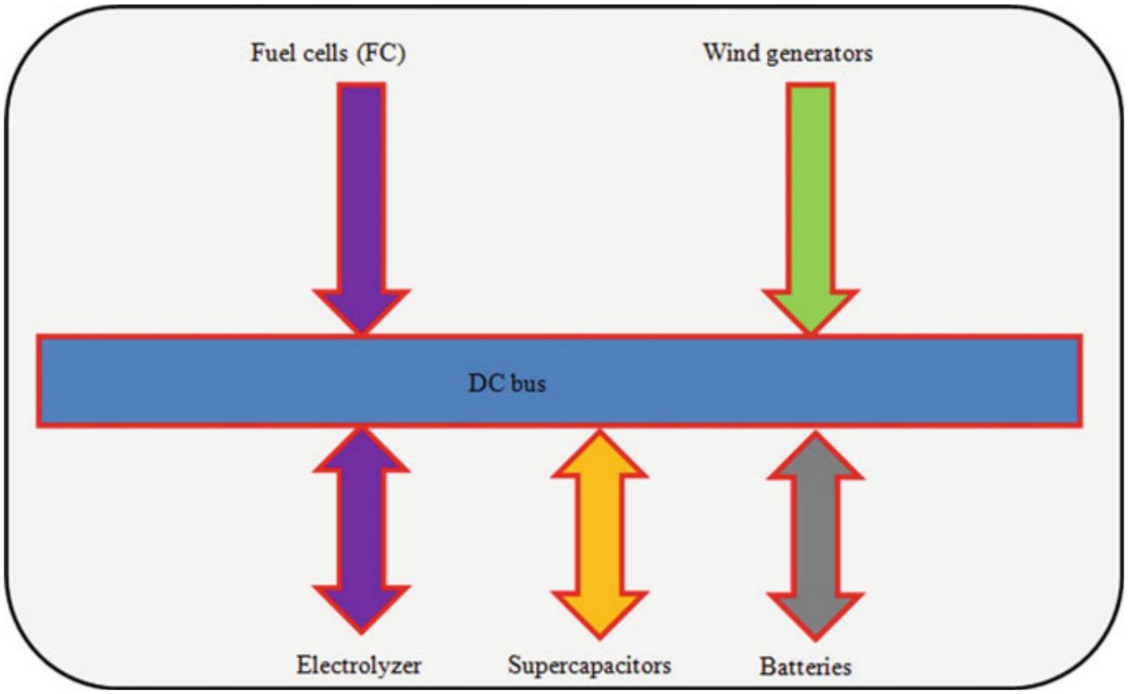


Fig. 1.28 Hybrid wind/fuel cell system with hybrid storage

5.5.11 PV System with Diesel Generators

It is the most used hybrid system. It comprises a photovoltaic generator with a diesel generator (Fig. 1.29)

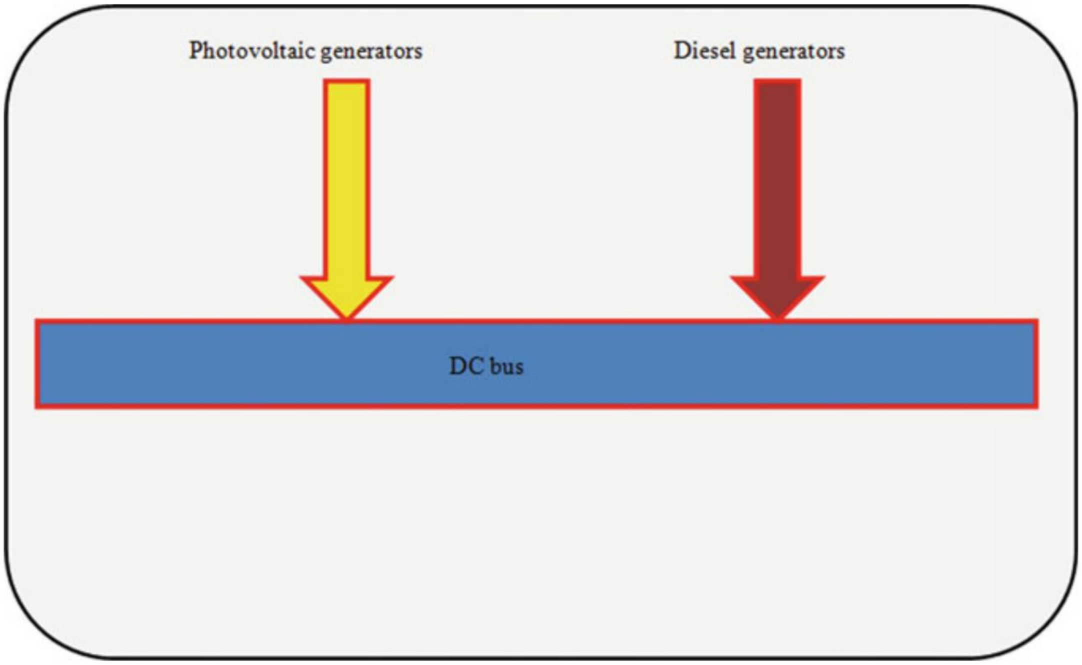


Fig. 1.29 Hybrid photovoltaic system/diesel generators

5.5.12 PV System with Diesel Generators with Battery Storage

Battery storage can be added to the previous system (Fig. 1.30)

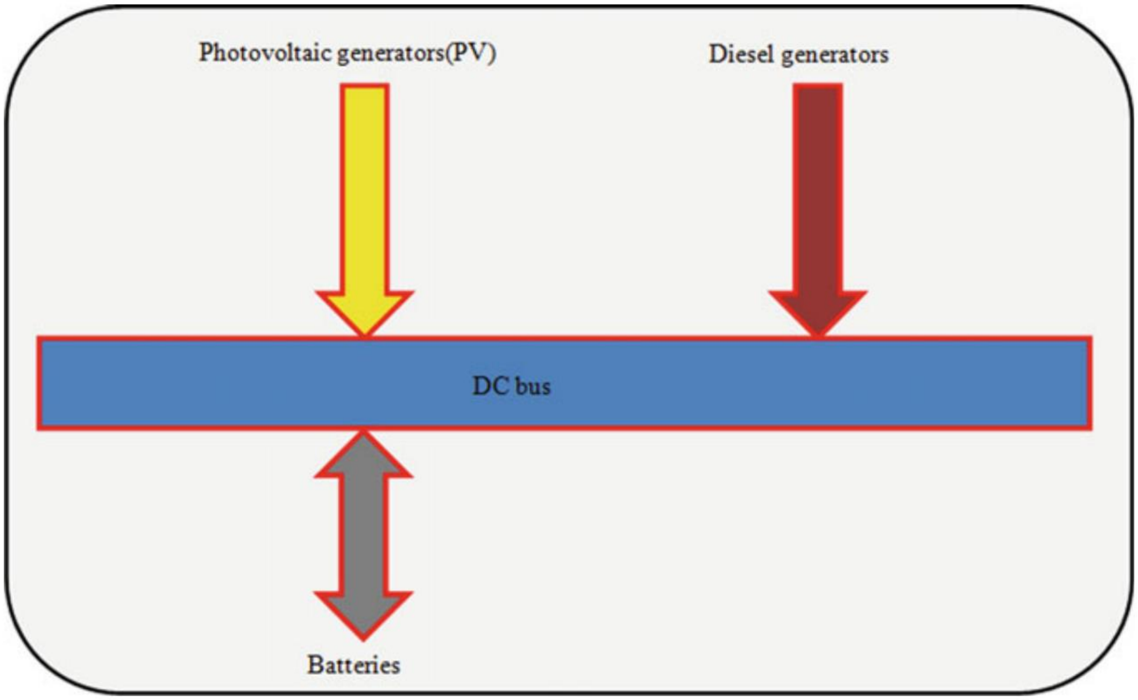


Fig. 1.30 Hybrid wind/photovoltaic system with battery storage

5.5.13 PV System with Wind Turbine System and Diesel Generators

Diesel generators are added as a backup system to PV/wind turbine system (Fig. 1.31).

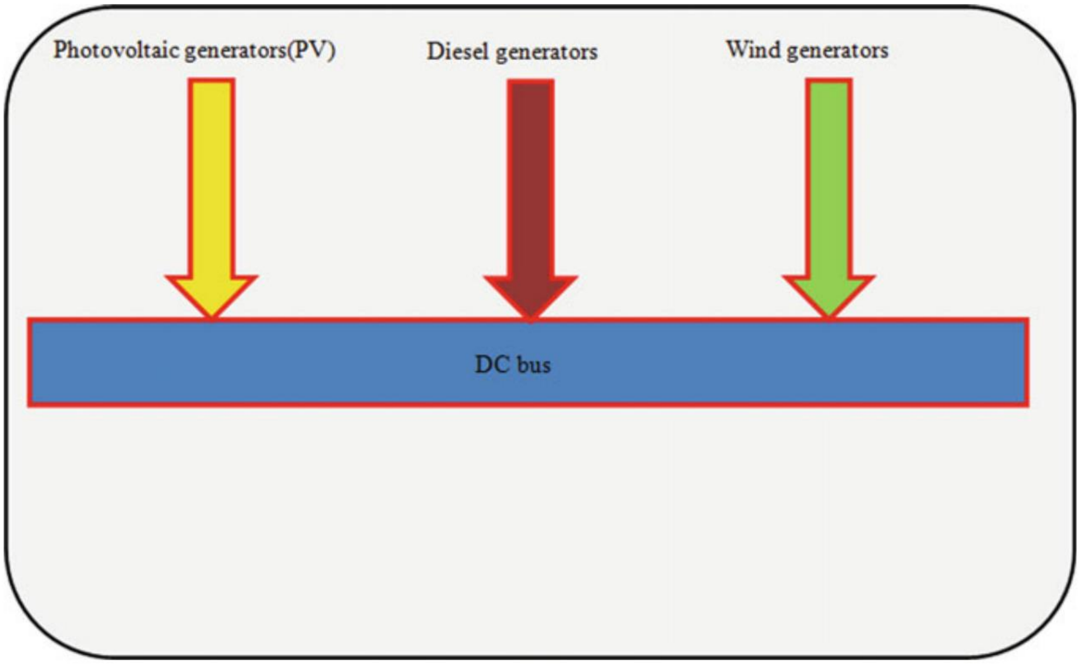


Fig. 1.31 Hybrid wind/photovoltaic system

5.5.14 PV System with Wind Turbine and Diesel Generators with Battery Storage

In this case, battery storage is added to the previous system (Fig. 1.32)

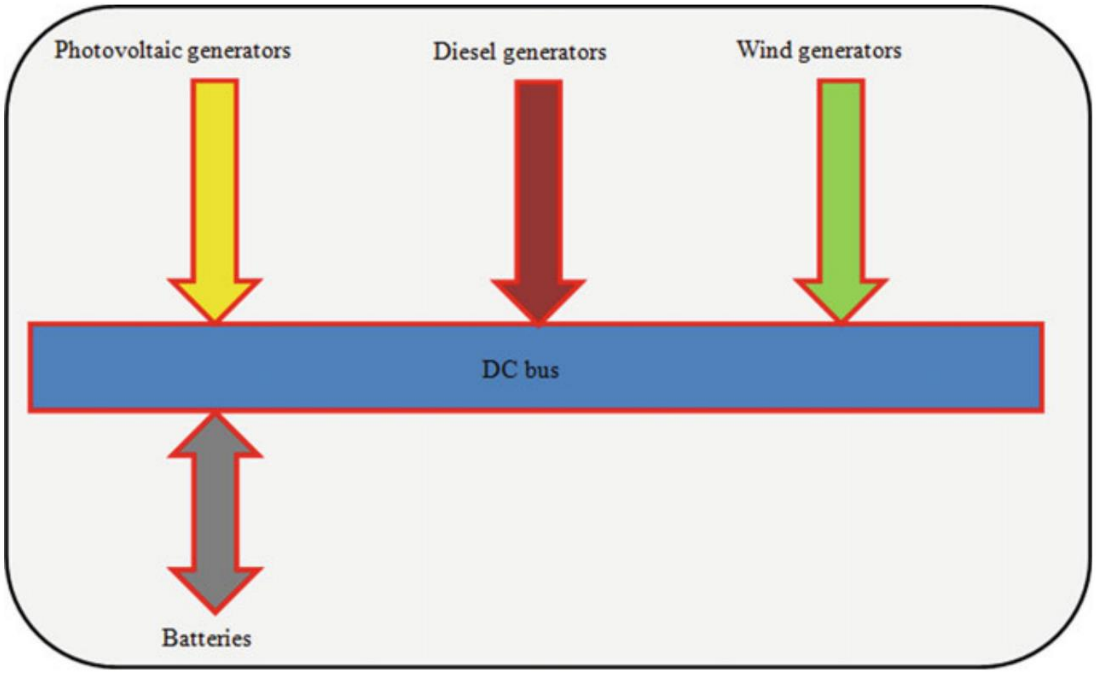


Fig. 1.32 Hybrid wind/photovoltaic system/diesel generators with battery storage

5.6 Sizing of hybrid system:

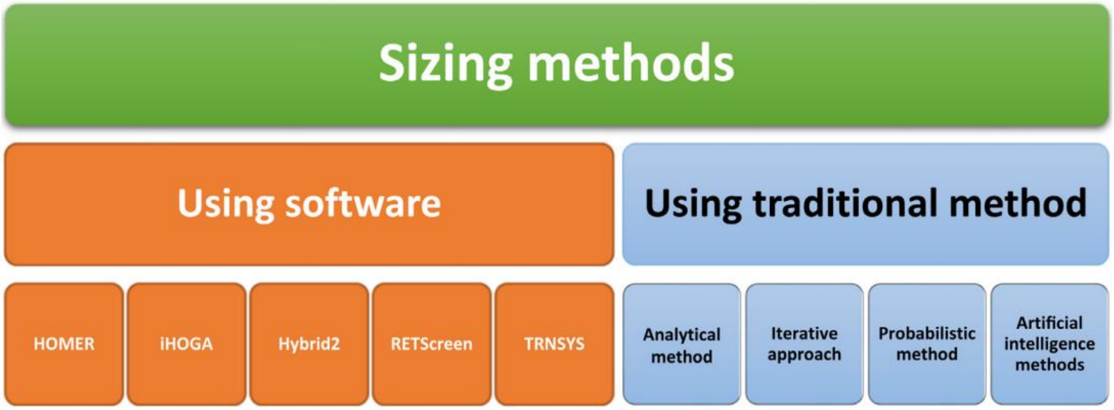


Fig. 1. Sizing methods of hybrid system.

Sizing of the hybrid system is an important step to define the capacity of the generators. Without an appropriate sizing there is a risk of under- sizing or over-sizing the system. The most difficulties encountered are the evaluation of real load and step time to accurately take fluctuations in consideration. However, most researchers take average hours, days or months as data samples.

There are two categories of sizing method; the first one is by using software and the second one is by using traditional methods (Fig. 1).

5.6.1 Sizing hybrid renewable energy system using software

Many commercial applications are available for sizing hybrid sys- tems, and most of these applications use Windows as computer platform with the programming language visual C++ like RET Screen, iHOGA(Hybrid Optimization by Genetic Algorithm), INSEL (Integrated Simulation Environment Language), HOMER (Hybrid Optimization Model for Electric Renewable) and other software.

Baneshi et al. use HOMER software for sizing hybrid system based on diesel generator, photovoltaic generator and wind turbine with storage system (battery) in Shiraz (Iran) for large supply. The purpose of this study is to use a hybrid system with minimum cost and less dioxide carbon. After simulation, the best economic result is the system levilized cost between 9,3 to 12,6 c/kWh with 43,9% from global production and renewable resource.

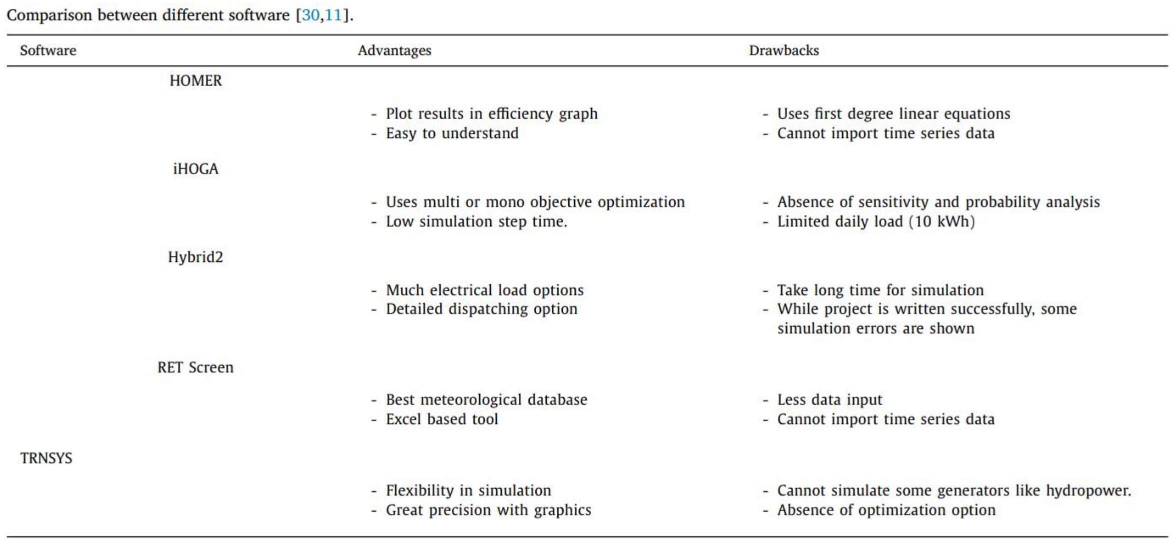
Using iHOGA software, Fadaeenejad et al. sized hybrid system use formed by two renewable generators (photovoltaic generator and wind turbine) and two conventional generators (diesel generator and battery) in Kampung Opar in Malaysia for supplying a rural village. T Table 1 below show the characterize of the input and the output of each sizing software:

Hybrid2 software is developed by Renewable Energy Research Lab- oratory (RERL) of the University of Massachusetts, USA with support from National Renewable Energy Laboratory [30]. Mills et al. use this software for sizing solar/wind/fuel cell hybrid system in Chicago (USA), simulation shows sufficient renewable resource to cover load profile with possibility of omitting fuel cell.

In 1998, the Ministry of Natural Resources in Canada developed a software for energy systems sizing and optimization called “RET Screen” that simulate systems under different aspects; technical, financial, environmental analysis, power efficiency…etc.. simulate their system using Canadian software for photovoltaic generator, wind turbine, diesel generator and a battery hybrid system in Shanghai (China). The results show a reduction in greenhouse gas emission be- cause the hybrid system is basically based on Renewable energy (more than 99%).

The University of Wisconsin in Madison (USA) developed “TRNSYS” software, it is mainly used for simulating thermic systems. This software has been used to model and simulate photovoltaic and thermic hybrid system in results show that hybrid system is technically and economically better than a solar photovoltaic system.

According to Table 2, the comparison between this software show different characteristics and limitations for each one and the most im- portant notes select the best software based on system uses and degree of optimization for sizing, that mean HOMER and RET Screen can size any system but uses simple optimization equation, iHOGA size any system with 10 kW limit, Hybrid2 have some internal problems and TRNSYS cannot size all generators without any optimization. After this compar- ison, we can say that HOMER and RET Screen is the best software for sizing hybrid renewable energy system.



Comparison between different software [30,11].

Software	Advantages	Drawbacks
HOMER	- Plot results in efficiency graph - Easy to understand	- Uses first degree linear equations - Cannot import time series data
iHOGA	- Uses multi or mono objective optimization - Low simulation step time.	- Absence of sensitivity and probability analysis - Limited daily load (10 kWh)
Hybrid2	- Much electrical load options - Detailed dispatching option	- Take long time for simulation - While project is written successfully, some simulation errors are shown
RET Screen	- Best meteorological database - Excel based tool	- Less data input - Cannot import time series data
TRNSYS	- Flexibility in simulation - Great precision with graphics	- Cannot simulate some generators like hydropower. - Absence of optimization option

5.6.2 Sizing hybrid renewable energy system using traditional methods

There are four essential traditional sizing methods:

- Analytical method
- Iterative approach
- Probabilistic method
- Artificial intelligence methods

Analytical method

This approach considers the hybrid system as a means of a numerical model and defines the size of the hybrid system as a function of viability. In 2015, a study for a hybrid system using analytical method, where the components of the hybrid system are photovoltaic generator and a wind turbine in South Africa. The objective is investigating water efficiency optimization of the hybrid system. The obtained results show that hybrid central generates 100000 MWh every year,0,97€/kWh and 75000 m3 of water yearly

Iterative approach

This method is an algorithm program based on recursive process, ending when the optimum system design is attained used this method for sizing stand-alone hybrid system based on solar photovoltaic, wind power with batteries for supply to a rural village in Brazil. The objective of this study is to produce a system with minimum cost and high reliability. After simulation, the optimum configuration for hybrid system is 0,5 kW of solar photovoltaic, 3 wind turbines (0,6 kW for each one) and 5 batteries (each one has 1,2 kWh). The total cost of this system is 25672.01R$ (Brazilian real is the official currency of Brazil) with levilized cost1.044 R$ /kWh.

Probabilistic method

The probabilistic approaches to size of an integrated system take into account the impact of wind speed isolation and adjustments in the system design. This method is one of the simplest used sizing methods but results show that it may not be appropriate to find the best possible solution.

An algorithm used for sizing solar photo- voltaic/wind turbine/biomass and battery using Probability-PowerPinch Analysis (P-PoPA) method. The result shows maximization in energy storage capacity and power rating of the storage system with minimization in outsourced energy.

Artificial intelligence methods

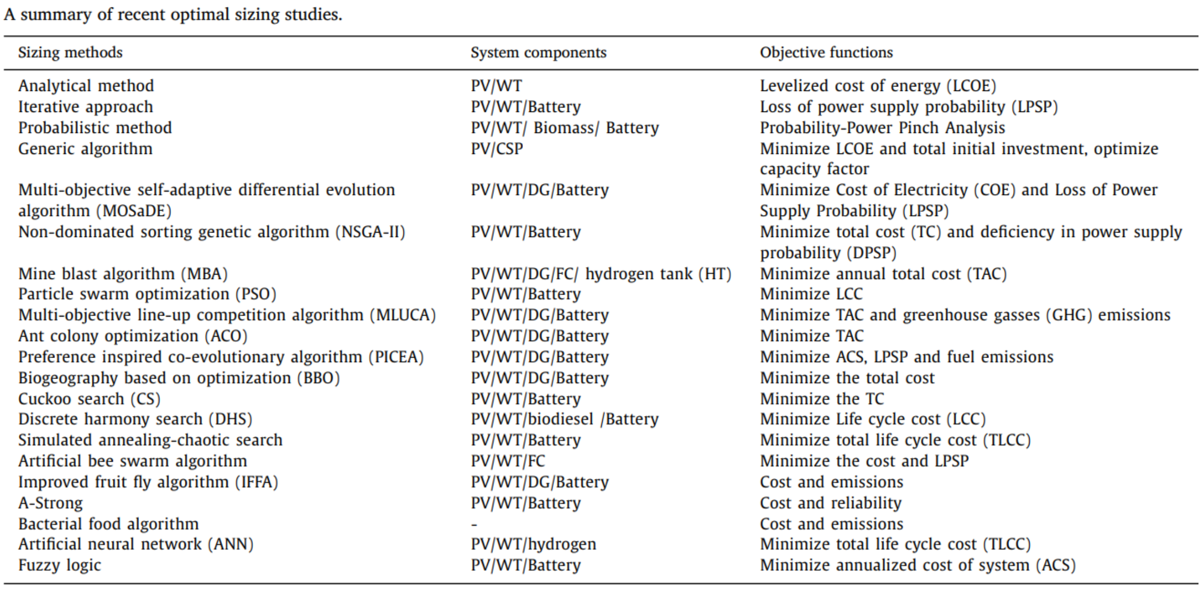
Subho Upadhyay defined artificial intelligence in his review article “A review on configurations, control and sizing methodologies of hybrid power systems” and wrote: “Artificial intelligence is a term that in its broadest sense would mean the ability of a machine or artifact to perform similar kinds of functions that characterize human thought” [9].

Several types of algorithm are used by researchers to find optimum sizing for hybrid system like genetic algorithm [40], multi- objective self-adaptive differential evolution algorithm (MOSaDE) [41], non-dominated sorting genetic algorithm (NSGA-II) [42], mine blast algorithm (MBA) [43], Particle swarm optimization (PSO) [44], multi- objective line-up competition algorithm (MLUCA) [45], Ant colony optimization (ACO) [46], and preference inspired coevolutionary algorithm (PICEA) [47]. biogeography based on optimization (BBO) [48], cuckoo search (CS) [49], discrete harmony search (DHS) [50], and simulated annealing-chaotic search [51], Artificial bee swarm algorithm [52], Improved fruit fly algorithm (IFFA) [53], A-Strong [54], bacterial food algorithm [55], Artificial neural network (ANN) [56], fuzzy logic [57]. Table 3 summarize sizing methods with system components and objective functions of each one.

5.7 Comparison between sizing methods

Traditional methods characterize by simplicity and rapidity, these advantages make these methods limited in performance and analysis. This drawback can ignore by using artificial intelligence approach be- cause this method uses multi objective function to solve complex prob- lems.

Based on simple numerical model, analytical method size hybrid sys- tem quickly with low flexibility, this problem can solve using iterative approach when this method is based on simple algorithm use recursive process to achieve the best size system, the inconvenient of this approach is ignore some important parameters. Comparing to previous methods (analytical and iterative), artificial intelligence is the best solution for all complex methods, without limitation and present good results again other methods, the most difficult of this problem is the complexity codes uses in this algorithm.Table 4 illustrate comparison between different sizing methods used in hybrid system



A summary of recent optimal sizing studies.

Sizing methods	System components	Objective functions
Analytical method	PV/WT	Levelized cost of energy (LCOE)
Iterative approach	PV/WT/Battery	Loss of power supply probability (LPSP)
Probabilistic method	PV/WT/ Biomass/ Battery	Probability-Power Pinch Analysis
Generic algorithm	PV/CSP	Minimize LCOE and total initial investment, optimize capacity factor
Multi-objective self-adaptive differential evolution algorithm (MOSaDE)	PV/WT/DG/Battery	Minimize Cost of Electricity (COE) and Loss of Power Supply Probability (LPSP)
Non-dominated sorting genetic algorithm (NSGA-II)	PV/WT/Battery	Minimize total cost (TC) and deficiency in power supply probability (DPSP)
Mine blast algorithm (MBA)	PV/WT/DG/FC/ hydrogen tank (HT)	Minimize annual total cost (TAC)
Particle swarm optimization (PSO)	PV/WT/Battery	Minimize LCC
Multi-objective line-up competition algorithm (MLUCA)	PV/WT/DG/Battery	Minimize TAC and greenhouse gasses (GHG) emissions
Ant colony optimization (ACO)	PV/WT/DG/Battery	Minimize TAC
Preference inspired co-evolutionary algorithm (PICEA)	PV/WT/DG/Battery	Minimize ACS, LPSP and fuel emissions
Biogeography based on optimization (BBO)	PV/WT/DG/Battery	Minimize the total cost
Cuckoo search (CS)	PV/WT/Battery	Minimize the TC
Discrete harmony search (DHS)	PV/WT/biodiesel /Battery	Minimize Life cycle cost (LCC)
Simulated annealing-chaotic search	PV/WT/Battery	Minimize total life cycle cost (TLCC)
Artificial bee swarm algorithm	PV/WT/FC	Minimize the cost and LPSP
Improved fruit fly algorithm (IFFA)	PV/WT/DG/Battery	Cost and emissions
A-Strong	PV/WT/Battery	Cost and reliability
Bacterial food algorithm	-	Cost and emissions
Artificial neural network (ANN)	PV/WT/hydrogen	Minimize total life cycle cost (TLCC)
Fuzzy logic	PV/WT/Battery	Minimize annualized cost of system (ACS)

5.8Types of hybrid systems

Few hybrid energy systems that are operative in prevailing Indian conditions in various states are given: It is assumed that a battery bank of a suitable size is installed as the storage tank for the period of low wind speed, during ‘No Sun’ cloudy day and night period. Correct choice for an option will include the parameters

- Available solar insolation at optimum array tilt,
- Free wind velocity at 10 m or 20 m height,
- Number of cattle available in a village or a cluster community.

- PV – Diesel
- Wind – Diesel
- Biomass – Diesel
- Wind – PV
- Micro hydel – PV
- Biogas – Solar Thermal
- Solar – Biomass
- Electric and electric hybrid vehicles

5.8.1 PV Hybrid with Diesel Generator

Renewable energy technologies are possible for electrification of remote villages including small hydro, wind, biomass and solar energy, yet solar PV lighting remains the most preferred. Such systems are used in Orissa, Assam, Sikkim, Jammu and Kashmir, and Uttarakhand. This power plant contains one PV array with a Diesel electric generator and a battery bank. Energy generatedfrom PV array feeds load demand and then charges the battery bank. Diesel generator keeps the battery fully charged and sometime supplies load demand when PV output is not sufficient and battery charge is low to supplement.

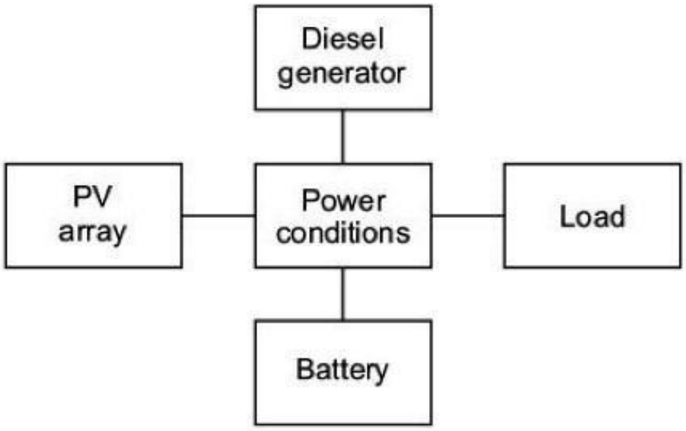


Figure 1 Block diagram of PV – Diesel hybrid power plant.

Figure 1 is a block diagram of such a power plant where Power conditioner performs three functions:

To convert alternating current (ac) diesel generated output into direct current (dc) for charging battery bank.

To invert direct current (dc) from PV array and battery bank into ac for feeding load.

To regulate battery current and voltage for input from generator and output for load. Several experiments have been carried out to find where 10 per cent diesel fuel would be required with a given solar PV array area to replace 90 per cent of diesel fuel that would be consumed for a diesel system only. Experimental values have been used to draw a graph. Figure 2 shows ‘life cycle cost’ versus array area (10 3 × m2).

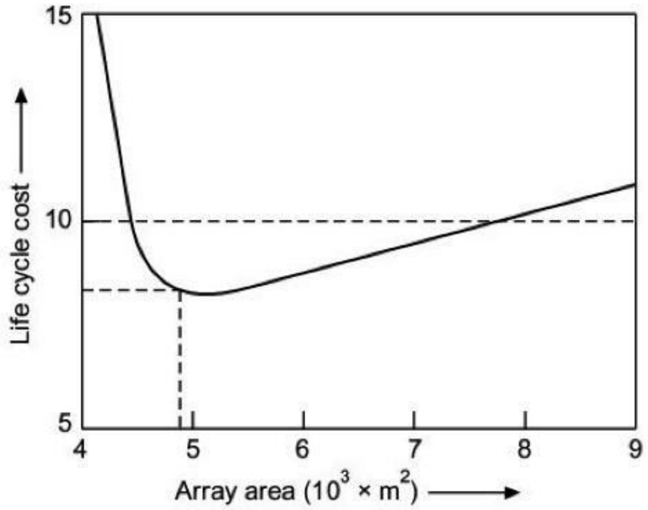


Figure 2 Graph of photo voltaic-diesel system i.e., life cycle cost and array area.

Graph indicates a minimum cost point corresponding to a cost effective design for a PV-diesel hybrid power plant where PV has replaced 90 per cent of the diesel fuel; had it been a diesel system only. Thus, a PV-diesel hybrid power plant ensures continuous power supply and is more

Cost effective as compared to stand alone PV system or stand-alone diesel.

5.8.2 Wind-Diesel Hybrid System

Remote coastal areas where wind speed is sufficient to operate a wind turbine but there is no state grid supply, wind generators are installed to electrify the area. Wind energy being intermittent a backup of diesel generator is required to maintain 24 hour power supply. Thus, wind-diesel hybrid system is installed to supply electric power to emergency load of hospitals, communication services, and defence, commercial and domestic load. Wind-Diesel hybrid system constitutes components, wind turbine, diesel generator, Controller battery and the load, detailed in Figure 3.

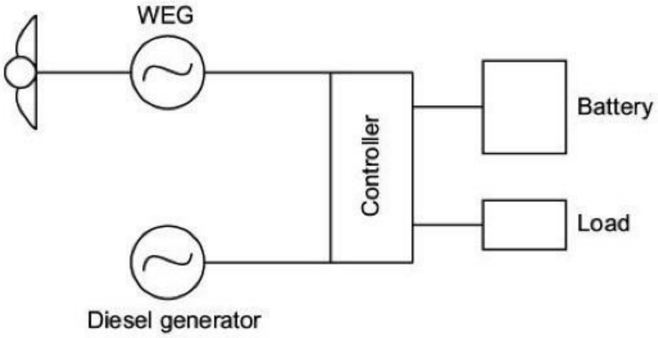


Figure 3 Wind-diesel hybrid system.

During favorable wind 400 V ac is delivered to the controller. The controller converts AC voltage to 120 V dc for charging the battery and it also controls the current required for its charging. Controller also ensures continuous power supply to the load. As the wind speed drops the lower limit, WTG stops and the diesel generator automatically starts to supply energy to the load and also for battery charging.

Thus, wind-diesel hybrid system ensures maximum utilization of free wind energy and continuity of power supply in remote inaccessible areas.

5.8.3 Biomass-Diesel Hybrid System

Combustion is a common process in biomass conversion technology. Application of combustion process is for solid fuels either from cultivated biomass or waste biomass. Biomass is widely available in hills and remote forest areas but becomes scarce during snowy winter. When its supply stops and stock dwindles, energy route of biomass to electrical energy by incineration suffers a setback. This system needs a backup by diesel power electric generator to meet the known lighting and plug loads of residences, commercial establishments, hospitals and other life sustaining loads. Essential components of this hybrid configuration are:

25 kW biomass generator.

Battery bank of 1000 Ah capacity

15 kVA diesel generator.

A biomass-fired steam power plant is made hybrid with a diesel generator along with a controller, battery bank and load is shown in Figure 4.

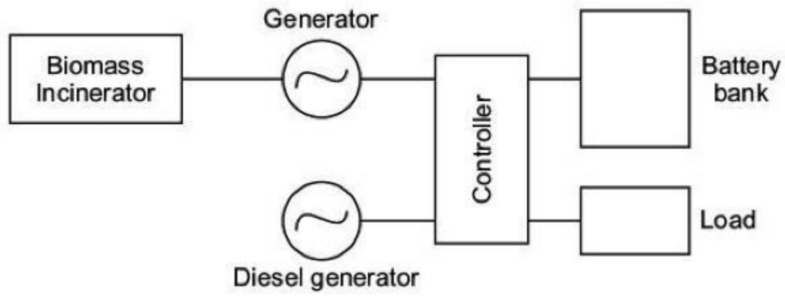


Figure 4 Biomass-diesel hybrid system.

To operate this system, economic viability is necessary by utilizing biomass generator to the full capacity and minimum use of diesel generator, for essential and lifesaving load during crisis period of biomass availability.

5.8.4 Wind-PV Hybrid System

Wind and solar hybrid energy systems are located in open terrains away from multistorey buildings and forests. Locations are selected in those areas where the sunshine and wind are favorable for more than 8 months during a year. A schematic wind-PV hybrid system is shown in Figure 5. During the day when sun shines, the solar photovoltaic plant generate dc electric energy conditioner provided, converts dc to ac and supplies power to the load. During favorable wind speed, wind turbine generator produce ac electrical power. It supplies power to the load and excess energy after conversion to dc is stored by the battery bank. The plant may operate as stand-alone load or may be connected to the state grid.

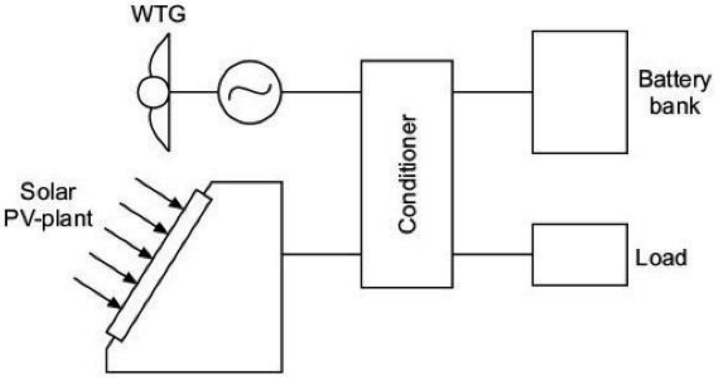


Figure 5 Wind-PV hybrid system.

5.8.5 Micro Hydel-PV Hybrid System

Micro hydel (up to 100 kW) power stations are low head (less than 3 m) installations and provide decentralized power in mountain regions, also in plains on canal falls. In remote areas of J & K, boarder districts of Arunachal Pradesh micro hydro power plants are the only source of energy. With the help of micro hydro power, rural electrification can be achieved besides providing power for pumped irrigation and grinding mills. In Arunachal Pradesh, 425 villages are being electrified by completing 46 small/ micro hydro power projects. However, there are 1058 villages which cannot be illuminated by micro hydel projects as at several locations, head is very low, while at other, quantity of water is small. Solution is to provide micro hydel-PV hybrid system as sunshine is available practically at all locations. Portable micro hydel sets of 15 kW capacities are installed with solar PV panels to complement each other as given in Figure 6.

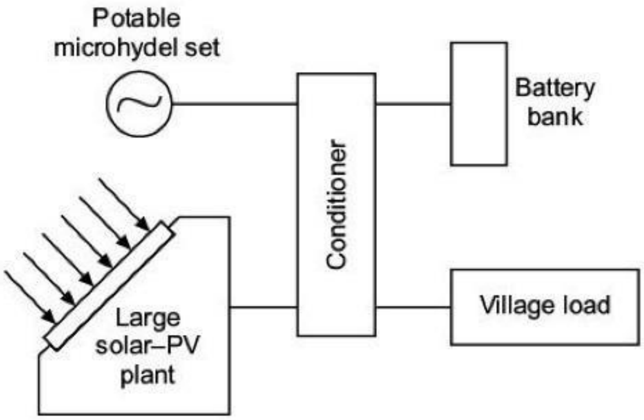


Figure 6 Micro hydel-PV hybrid system.

Micro hydel systems are provided with small dam store water to be used during night when solar PV panels stops power supply. A battery bank may be provided for emergency power supply. A battery bank may be provided for emergency power supply wherever required. Load management is carried out to maintain continuity of supply for 24 hours matching with the capacity of generating equipment.

5.8.6 Biogas-Solar Thermal Hybrid System (A Case Study)

It is a case study of milk chilling Centre located in a remote village Vasna Margia in Kheda district of Gujarat. Major components of this system are:

Biogas plant to be operated with an input of 300 kg cow dung daily.

One 5 H.P. dual fuel engine. Initially it starts with 100 per cent diesel fuel. Subsequently, engine switches to dual fuel mode with fuel ratio 80 per cent biogas and 20 per cent diesel.

Flat plate solar collector is installed on the roof of a building for the supply of hot water (100 litres per day at 60 ° C) required for cleaning the cans and milk chilling equipment parts.

An insulated water storage tank placed over the building connected to the solar collector. Biogas is generated in a KVIC type floating dome vertical design plant with a capacity of 12 cu m/ day gas production.

Biogas from the plant is taken to milk chilling centre (Figure 7) through a G.I. pipeline.

To begin operation, duel fuel engine is started where power transmission to the chilling plant is obtained with a common shaft coupled to the engine. This shaft further operates refrigeration compressor, chilled water circulating pump and air blower detailed in Figure 7.

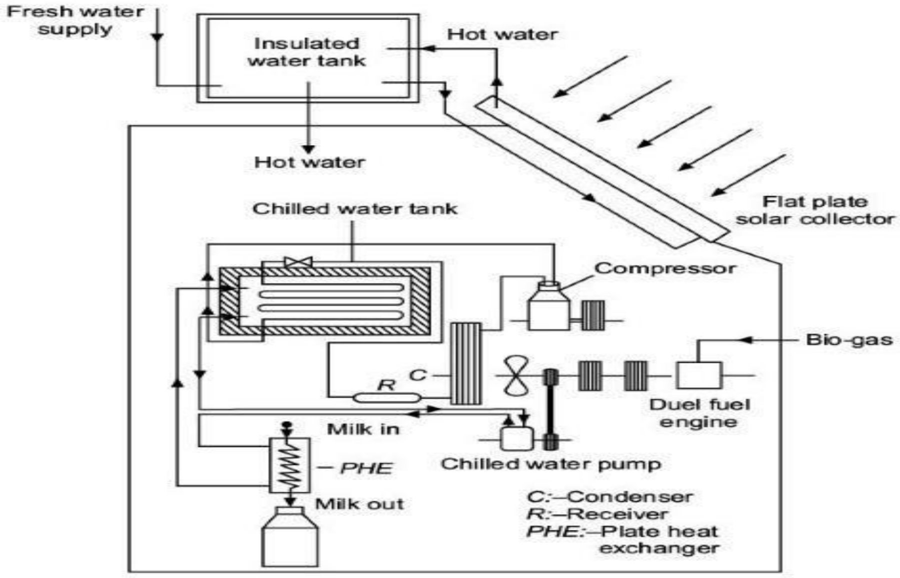


Figure 7 Schematic of milk chilling centre powered by Biogas and solar energy.

With the successful commissioning of this plant, milk cooperative society has become economically viable and milk producing farmers of the area are earning well. Really a combination of two renewable source of energy, i.e., biogas and solar thermal has proved a boon for remote villages.

5.9 Solar-cum-Biomass Dryer Hybrid (A Case Study)

Energy is required for mechanical drying of agricultural products in rural areas where grid electric supply is scarce. Solar and biomass are two main renewable sources of energy that may be used for drying of spices, herbs, and agricultural products for commercial production at low cost. Analysis showed that traditional drying, i.e., open sun drying, dried the turmeric rhizomes in 12 days while solar cum biomass dryer took only 1.5 days and produced better quality products in terms of colour, taste and texture. Selecting right drying technique is necessary in tropical regions where herbs and spices are harvested during winter or rainy season. The solar-cum-biomass dryer was developed at I.I.T. Delhi for 15–18 kg capacity of turmeric rhizomes and other such products. The dryer has two parts: (i) solar dryer

(ii) biomass burner as shown in Figure 15.8.

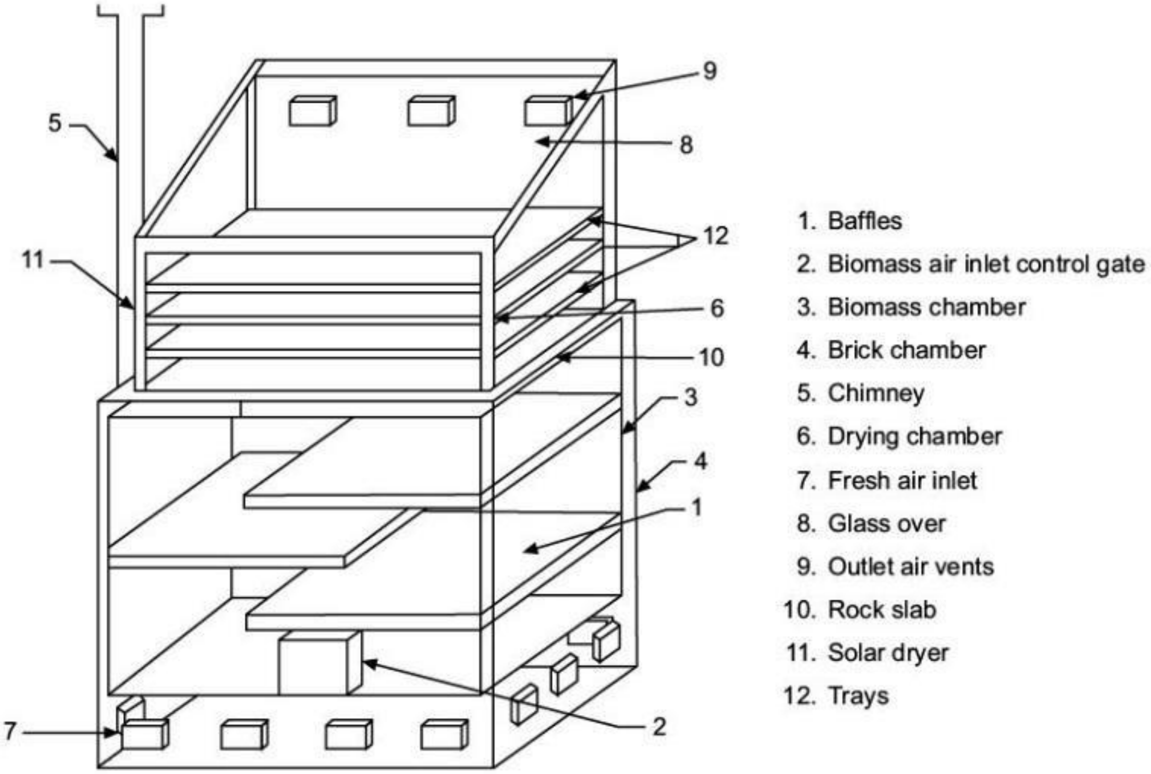


Figure8 Schematic diagram of solar-cum-biomass dryer.

5.9 Solar dryer

It consists of single glazed (2 mm thick) solar dryer mounted on a rock slab supported on a brick wall chamber. Top glass surface is inclined at an angle of 28.5 ° to capture maximum solar radiation at Delhi (latitude 28 ° 32 ▯ N during winter). There are three drying trays of wire mesh with a drying area of 0.94 m2 each. Three adjustable vents are at the top of the dryer. Two doors are at the front for unloading the products.

5.10 Biomass burner

Biomass burner is a rectangular box. A door at the bottom is to feed the biomass and the control airflow for combustion. There is a iron grate for burning biomass. Exhaust gases exit through a chimney. Three metal baffle plates are above the iron grate to lengthen the flow path of combustion gases. A brick chamber encloses the burner which is covered with a rock slab to maintain correct air temperature. Dryer uses solar energy when solar radiations are more than 100 W/m2. When solar radiations fall on glass surface, these are absorbed resulting in increase of dryer temperature. Heated air inside the cabinet goes upward; picks up moisture from the product and goes out from the vents. It reduces pressure inside the cabinet an ambient air is drawn into the dryer through inlet holes. A continuous flow of air is thus established. During period of low or zero solar radiation, biomass burner is used for back up heating. Combustion gases warm the air as it moves over the outer surface. Warm air rises up in the drying chamber; evaporating and picking up moisture from turmeric as it passes through the trays and then escapes through vents. Temperature inside the dryer is controlled to avoid burning of product.

5.11 Dryer efficiency

Thermal efficiency over an entire drying trial (h) is the ratio of the energy used to evaporate the moisture from the crop product to the energy supplied to the dryer. With this dryer, both solar radiation and biomass supplied the energy, so

$$\eta = \frac{W\lambda}{IA + \mathrm{cm}}$$

Where W is the mass of water evaporated (Kg), l is the latent heat of vaporization (MJ kg–1), I is the total radiation on the dryer (MJ m–2), A is the solar collection area (m 2), c is the calorific value of biomass (MJ kg–1), and m is the mass of used biomass (kg). As a test case, 8 kg of fuel wood (calorific value 28.7 MJ kg–1) was burned. Solar biomass dryer removed 12.6 kg of water to dry 15 kg of turmeric to moisture content of 9 per cent (dB). Overall thermal efficiency of the dryer is calculated to be 28.11 per cent. Quality of product maintained in this dryer where as in open sun drying, it gets deteriorated.

5.12 Electric and hybrid electric vehicles

Electric vehicles are propelled by an electric motor powered by rechargeable battery packs. These vehicles need not have Internal Combustion Engines (IEC) system, the drive train and fuel tank. Electric motor replaces the engine and it gets power from rechargeable batteries through a controller. The electronic motor controller provides electric power to the motor based on inputs from accelerator. Electric power is delivered from battery pack, which is like the fuel tank of an electric (e) vehicle. However, they are slow in speed and move only up to 80 km on a charge. Full battery recharge takes nearly four hours. A hybrid electric vehicle combines a conventional internal combustion engine with an electric propulsion system. Presence of electric power train is intended to achieve better fuel economy than conventional vehicle or better performance. Most common of HEV is the hybrid electric car. Hybrid vehicles use both petrol and electric propulsion systems. In such vehicles, the electric motor provides a boost during starting and is recharged during vehicle operations. This cuts emissions significantly and improves fuel economy.

5.13 E-Vehicle Need

E-vehicle are gaining popularity concerning to: (i) High oil prices (ii) Greenhouse gas emissions (iii) Ambient air quality Concern over high oil prices and stringency in pollution and climate regulations have spurred new interest in e-vehicles. These are fuel-efficient, as, technically conversion of electrical energy into motive power is more efficient than burning fuel in an internal combustion engine. According to California Air Resource Board, fuel efficiency of an e-vehicle is three times higher than convention car. As electricity costs less than oil, operating cost per km falls to a fraction of a petrol car.

5.14 Emissions

E-vehicles emit nothing from their tail pipe. But the emissions from power generation are accounted for in the life cycle assessment of e-vehicle. Reva electric car company in UK showed when emissions of power stations wereincluded; the vehicle emitted 63 g CO2 per km. The best hybrid car gives 104 g CO2 per km. A UK study said that the life time emission of an e-vehicle is 3 times less than average emission from internal combustion engines CO2 emission per km from e-cars and hybrids. (Emission from power plants and internal combustion engines) accounted for are given in Figure 9.

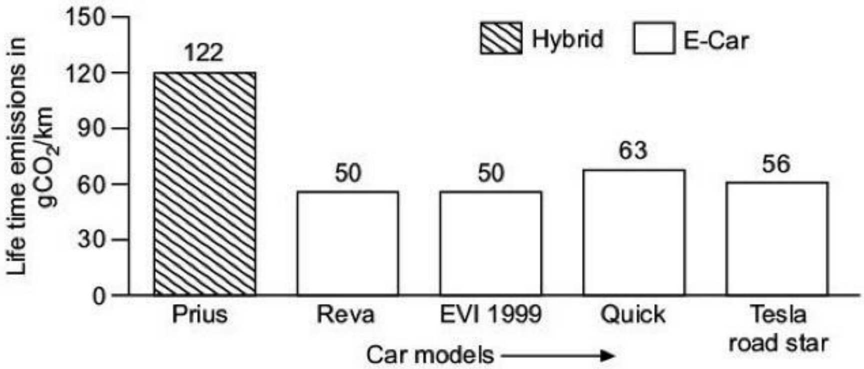


Figure 9 CO_2 emission per km e-cars and hybrids.

The other advantage of an e-vehicle is that there are no oil filters, air filters, spark plugs and radiators which need maintenance.

5.15 Limitations

Widespread use of battery operated vehicles is constrained by high prices, limited driving range, bar on maximum speed and battery efficiency. In India, most e-vehicles run on lead-acid batteries which provide short bursts of power to starter motors in cars. Also, lead is a known environmental hazard with serious health consequences. Lead-acid batteries will have to give way to lithium-ion batteries that improve performance four times over. Lithium ion is currently a dominant battery technology in portable applications. It provides the highest energy density of all rechargeable systems. REVA NXR is a new lithium-ion powered e-car claims that a first charge for 90 minute would offer a range of 320 km a day. The biggest challenge of e- vehicle industry is to produce batteries that can store large amount of energy that can be released and recharged quickly.

5.16 Hydrogen-powered-electric vehicles

Hydrogen is a clean energy carrier that can replace liquid and gaseous fossil fuels. Hydrogen can be used to power electric vehicles for longer distance, better speed, and acceleration and cost comparable with fossil fuel driven vehicles. Conversion of hydrogen to electricity is achieved through fuel cells. Fuelcells are an electrochemical device that converts chemical energy of hydrogen directly into electricity and heat without combustion. Fuel cell systems operate on pure hydrogen and air/ oxygen to produce electricity with water and heat as by-products. A phosphoric acid fuel cell (PAFC) is suitable for hydrogen powered electric vehicles. In India, BHEL has field tested them and commercially available in 40 kW, 200 kW and more sizes. Around Ajanta caves (Maharashtra), fuel cell operated bus ply within 7 km route to avoid pollution. Fuel cell operated vehicles are eco-friendly as it eliminates noise, SO2 and nitric oxide emissions.

5.17 Clean Mobility Options

Low speed e-vehicles with power less than 250 W and speed less than 25 kW/ h are exempt from Central Motor Vehicle Act and Rules. These are not categorized as motor vehicles, so driving licenses are not required. E-vehicles are part of the solution to air pollution and climate change. The e-vehicles will truly become zero emitters when these are charged with electricity from renewable sources such as solar and wind.

Questions

Define hybrid energy systems. What was the need for hybrid systems?

Discuss different types of hybrid systems.

Differentiate between wind-diesel hybrid system and wind-PV hybrid system.

Discuss a case study of installed hybrid energy systems in your city/ state.

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