LECTURE NOTES

ON

SOLAR ENERGY SYSTEMS

B. Tech VI semester

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UNIT-I

INTRODUCTION TO SOLAR ENERGY

1. Solar Energy Basics

Solar is the Latin word for sun—a powerful source of energy that can be used to heat, cool, and light our homes and businesses. That's because more energy from the sun falls on the earth in one hour than is used by everyone in the world in one year. A variety of technologies convert sunlight to usable energy for buildings. The most commonly used solar technologies for homes and businesses are solar water heating, passive solar design for space heating and cooling, and solar photovoltaics for electricity.

Solar Energy Basics:

1. Solar Photovoltaic Technology. These technologies convert sunlight directly into electricity to power homes and businesses.
2. Concentrating Solar Power. These technologies harness heat from the sun to provide electricity for large power stations.
3. Solar Process Heat.
4. Passive Solar Technology.
5. Solar Water Heating.

Solar EnergyBased on the principle of photovoltaic effect, solar cells or photovoltaic cells are made. They convert sunlight into direct current (DC) electricity. But, a singlephotovoltaic cell does not produce enough amount of electricity.

Solar Energy Technologies:

Photovoltaic Systems. Producing electricity directly from sunlight.

1. Solar Hot Water. Heating water with solar energy.
2. Solar Electricity. Using the sun's heat to produce electricity.
3. Passive Solar Heating and Daylighting. Using solar energy to heat and light buildings.
4. Solar Process Space Heating and Cooling.

ENERGY SCENARIO

Any physical activity in this world, whether carried out by human beings or by nature, is cause due to flow of energy in one form or the other. The word ‘energy’ itself is derived from the Greek word ‘en-ergon’, which means ‘in-work’ or ‘work content’. The work output depends on the energy input.

Energy is one of the major inputs for the economic development of any country. In the case of the developing countries, the energy sector assumes a critical importance in view of the ever-increasing energy needs requiring huge investments to meet them.

Energy can be classified into several types based on the following criteria:

- Primary and Secondaryenergy
- Commercial and Non commercialenergy
- Renewable and Non-Renewableenergy
- Conventional and Non-conventionalenergy

1.1 Primary and SecondaryEnergy

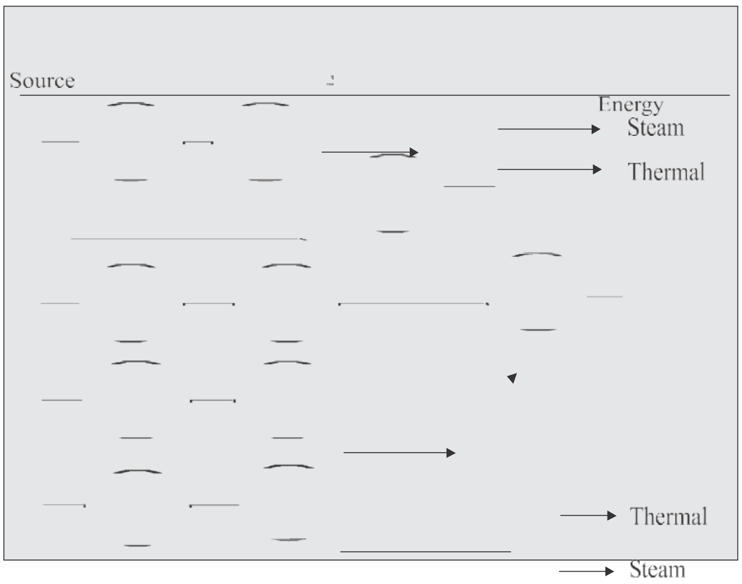


Fig1.1. Major Primary and Secondary sources

Primary energy sources are those that are either found or stored in nature. Common primary energy sources are coal, oil, natural gas, and biomass (such as wood). Other primaryenergy sources available include nuclear energy from radioactive substances, thermal energy stored in earth's interior, and potential energy due to earth's gravity. The major primary and secondary energy sources are shown in Figure1.1

Primary energy sources are costly converted in industrial utilities into secondary energy sources;

for example coal, oil or gas converted into steam and electricity. Primary energy can also be used directly. Some energy sources have non energy uses, for example coal or natural gas can be used as a feedstock in fertilizerplants.

1.2 Commercial Energy and Non CommercialEnergy

Commercial Energy

The energy sources that are available in the market for a definite price are known as commercial energy.By far the most important forms of commercial energy are electricity, coal and refined petroleum products. Commercial energy forms the basis of industrial, agricultural, transport and commercial development in the modern world. In the industrialized countries, commercialized fuels are predominant source not only for economic production, but also for many household tasks of general population.

Examples: Electricity, lignite, coal, oil, natural gas etc.

Non-Commercial Energy

The energy sources that are not available in the commercial market for a price are classified as non-commercial energy. Non-commercial energy sources include fuels such as firewood, cattle dung and agricultural wastes, which are traditionally gathered, and not bought at a price used especially in rural households. These are also called traditional fuels. Non-commercial energy is often ignored in energy accounting.

Example: Firewood, agro waste in rural areas; solar energy for water heating, electricity generation, for drying grain, fish and fruits; animal power for transport, threshing, lifting water for irrigation, crushing sugarcane; wind energy for lifting water and electricitygeneration.

1.3 Renewable and Non-RenewableEnergy

Renewable energy is energy obtained from sources that are essentially inexhaustible. Examples of renewable resources include wind power, solar power, geothermal energy, tidal power and hydroelectric power (See Figure 1.2). The most important feature of renewable energy is that it can be harnessed without the release of harmfulpollutants.

Non-renewable energy is the conventional fossil fuels such as coal, oil and gas, which are likely to deplete with time.

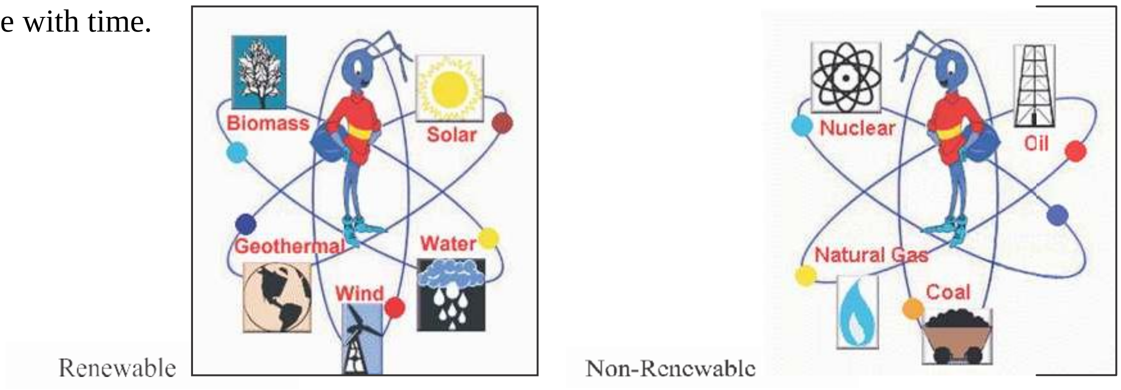


Figure 1.2 Renewable and Non-Renewable Energy

1.4 Conventional and Non-conventional energyresources:

Conventional Energy

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

Non-conventional energy

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

Energy Consumption and Standard Of Living:

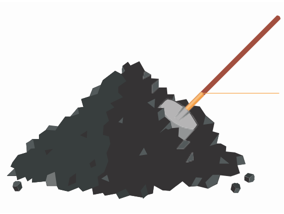
The energy consumption of a nation can be broadly divided into the following areas or sectors depending on energy-related activities. These can be further subdivided into subsectors:

- Domestic sector (houses and offices including commercialbuildings)
- Transportationsector
- Agriculturesector

- Industrysector

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

1.5 Global Primary EnergyReserves*

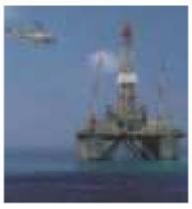


Coal

The proven global coal reserve was estimated to be 9,84,453 million tonnes by end of 2003. The USA had the largest share of the global reserve (25.4%) followed by Russia (15.9%), China (11.6%). India was 4thin the list with8.6%.

Oil

The global proven oil reserve was estimated to be 1147 billion barrels by the end of 2003. Saudi Arabia had the largest share of the reserve with almost 23%. (One barrel of oil is approximately 160 liters)



Gas

The global proven gas reserve was estimated to be 176 trillion cubic metres by the end of 2003. The Russian Federation had the largest share of the reserve with almost27%.

(*Source: BP Statistical Review of World Energy, June 2004)

Global Primary Energy Consumption

The global primary energy consumption at the end of 2003 was equivalent to 9741 million tons of oil equivalent (MTones). The Figure 1.3 shows in what proportions the sources mentioned above contributed to this global figure.

Energy distribution between developed and developing Countries

Although 80 percent of the world's population lies in the developing countries (a four- fold population increase in the past 25 years), their energy consumption amounts to only 40 percent of the world total energy consumption. The high standards of living in the developed countries are attributable to high energy consumptionlevels.

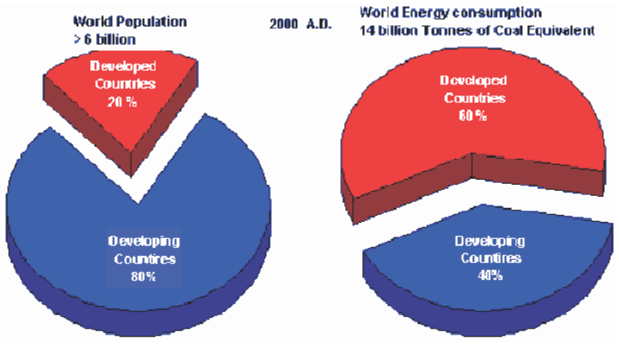


Fig. 1.4: Energy Distribution Between Developed and Developing Countries

Also the rapid population growth in the developing countries has kept the per capita energy consumption low compared with that of highly industrialized developed countries. The world average energy consumption per person is equivalent to 2.2 tones of coal. In industrialized countries, people use four to five times more than the world average and nine times more than the average for the developing countries. An American uses 32 times more commercial energy than an Indian.

1.6 Indian EnergyScenario

Coal dominates the energy mix in India, contributing to 55% of the total primary energy production. Over the years, there has been a marked increase in the share of natural gas in primary energy production from 10% in 1994 to 13% in 1999. There has been a decline in the share of oil in primary energy production from 20% to 17% during the sameperiod.

Energy Supply

Coal Supply

India has huge coal reserves, at least 84,396 million tones of proven recoverable reserves (at the end of 2003). These amounts to almost 8.6% of the world reserves and it may last for about 230 years at the current Reserve to Production (R/P) ratio. In contrast, the world's proven coal reserves are expected to last only for 192 years at the current R/Pratio.

Reserves/Production (R/P) ratio- If the reserves remaining at the end of the year are divided by the production in that year, the result is the length of time that the remaining reserves would last if production were to continue at that level.

India is the fourth largest producer of coal and lignite in the world. Coal production is concentrated in these states (Andhra Pradesh, Uttar Pradesh, Bihar, Madhya Pradesh, Maharashtra, Orissa, Jharkhand, and West Bengal).

Oil Supply

Oil accounts for about 36 % of India’s total energy consumption. India today is one of the top ten oil-guzzling nations in the world and will soon overtake Korea as the third largest consumer of oil in Asia after China and Japan. The country's annual crude oil production is peaked at about 32 million tonne as against the current oil consumption by end of 2007 is expected to reach 136 million tonne(MT), of which domestic production will be only 34 MT. India will have to pay an oil bill of roughly $50 billion, assuming a weighted average price of $50 per barrel of crude. In 2003-04, against total export of $64 billion, oil imports accounted for $21 billion. India imports 70% of its crude needs mainly from gulf nations. The majority of India's roughly 5.4 billion barrels in oil reserves are located in the Bombay High, upper Assam, Cambay, Krishna-Godavari. In terms of sector wise petroleum product consumption, transport accounts for 42% followed by domestic and industry with 24% and 24% respectively. India spent more than Rs.1,10,000 crore on oil imports at the end of 2004.

Natural Gas Supply

Natural gas accounts for about 8.9 per cent of energy consumption in the country. The current demand for natural gas is about 96 million cubic metres per day (mcmd) as against availability of 67 mcmd. By 2007, the demand is expected to be around 200 mcmd. Natural gas reserves are estimated at 660 billion cubicmeters.

Electrical Energy Supply

The all India installed capacity of electric power generating stations under utilities was 1,12,581 MW as on 31st May 2004, consisting of 28,860 MW- hydro, 77,931 MW- thermal and 2,720 MW- nuclear and 1,869 MW- wind (Ministry ofPower).

Nuclear Power Supply

Nuclear Power contributes to about 2.4 per cent of electricity generated in India. India has ten nuclear power reactors at five nuclear power stations producing electricity. More nuclear reactors have also been approved forconstruction.

Hydro Power Supply

India is endowed with a vast and viable hydro potential for power generation of which only

15% has been harnessed so far. The share of hydropower in the country's total generated units has steadily decreased and it presently stands at 25% as on 31st May 2004. It is assessed that exploitable potential at 60% load factor is 84,000 MW.

Final Energy Consumption

Final energy consumption is the actual energy demand at the user end. This is the difference between primary energy consumption and the losses that takes place in transport, transmission & distribution and refinement. The actual final energy consumption (past and projected) is given in Table1.2.

TABLE 1.2 DEMAND FOR COMMERCIAL ENERGY FOR FINAL CONSUMPTION (BAUSCENARIO)

Source	**Units**	**1994-95**	**2001-02**	**2006-07**	**2011-12**
Electricity	Billion Units	289.36	480.08	712.67	1067.88
Coal	Million Tonnes	76.67	109.01	134.99	173.47
Lignite	Million Tonnes	4.85	11.69	16.02	19.70
Natural Gas	Million Cubic	9880	15730	18291	20853
Oil	Million Tonnes	63.55	99.89	139.95	196.47

Source: Planning Commission *BAU:_Business As Usual*

Sector Wise Energy Consumption in India

The major commercial energy consuming sectors in the country are classified as shown in the Figure 1.5. As seen from the figure, industry remains the biggest consumer of commercial energy and its share in the overall consumption is 49%. (Reference year: 1999/2000)

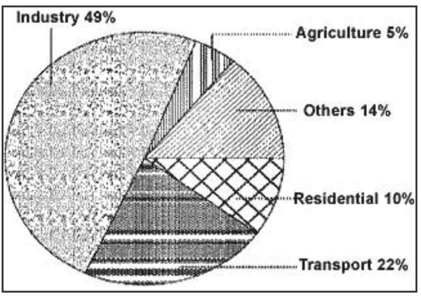


Figure 1.5 Sector Wise Energy Consumption (1999-2000)

1.7 Energy Needs of GrowingEconomy

Economic growth is desirable for developing countries, and energy is essential for economic growth. However, the relationship between economic growth and increased energy demand is not always a straightforward linear one. For example, under present conditions, 6% increase in India's Gross Domestic Product (GDP) would impose an increased demand of 9 % on its energy sector.

In this context, the ratio of energy demand to GDP is a useful indicator. A high ratio reflects energy dependence and a strong influence of energy on GDP growth. The developed countries, by focusing on energy efficiency and lower energy-intensive routes, maintain their energy to GDP ratios at values of less than 1. The ratios for developing countries are muchhigher.

India's Energy Needs

Theplanoutlayvis-à-visshareofenergyisgiveninFigure1.6.AsseenfromtheFigure,18.0% of the total five-year plan outlay is spent on the energysector.

PLANWISE OUTLAY

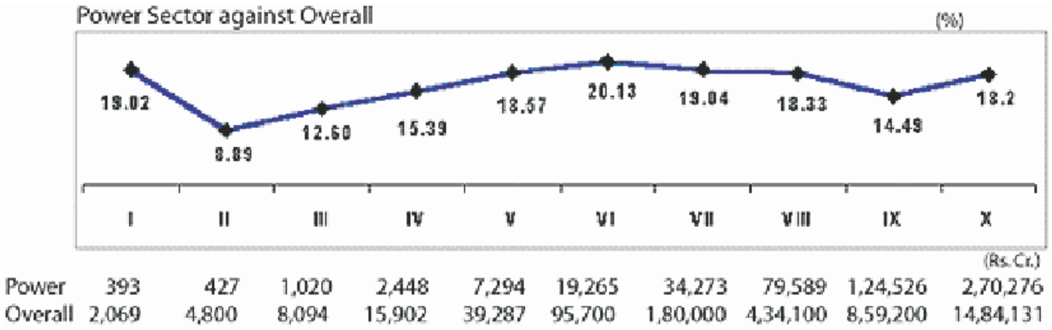


Figure 1.6 Expenditure Towards Energy Sector

Energy Intensity

Energy intensity is energy consumption per unit of GDP. Energy intensity indicates thedevelopmentstageofthecountry.India'senergyintensity is3.7timesofJapan,1.55timesofUSA, 1.47 times of Asia and 1.5 times of World average.

Figure 1.7 Per Capita Energy Consumption

1.8 Long Term Energy Scenario forIndia

Coal: Coal is the predominant energy source for power production in India, generating approximately 70% of total domestic electricity. Energy demand in India is expected to increase over the next 10-15 years; although new oil and gas plants are planned, coal is expected to remain the dominant fuel for power generation. Despite significant increases in total installed capacity dur- ing the last decade, the gap between electricity supply and demand continues to increase. The resulting shortfall has had a negative impact on industrial output and economic growth. However, to meet expected future demand, indigenous coal production will have to be greatly expanded. Production currently stands at around 290 Million tonnes per year, but coal demand is expected to more than double by 2010. Indian coal is typically of poor quality and as such requires to be beneficiated to improve the quality; Coal imports will also need to increase dramatically to satisfy industrial and power generation requirements.

Oil

India's demand for petroleum products is likely to rise from 97.7 million tonnes in 2001-02 to around 139.95 million tonnes in 2006-07, according to projections of the Tenth Five-Year Plan. The plan document puts compound annual growth rate (CAGR) at 3.6 % during the plan period. Domestic crude oil production is likely to rise marginally from 32.03 million tonnes in2001-02 to33.97milliontonnesbytheendofthe10thplanperiod(2006-07).India'sselfsufficiencyinoil has consistently declined from 60% in the 50s to 30% currently. Same is expected to go down to 8% by 2020. As shown in the figure 1.8, around 92% of India's total oil demand by 2020 has to be met by imports.

Natural Gas

India's natural gas production is likely to rise from 86.56 million cmpd in 2002-03 to 103.08 million cmpd in 2006-07. It is mainly based on the strength of a more than doubling of production by private operators to 38.25 mm cmpd.

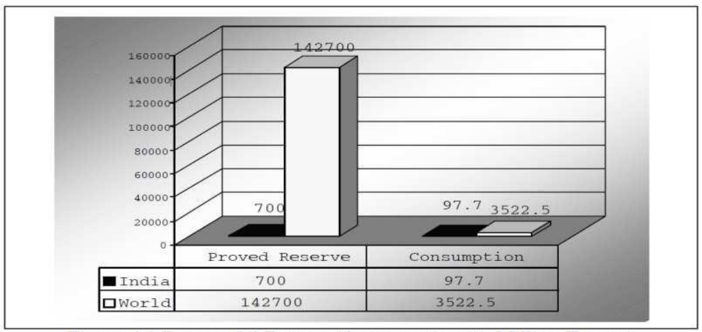
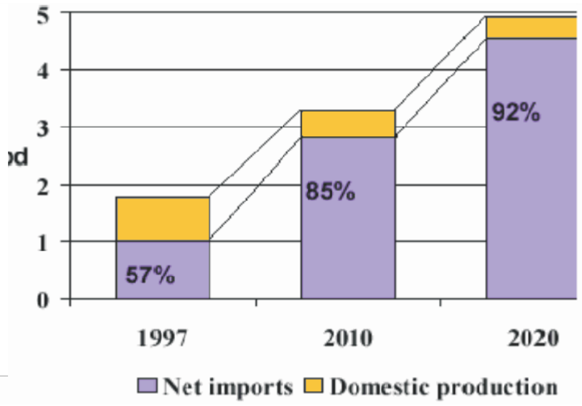


Figure 1.9 Proven Oil Reserve/Consumption (in Million Tonnes) India Vs World (At End 2002)



Electricity

India currently has a peak demand shortage of around 14% and an energy deficit of 8.4%. Keeping this in view and to maintain a GDP (gross domestic product) growth of 8% to 10%, the Government of India has very prudently set a target of 215,804 MW power generation capacity by March 2012 from the level of 100,010 MW as on March 2001, that is a capacity addition of 115,794 MW in the next 11 years. In the area of nuclear power the objective is to achieve 20,000 MW of nuclear generation capacity by the year2020.

TABLE 1.3 INDIA'S PERSPECTIVE PLAN FOR POWER FOR ZERO DEFICIT POWER BY 2011/12 (SOURCE TENTH AND ELEVENTH FIVE-YEAR PLAN PROJECTIONS)

	Thermal (Coal) (MW)	**Gas / LNG / Diesel (MW)**	**Nuclear (MW)**	**Hydro (MW)**	**Total(MW)**
Installed capacity as on March 2001	61,157	Gas:10,153 Diesel:864	2720	25,116	100,010
Additional capacity (2001-2012)	53,333	20,408	9380	32,673	115,794
Total capacity as on March 2012	114,490 (53.0%)	31,425 (14.6%)	12,100 (5.6%)	57,789 (26.8%)	215,804

1.9 Energy Pricing inIndia

Price of energy does not reflect true cost to society. The basic assumption underlying efficiency of marketplacedoesnotholdinoureconomy,sinceenergypricesareundervaluedandenergywastages arenottakenseriously.PricinpracticesinIndialikemanyotherdevelopingcountries areinfluenced by political, social and economic compulsions at the state and central level. More often than not, this has been the foundation for energy sector policies in India. The Indian energy sector offers many examples of cross subsidies e.g., diesel, LPG and kerosene being subsidized by petrol, petroleum products for industrial usage and industrial, and commercial consumers of electricity subsidizing the agricultural and domesticconsumers.

Coal

Grade wise basic price of coal at the pithead excluding statutory levies for run-of-mine (ROM) coal are fixed by Coal India Ltd from time to time. The pithead price of coal in India compares favorably with price of imported coal. In spite of this, industries still import coal due its higher calorific value and low ash content.

Oil

As part of the energy sector reforms, the government has attempted to bring prices for many of the petroleum products (naphtha, furnace oil, LSHS, LDO and bitumen) in line with international prices. The most important achievement has been the linking of diesel prices to international prices and a reduction in subsidy. However, LPG and kerosene, consumed mainly by domestic sectors, continue to be heavily subsidized. Subsidies and cross-subsidies have resulted in serious distortions in prices, as they do not reflect economic costs in manycases

Natural Gas

The government has been the sole authority for fixing the price of natural gas in the country. It has also been taking decisions on the allocation of gas to various competing consumers. The gas prices varies from Rs 5 to Rs.15 per cubic meter.

Electricity

Electricity tariffs in India are structured in a relatively simple manner. While high tension consumers are charged based on both demand (kVA) and energy (kWh), the low-tension (LT) consumer pays only for the energy consumed (kWh) as per tariff system in most of the electricity boards. The price per kWh varies significantly across States as well as customer segments with- in a State. Tariffs in India have been modified to consider the time of usage and voltage level of supply. In addition to the base tariffs, some State Electricity Boards have additional recovery from customers in form of fuel surcharges, electricity duties and taxes. For example, for an industrial consumer the demand charges may vary from Rs. 150 to Rs. 300 per kVA, whereas the energy charges may vary anywhere between Rs. 2 to Rs. 5 per kWh. As for the tariff adjustment mechanism, even when some States have regulatory commissions for tariff review, the decisions to effect changes are still political and there is no automatic adjustment mechanism, which can ensure recovery of costs for the electricityboards.

1.10 Energy andEnvironment

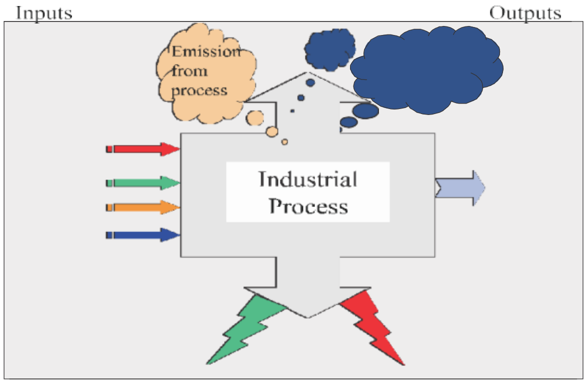


Figure 1.10 Inputs & Outputs of Process

The usage of energy resources in industry leads to environmental damages by polluting the atmosphere. Few of examples of air pollution are sulphur dioxide (SO_2), nitrous oxide (NO_X) and carbon monoxide (CO) emissions from boilers and furnaces, Chlorofluro carbons (CFC) emissions from refrigerants use, etc. In chemical and fertilizers industries, toxic gases are released. Cement plants and power plants spew out particulate matter. Typical inputs, outputs, and emissions for a typical industrial process are shown in Figure.

Air Pollution

A variety of air pollutants have known or suspected harmful effects on human health and the environment. These air pollutants are basically the products of combustion from fossil fuel use. Air pollutants from these sources may not only create problems near to these sources but also can cause problems far away. Air pollutants can travel long distances, chemically react in the atmosphere to produce secondary pollutants such as acid rain or ozone.

Evolutionary Trends in Pollution Problems

both developed and rapidly industrializing countries, the major historic air pollution problem has typically been high levels of smoke and SO_2 arising from the combustion of sulphur-containing fossil fuels such as coal for domestic and industrialpurposes.

Smogs resulting from the combined effects of black smoke, sulphate / acid aerosol and fog have been seen in European cities until few decades ago and still occur in many cities in developing world. In developed countries, this problem has significantly reduced over recent decades as a result of changing fuel-use patterns; the increasing use of cleaner fuels such as natural gas, and the implementation of effective smoke and emission controlpolicies.

In both developed and developing countries, the major threat to clean air is now posed by traffic emissions. Petrol- and diesel engine motor vehicles emit a wide variety of pollutants, principally carbon monoxide (CO), oxides of nitrogen (NOx), volatile organic compounds (VOCs) and particulates, which have an increasing impact on urban airquality.

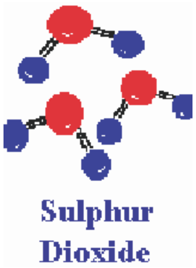
Inaddition,photochemicalreactionsresultingfromtheactionofsunlightonNO$_2$andVOCsfrom vehicles leads to the formation of ozone, a secondary long-range pollutant, which impacts in rural areas often far from the original emission site. Acid rain is another long-range pollutant influenced by vehicle NOxemissions.

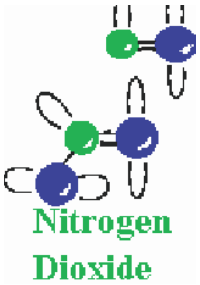
Industrial and domestic pollutant sources, together with their impact on air quality, tend to be steady-state or improving over time. However, traffic pollution problems are worsening world-wide. The problem may be particularly severe in developing countries with dramatically increasing vehicle population, infrastructural limitations, poor engine/emission control technologies and limited provision for maintenance or vehicle regulation.

The principle pollutants produced by industrial, domestic and traffic sources are sulphur dioxide, nitrogen oxides, particulate matter, carbon monoxide, ozone, hydrocarbons, benzene, 1,3-butadiene, toxic organic micro pollutants, lead and heavymetals.

Brief introduction to the principal pollutants are as follows:

Sulphur dioxide is a corrosive acid gas, which combines with water vapour in the atmosphere to produce acid rain. Both wet and dry deposition have been implicated in the damage and destruction of vegetation and in the degradation of soils, building materials and watercourses. SO$_2$ in ambient air is also associated with asthma and chronic bronchitis. The principal source of this gas is power stations and industries burning fossil fuels, which contain sulphur.





Nitrogen oxides are formed during high temperature combustion processes from the oxidation of nitrogen in the air or fuel. The principal source of nitrogen oxides - nitric oxide (NO) and nitrogen dioxide (NO$_2$), collectively known as NOx is road traffic. NO and NO$_2$ concentrations are greatest in urban areas where traffic is heaviest. Other important sources are power stations and industrialprocesses.

Nitrogen oxides are released into the atmosphere mainly in the form of NO, which is then readily oxidized to NO$_2$ by reaction with ozone.

Elevated levels of NO$_x$ occur in urban environments under stable meteorological conditions,

when the air mass is unable to disperse.

Nitrogen dioxide has a variety of environmental and health impacts. It irritates the respiratory system and may worsen asthma and increase susceptibility to infections. In the presence of sunlight, it reacts with hydrocarbons to produce photochemical pollutants such asozone.

Nitrogen oxides combine with water vapour to form nitric acid. This nitric acid is in turn removedfromtheatmospherebydirectdepositiontotheground,ortransfertoaqueousdroplets(e.g. cloud or rainwater), thereby contributing to aciddeposition.

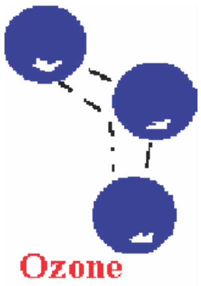
Acidification from SO_2 and NO_x

Acidification of water bodies and soils, and the consequent impact on agriculture, forestry and fisheries are the result of the re-deposition of acidifying compounds resulting principally from the oxidation of primary SO_2 and NO_2 emissions from fossil fuel combustion. Deposition may be by either wet or dry processes, and acid deposition studies often need to examine both of these acidification routes.

Airborne **particulate matter** varies widely in its physical and chemical composition, source and particle size. PM_{10} particles (the fraction of particulates in air of very small size (<10 µm)) are of major current concern, as they are small enough to penetrate deep into the lungs and so potentially pose significant health risks. In addition, they may carry surface-absorbed carcinogenic compounds into the lungs. Larger particles, combustion, where transport of hot exhaust vapour into a cooler exhaust pipe can lead to spontaneous nucleation of "carbon" particles before emission. Secondary particles are typically formed when low volatility products are generated in the atmosphere, for example the oxidation of sulphur dioxide to sulphuric acid. The atmospheric lifetime of particulate matter is strongly related to particle size, but may be as long as 10 days for particles of about 1mm indiameter.

Concern about the potential health impacts of PM_{10} has increased very rapidly over recent years. Increasingly, attention has been turning towards monitoring of the smaller particle fraction $PM_{2.5}$ capable of penetrating deepest into the lungs, or to even smaller size fractions or total particle numbers.

Carbon monoxide (CO) is a toxic gas, which is emitted into the atmosphere as a result of combustion processes, and from oxidation of hydrocarbons and other organic compounds. In urban areas, CO is produced almost entirely (90%) from road traffic emissions. CO at levels found in ambient air may reduce the oxygen-carrying capacity of the blood. It survives in the atmosphere for a period of approximately 1 month and finally gets oxidized to carbon dioxide(CO_2).



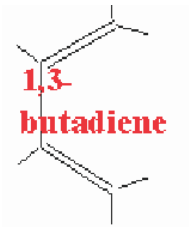
Ground-level ozone (O_3), unlike other primary pollutants mentioned above, is not emitted directly into the atmosphere, but is a secondary pollutant produced by reaction between nitrogen dioxide (NO_2), hydrocarbons and sunlight. Ozone can irritate the eyes and air passages causing breathing difficulties and may increase susceptibility to infection. It is a highly reactive chemical, capable of attacking surfaces, fabrics and rubber materials. Ozone is also toxic to some crops, vegetation andtrees.

Whereas nitrogen dioxide (NO_2) participates in the formation of ozone, nitrogen oxide (NO) destroys ozone to form oxygen (O_2) and nitrogen dioxide (NO_2). For this reason, ozone levels are not as high in urban areas (where high levels of NO are emitted from vehicles) as in rural areas. As the nitrogen oxides and hydrocarbons are transported out of urban areas, the ozone-destroying NO is oxidized to NO_2, which participates in ozoneformation.

Hydrocarbons

There are two main groups of hydrocarbons of concern: volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs). VOCs are released in vehicle exhaust gases either as unburned fuels or as combustion products, and are also emitted by the evaporation of solvents and motor fuels. Benzene and 1,3-butadiene are of particular concern, as they are known carcinogens. Other VOCs are important because of the role they play in the photochemical formation of ozone in the atmosphere.

Benzene is an aromatic VOC, which is a minor constituent of petrol (about 2% by volume). The main sources of benzene in the atmosphere are the distribution and combustion of petrol. Of these, combustion by petrol vehiclesisthesinglebiggestsource(70%oftotalemissions) whilst the refining, distribution and evaporation of petrol from vehicles accounts for approximately a further 10% of total emissions. Benzene is emitted in vehicle exhaust not only as unburnt fuel but also as a product of the decomposition of other aromatic compounds. Benzene is a known human carcinogen.



1,3-butadiene, like benzene, is a VOC emitted into the atmosphere principally from fuel combustion of petrol and diesel vehicles. Unlike benzene, however, it is not a constituent of the fuel but is produced by the combustion of olefins. 1,3-butadiene is also an important chemical in certain industrial processes, particularly the manufacture of synthetic rubber. It is handled in bulk at a small number of industrial locations. Other than in the vicinity of such locations, the dominant source of 1,3-butadiene in the atmosphere are the motor vehicles. 1,3 Butadiene is also a known, potent, humancarcinogen.

TOMPs (Toxic Organic Micro pollutants) are produced by the incomplete combustion of fuels. They comprise a complex range of chemicals some of which, although they are emitted in very small quantities, are highly toxic or and carcinogenic. Compounds in this category include:

- PAHs (PolyAromaticHydrocarbons)
- PCBs (PolyChlorinatedBiphenyls)
- Dioxins
- Furans

Heavy Metals and Lead

Particulate metals in air result from activities such as fossil fuel combustion (including vehicles), metal processing industries and waste incineration. There are currently no emission standards for metals other than lead. Lead is a cumulative poison to the central nervous system, particularly detrimental to the mental development of children.

Lead is the most widely used non-ferrous metal and has a large number of industrial applications. Its single largest industrial use worldwide is in the manufacture of batteries and it is also used in paints, glazes, alloys, radiation shielding, tank lining and piping.

As tetraethyl lead, it has been used for many years as an additive in petrol; with the increasing use of unleaded petrol, however, emissions and concentrations in air have reduced steadily in recent years.

Climatic Change

Human activities, particularly the combustion of fossil fuels, have made the blanket of green-house gases (water vapour, carbon dioxide, methane, ozone etc.) around the earth thicker. The resulting increase in global temperature is altering the complex web of systems that allow life to thrive on earth such as rainfall, wind patterns, ocean currents and distribution of plant and animalspecies.

Greenhouse Effect and the Carbon Cycle

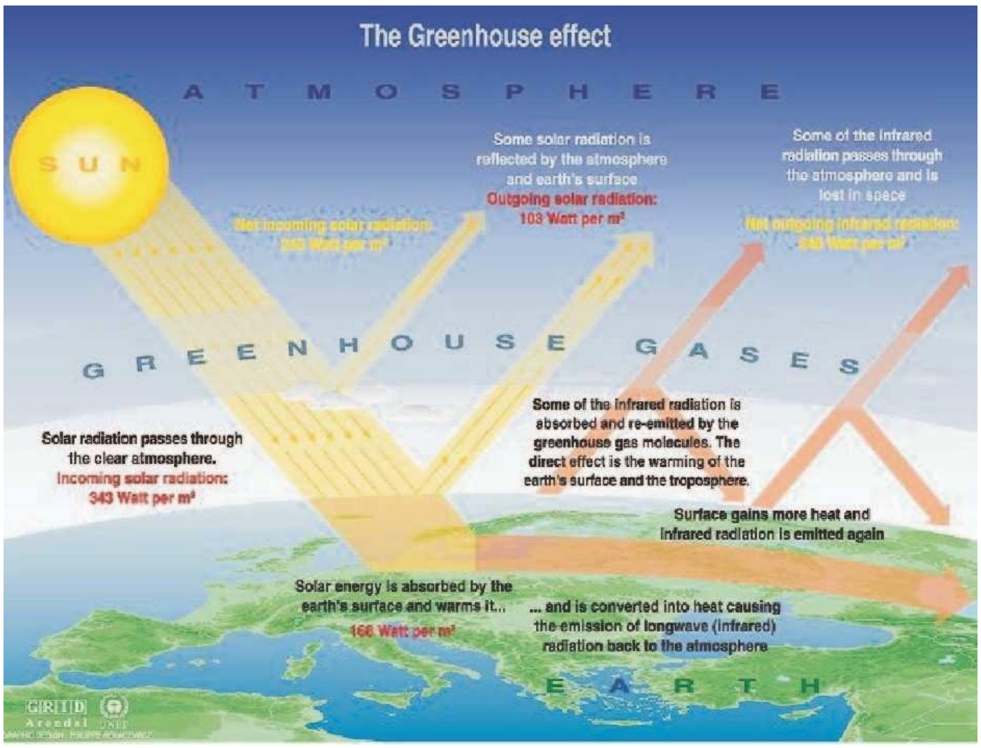


Fig 1.11 Thegreen house effect

Life on earth is made possible by energy from the sun, which arrives mainly in the form of visible light. About 30 percent of the sunlight is scattered back into space by outer atmosphere and the balance 70 percent reaches the earth's surface, which reflects it in form of infrared radiation. The escape of slow moving infrared radiation is delayed by the green house gases. A thicker blanket of greenhouse gases traps more infrared radiation and increase the earth's temperature (Refer Figure1.11).

Greenhouse gases makeup only 1 percent of the atmosphere, but they act as a blanket aroundtheearth,orlikeaglassroofofagreenhouseandkeeptheearth30degreeswarmerthan it would be otherwise - without greenhouse gases, earth would be too cold to live. Human activities that are responsible for making the greenhouse layer thicker are emissions of carbon dioxide from the combustion of coal, oil and natural gas; by additional methane and nitrous oxide from farming activities and changes in land use; and by several man made gases that have a long life in theatmosphere.

The increase in greenhouse gases is happening at an alarming rate. If greenhouse gases emissions continue to grow at current rates, it is almost certain that the atmospheric levels of carbon dioxide will increase twice or thrice from pre-industrial levels during the 21st century.

Even a small increase in earth's temperature will be accompanied by changes in climate-such as cloud cover, precipitation, wind patterns and duration of seasons. In an already highly crowded and stressed earth, millions of people depend on weather patterns, such as monsoon rains, to continue as they have in the past. Even minimum changes will be disruptive and difficult.

Carbon dioxide is responsible for 60 percent of the "enhanced greenhouse effect". Humans are burning coal, oil and natural gas at a rate that is much faster than the rate at which these fossil fuels were created. This is releasing the carbon stored in the fuels into the atmosphere and upsetting the carbon cycle (a precise balanced system by which carbon is exchanged between the air, the oceans and land vegetation taking place over millions of years). Currently, carbon dioxide levels in the atmospheric are rising by over 10 percent every 20 years.

Current Evidence of Climatic Change

Cyclones, storm, hurricanes are occurring more frequently and floods and draughts are more intense than before. This increase in extreme weather events cannot be explained away as random events.

This trend toward more powerful storms and hotter, longer dry periods is predicted by computer models. Warmer temperatures mean greater evaporation, and a warmer atmosphere is able to hold more moisture and hence there is more water aloft that can fall as precipitation. Similarly, dry regions are prone to lose still more moisture if the weather is hotter and hence this leads to more severe droughts and desertification.

Future Effects

Even the minimum predicted shifts in climate for the 21st century are likely to be significant and disruptive. Predictions of future climatic changes are wide-ranging. The global temperaturemayclimbfrom1.4to5.8degreesC;thesealevelmayrisefrom9to88cm.Thus, increases in sea level this century are expected to range from significant to catastrophic. This uncertainty reflects the complexity, interrelatedness, and sensitivity of the natural systems that make up theclimate.

Severe Storms and Flooding

The minimum warming forecast for the next 100 years is more than twice the 0.6 degree C increase that has occurred since 1900 and that earlier increase is already having marked consequences. Extreme weather events, as predicted by computer models, are striking more often and can be expected to intensify and become still more frequent. A future of more severe storms and floods along the world's increasingly crowded coastlines is likely.

Food Shortages

Although regional and local effects may differ widely, a general reduction is expected in potential crop yields in most tropical and sub-tropical regions. Mid-continental areas such as the United States' "grain belt" and vast areas of Asia are likely to become dry. Sub-Saharan Africa where dry land agriculture relies solely on rain, the yields would decrease dramatically even with minimum increase in temperature. Such changes could cause disruptions in food supply in a world is already afflicted with food shortages andfamines.

Dwindling Freshwater supply

Salt-water intrusion from rising sea levels will reduce the quality and quantity of freshwater supplies. This is a major concern, since billions of people on earth already lack access to freshwater. Higher ocean levels already are contaminating underground water sources in many parts of the world.

Loss of Biodiversity

Mostoftheworld'sendangeredspecies(some25percentofmammalsand12percentofbirds) may become extinct over the next few decades as warmer conditions alter the forests,wetlands, and rangelands they depend on, and human development blocks them from migrating else where.

Increased Diseases

Higher temperatures are expected to expand the range of some dangerous "vector-borne" diseases, such as malaria, which already kills 1 million people annually, most of them children.

A World Under Stress

Ongoing environmentally damaging activities such as overgrazing, deforestation, and denuded agricultural soils means that nature will be more vulnerable than previously to changes in climate.

Similarly, the world's vast human population, much of it poor, is vulnerable to climate stress. Millions live in dangerous places such as floodplains or in slums around the big cities of thedevelopingworld.Oftenthereisnowhereelseforpopulationtomove.Inthedistantpast, man and his ancestors migrated in response to changes in habitat. There will be much less room for migration in future.

Global warming almost certainly will be unfair. The industrialized countries of North America and Western Europe, and other countries such as Japan, are responsible for the vast amountofpastandcurrentgreenhouse-gasemissions.Theseemissionsareincurredforthehigh standards of living enjoyed by the people in thosecountries.

Yet those to suffer most from climate change will be in the developing world. They have fewer resources for coping with storms, with floods, with droughts, with disease outbreaks, and with disruptions to food and water supplies. They are eager for economic development themselves, but may find that this already difficult process has become more difficult because of climate change. The poorer nations of the world have done almost nothing to cause global warming yet is most exposed to its effects.

Acid Rain

Acid rain is caused by release of SO_X and NO_X from combustion of fossil fuels, which then mix with water vapor in atmosphere to form sulphuric and nitric acids respectively (Refer Figure 1.12).

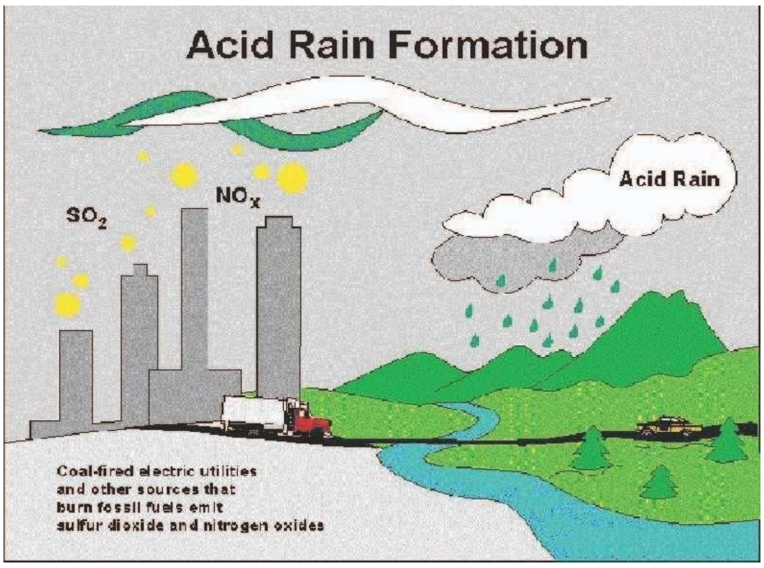


Fig 1.12 Acid Rain

The effects of acid rain are as follows:

- Acidification of lakes, streams, andsoils
- Directandindirecteffects(releaseofmetals,Forexample:Aluminumwhichwashesaway plantnutrients)

- Killing of wildlife (trees, crops, aquatic plants, andanimals)
- Decay of building materials and paints, statues, andsculptures
- Health problems (respiratory, burning- skin andeyes)

1.11 EnergySecurity

The basic aim of energy security for a nation is to reduce its dependency on the imported energy sources for its economic growth.

India will continue to experience an energy supply shortfall throughout the forecast period. This gap has widened since 1985, when the country became a net importer of coal. India has been unable to raise its oil production substantially in the 1990s. Rising oil demand of close to

10 percent per year has led to sizable oil import bills. In addition, the government subsidizes refined oil product prices, thus compounding the overall monetary loss to the government.

Imports of oil and coal have been increasing at rates of 7% and 16% per annum respectively during the period 1991-99. The dependence on energy imports is projected to increase in the future. Estimates indicate that oil imports will meet 75% of total oil consumption requirementsand coal imports will meet 22% of total coal consumption

As per requirements in 2006. The imports of gas and LNG (liquefied natural gas) are likely to increase in the coming years. This energy import dependence implies vulnerability to external price shocks and supply fluctuations, which threaten the energy security of the country.

Increasing dependence on oil imports means reliance on imports from the Middle East, a region susceptible to disturbances and consequent disruptions of oil supplies. This calls for diversification of sources of oil imports. The need to deal with oil price fluctuations also necessitates measures to be taken to reduce the oil dependence of the economy, possibly through fiscal measures to reduce demand, and by developing alternatives to oil, such as natural gas and renewableenergy.

Some of the strategies that can be used to meet future challenges to their energy security are

- Buildingstockpiles
- Diversification of energy supplysources
- Increased capacity of fuelswitching
- Demandrestraint,
- Development of renewable energysources.
- Energyefficiency

- Sustainabledevelopment

Although all these options are feasible, their implementation will take time. Also, for countries like India, reliance on stockpiles would tend to be slow because of resource constraints. Besides, the market is not sophisticated enough or the monitoring agencies experienced enough to predict the supply situation in time to take necessary action. Insufficient storage capacity is another cause for worry and needs to be a augmented, if India has to increase its energy stock pile.

However, out of all these options, the simplest and the most easily attainable is reducing demand through persistent energy conservation efforts.

1.12 Energy Conservation and itsImportance

Coal and other fossil fuels, which have taken three million years to form, are likely to deplete soon. In the last two hundred years, we have consumed 60% of all resources. For sustainable development, we need to adopt energy efficiency measures.

Today, 85% of primary energy comes from non- renewable, and fossil sources (coal, oil, etc.). These reserves are continually diminishing with increasing consumption and will not exist for future generations (see Figure 1.13).

What is Energy Conservation?

Energy Conservation and Energy Efficiency are separate, but related concepts. Energy conservation is achieved when growth of energy consumption is reduced, measured in physical terms. Energy Conservation can, therefore, be the result of several processes or developments, such as productivity increase or technological progress. On the other hand Energy efficiency is achieved when energy intensity in a specific product, process or area of production or consumption is reduced without affecting output, consumption or comfort levels. Promotion of energy efficiency will contribute to energy conservationand is there- fore an integral part of energy conservation promotionalpolicies.

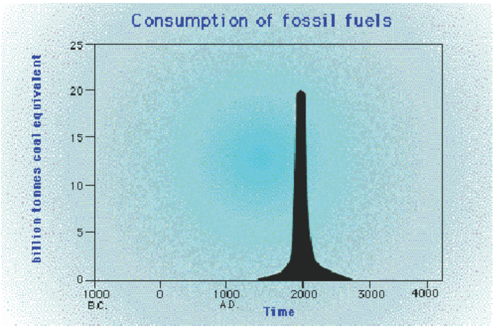


Fig1.13

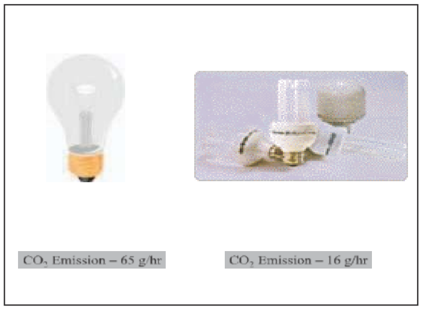


Fig 1.14

Energy efficiency is often viewed as a resource option like coal, oil or natural gas. It provides additional economic value by preserving the resource base and reducing pollution. For example, replacing traditional light bulbs with Compact Fluorescent Lamps (CFLs) means you will use only 1/4th of the energy to light a room. Pollution levels also reduce by the same amount (refer Figure 1.14).

Nature sets some basic limits on how efficiently energy can be used, but in most cases our products and manufacturing processes are still a long way from operating at this theoretical limit. Very simply, energy efficiency means using less energy to perform the same function. Although, energy efficiency has been in practice ever since the first oil crisis in 1973, it has today assumed even more importance because of being the most cost-effective and reliable means of mitigating the global climaticchange. Recognition of that potential has led to high expectations for the control of future CO_2 emissions through even more energy efficiency improvements than have occurred in the past. The industrial sector accounts for some 41 per cent of global primary energy demand and approximately the same share of CO_2 emissions.

1.13 Energy Strategy for theFuture

The energy strategy for the future could be classified into immediate, medium-term and long- term strategy. The various components of these strategies are listedbelow:

Immediate-term strategy:

- Rationalizing the tariff structure of various energyproducts.
- Optimum utilization of existingassets

- Efficiency in production systems and reduction in distribution losses, including those in traditional energysources.
- Promoting R&D, transfer and use of technologies and practices for environmentally sound energy systems, including new and renewable energy sources.

Medium-term strategy:

- Demand management through greater conservation of energy, optimum fuel mix, structural changes in the economy, an appropriate model mix in the transport sector, i.e. greater dependence on rail than on road for the movement of goods and passengers and a shift away from private modes to public modes for passenger transport; changes in design of different products to reduce the material intensity of those products, recycling,etc.
- There is need to shift to less energy-intensive modes of transport. This would include measures to improve the transport infrastructure viz. roads, better design of vehicles, use of compressed natural gas (CNG) and synthetic fuel, etc. Similarly, better urban planning would also reduce the demand for energy use in the transportsector.
- There is need to move away from non-renewable to renewable energy sources viz. solar, wind, biomass energy,etc.

Long-term strategy:

Efficient generation of energy resources

- Efficient production of coal, oil and naturalgas
- Reduction of natural gas flaring

Improving energyinfrastructure

- Building newrefineries
- Creation of urban gas transmission and distributionnetwork
- Maximizing efficiency of rail transport of coalproduction.
- Building new coal and gas fired powerstations.

Enhancing energy efficiency

- Improving energy efficiency in accordance with national, socio-economic, and environ- mentalpriorities
- Promoting of energy efficiency and emissionstandards
- Labelingprogramsforproductsandadoptionofenergyefficienttechnologiesin largeindustries

Deregulation and privatization of energy sector

- Reducing cross subsidies on oil products and electricitytariffs
- Decontrolling coal prices and making natural gas pricescompetitive
- Privatization of oil, coal and power sectors for improved efficiency.

Investment legislation to attract foreigninvestments.

- Streamlining approval process for attracting private sector participation in power generation, transmission and distribution.

Bureau of Energy Efficiency (BEE):

- The mission of Bureau of Energy Efficiency is to institutionalize energy efficiency services, enable delivery mechanisms in the country and provide leadership to energy efficiency in all sectors of economy. The primary objective would be to reduce energy intensity in the IndianEconomy.
- The general superintendence, directions and management of the affairs of the Bureau is vested in the Governing Council with 26 members. The Council is headed by Union Minister of Power and consists of members represented by Secretaries of various line Ministries, the CEOs of technical agencies under the Ministries, members representing equipment and appliance manufacturers, industry, architects, consumers and five power regions representing the states. The Director General of the Bureau shall be the exfficio member-secretary of theCouncil.
- The BEE will be initially supported by the Central Government by way of grants through budget, it will, however, in a period of 5-7 years become self-sufficient. It would be authorized to collect appropriate fee in discharge of its functions assigned to it. The BEE will also use the Central Energy Conservation Fund and other funds raised from various sources for innovative financing of energy efficiency projects in order to promote energy efficientinvestment.

1.14 DISTRIBUTEDGENERATION

1.0 Distributed Generation Basics

What is Distributed Generation?

Distributed generation (or DG) generally refers to small-scale (typically 1 kW – 50 MW) electric power generators that produce electricity at a site close to customers or that are tied to an electric distribution system. Distributed generators include, but are not limited to synchronous generators, induction generators, reciprocating engines, micro-turbines (combustion turbines that run on high-energy fossil fuels such as oil, propane, natural gas, gasoline or diesel), combustion gas turbines, fuel cells, solar photo-voltaic, and windturbines.

Applications of Distributed Generating Systems

There are many reasons a customer may choose to install a distributed generator. DG can be used to generate a customer's entire electricity supply; for peak shaving (generating a portion of a customer's electricity onsite to reduce the amount of electricity purchased during peak price periods); for standby or emergency generation (as a backup to Wires Owner's power supply); as a green power source (using renewable technology); or for increased reliability. In some remote locations, DG can be less costly as it eliminates the need for expensive construction of distribution and/or transmissionlines.

Benefits of Distributed Generating Systems

Distributed Generation:

Has a lower capital cost because of the small size of the DG (although the investment cost per kVA of a DG can be much higher than that of a large power plant). May reduce the need for large infrastructure construction or upgrades because the

DG can be constructed at the load location.

If the DG provides power for local use, it may reduce pressure on distribution and

transmission lines.

With some technologies, produces zero or near-zero pollutant emissions over its

useful life (not taking into consideration pollutant emissions over the entire product lifecycle ie. pollution produced during the manufacturing, or after decommissioning of the DGsystem).

With some technologies such as solar or wind, it is a form of renewable energy. Can increase power reliability as back-up or stand-by power to customers. Offers customers a choice in meeting their energyneeds.

Challenges associated with Distributed Generating Systems

There are no uniform national interconnection standards addressing safety, power quality and reliability for small distributed generation systems. The current process for interconnection is not standardized amongprovinces.

Interconnection may involve communication with several different organizations The environmental regulations and permit process that have been developed for larger distributed generation projects make some DG projects uneconomical. Contractual barriers exist such as liability insurance requirements, fees and charges, and extensive paperwork.

Solar Energy:

Introduction:

Solar energy is an important, clean, cheap and abundantly available renewable energy. It is received on Earth in cyclic, intermittent and dilute form with very low power density 0 to 1 kW/m2.Solar energy received on the ground level is affected by atmospheric clarity, degree of latitude, etc. For design purpose, the variation of available solar power, the optimum tilt angle of solar flat plate collectors, the location and orientation of the heliostats should be calculated.

Units of solar power and solar energy:

In SI units, energy is expressed in Joule. Other units are angley and Calorie where

1 angley = 1 Cal/cm2.day

1 Cal = 4.186 J

For solar energy calculations, the energy is measured as an hourly or monthly or yearly average and is expressed in terms of kJ/m2/day or kJ/m2/hour. Solar power is expressed in terms of W/m2 or kW/m2.

Essential subsystems in a solar energy plant:

1. **Solar collector or concentrator**: It receives solar rays and collects the energy. It may be of followingtypes:

a) Flat plate type withoutfocusing
b) Parabolic trough type with linefocusing
c) Paraboloid dish with centralfocusing
d) Fresnel lens with centrefocusing
e) Heliostats with centre receiverfocusing

2. **Energy transport medium**: Substances such as water/ steam, liquid metal or gasare usedto
transport the thermal energy from the collector to the heat exchanger or thermal storage. In solar PV systems energy transport occurs in electrical form.

3. **Energy storage**: Solar energy is not available continuously. So we need an energy storage medium for maintaining power supply during nights or cloudy periods. Thereare three major types ofenergy

storage: a) Thermal energy storage; b) Battery storage; c) Pumped storage hydro-electric plant.

4. **Energy conversion plant**: Thermal energy collected by solar collectors is used for producing steam, hot water, etc. Solar energy converted to thermal energy is fed to steam-thermal or gas-thermal powerplant.

5. **Power conditioning, control and protection system**: Load requirements of electrical energy vary with time. The energy supply has certain specifications like voltage,current, frequency, poweretc.

The power conditioning unit performs several functions such as control, regulation, conditioning,
protection, automation, etc.

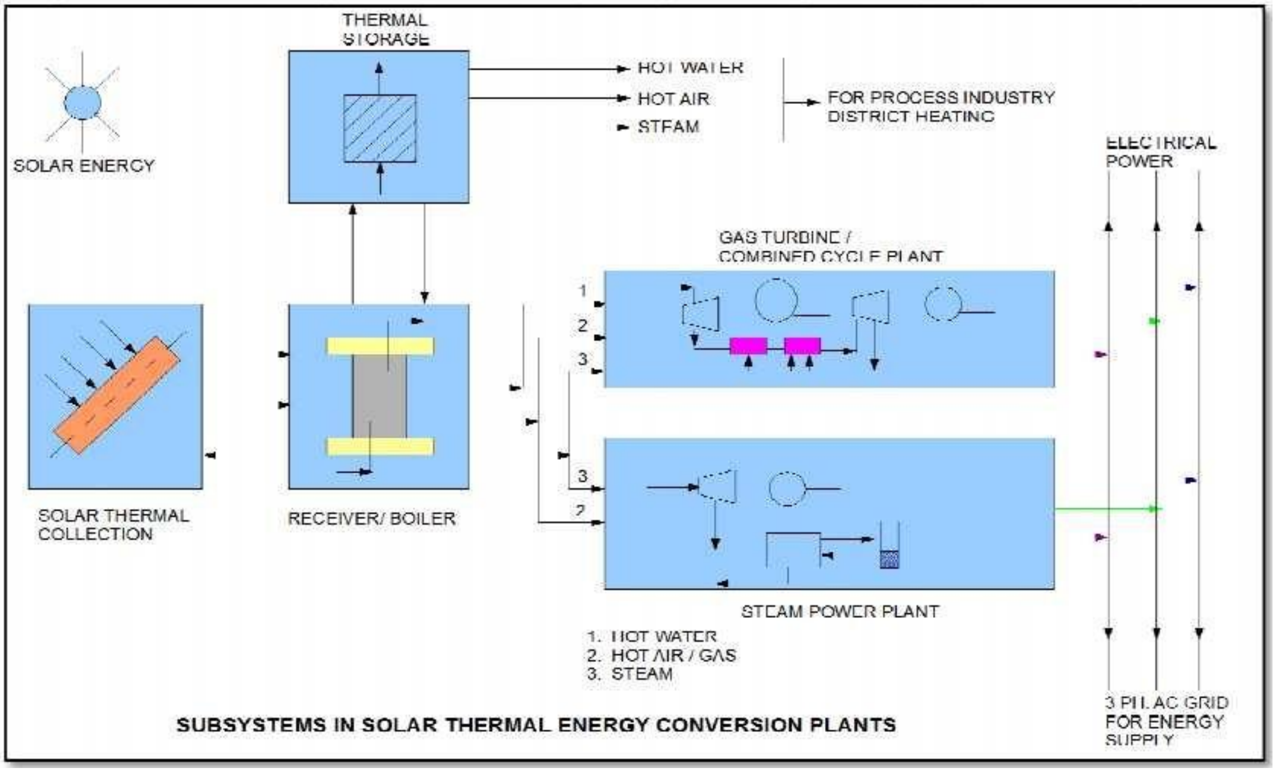


Fig Subsystems in solar thermal energy conversion plants

6. **Alternative or standby power supply**: The backup may be obtained as powerfrom electrical
network or standby diesel generator.

Energy from the sun:
The sun radiates about 3.8 x 10^{26} W of power in all the directions. Out of this about 1.7 x 10^{17} W is
received by earth. The average solar radiation outside the earth's atmosphere is 1.35 kW/m^2 varying from 1.43 kW/m^2 (in January) to 1.33 kW/m^2(in July).

Solar thermal energy (STE) is a form of energy and a technology for harnessing solar energy to generate thermal energy or electrical energy for use inindustry, and in the residential and commercial sectors. The first installation of solar thermal energy equipment occurred in the Sahara Desert approximately in1910

when a steam engine was run on steam produced by sunlight. Because liquid fuel engines were developed and found more convenient, the Sahara project was abandoned, only to be revisited several decades late.

Solar thermal collectors are classified by the United States Energy Information Administration as low-, medium-, or high-temperature collectors. Low-temperature collectors are flat plates generally used to heat swimming pools. Medium-temperature collectors are also usually flat plates but are used for heating water or air for residential and commercial use. High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for fulfilling heat requirements up to 300 deg C / 20 bar pressure in industries, and for electric power production. However, there is a term that used for both the applications. Concentrated Solar Thermal (CST) for fulfilling heat requirements in industries and Concentrated Solar Power (CSP) when the heat collected is used for power generation. CST and CSP are not replaceable in terms of application.

The 377 MW Ivanpah Solar Power Facility is the largest solar power plant in the world, located in the Mojave Desert of California. Other large solar thermal plants include the SEGS installation (354 MW), also in the Mojave, as well as the Solnova Solar Power Station (150 MW), theAndasol solar power station (150 MW), and Extresol Solar Power ion (100 MW), allinSpain.

The first three units of Solnova in the foreground, with the two towers of the PS10 and PS20 solar power stations in the background.

A solar thermal collector system gathers the heat from the solar radiation and gives it to the heat transport fluid. The heat-transport fluid receives the heat from the collector and delivers it to the thermal storage tank, boiler steam generator, heat exchanger etc. Thermal storage system stores heat for a few hours. The heat is released during cloudy hours and at night. Thermal-electric conversion system receives thermal energy and drives steam turbine generator or gas turbine generator. The electrical energy is supplied to the electrical load or to the AC grid. Applications of solar thermal energy systems range from simple solar cooker of 1 kW rating to complex solar central receiver thermal power plant of 200 MW rating.

SOLAR COLLECTORS

Solar thermal energy is the most readily available source of energy. The Solar energy is most important kind of non-conventional source of energy which has been used since ancient times, but in a most primitive manner. The abundant solar energy available is suitable for harnessing for a number of applications. The application of solar thermal energy system ranges from solar cooker of 1 kw to power plant of 200MW. These systems are grouped into low temperature ($<150^oC$), medium temperature ($150\text{-}300^oC$) applications.

Solar Collectors

Solar collectors are used to collect the solar energy and convert the incident radiations into thermal energy by absorbing them. This heat is extracted by flowing fluid (air or water or mixture with antifreeze) in the tube of the collector for further utilization in different applications. The collectors are classified as;

- Non concentratingcollectors
- Concentrating (focusing)collectors

Non Concentrating Collectors

In these collectors the area of collector to intercept the solar radiation is equal to the absorber plate and has concentration ratio of 1. Flat Plate Collectors (Glaze Type) Flat plate collector is most important part of any solar thermal energy system. It is simplest in design and both direct and diffuse radiations are absorbed by collector and converted into useful heat. These collectors are suitable for heating to temperature below 100^oC. The main advantages of flat plate collectors are:

- It utilizes the both the beam as well as diffuse radiation forheating.
- Requires lessmaintenance.

Disadvantages

- Large heat losses by conduction and radiation because of largearea.
- No tracking ofsun.
- Low water temperature isachieved.

The constructional details of flat plate collector is given below

(a) Insulated Box: The rectangular box is made of thin G.I sheet and is insulated from sides and bottom using glass or mineral wool of thickness 5 to 8 cm to reduce losses from conduction to back and side wall. The box is tilted at due south and a tilt angle depends on the latitude of location. The face area of the collector box is kept between 1 to $2m^2$.

(b) Transparent Cover: This allows solar energy to pass through and reduces the convective heat losses from the absorber plate through air space. The transparent tampered glass cover is placed on top of rectangular box to trap the solar energy and sealed by rubber gaskets to prevent the leakage of hot air. It is made of plastic/glass but glass is most favourable because of its transmittance and low surface degradation. However with development of improved quality of plastics, the degradation quality has been improved. The plasticsare available at low cost, light in weight and can be used to make tubes, plates and cover but are suitable for low temperature application 70-120^{o}C with single cover plate or up to 150^{o}C using double cover plate. The thickness of glass cover 3 to 4 mm is commonly used and 1 to 2 covers with spacing 1.5 to 3 cm are generally used between plates. The temperature of glass cover is lower than the absorber plate and is a good absorber of thermal energy and reduces convective and radiative losses ofsky.

(c) Absorber Plate: It intercepts and absorbs the solar energy. The absorber plate is made of copper, aluminum or steel and is in the thickness of1 to 2 mm. It is the most important part of collector along with the tubes products passing the liquid or air to be heated. The plate absorbs the maximum solar radiation incident on it through glazing (cover plate) and transfers the heat to the tubes in contact with minimum heat losses to atmosphere. The plate is black painted and provided with selective material coating to increase its absorption and reduce the emission. The absorber plate has high absorption (80-95%) and lowtransmission/reflection.

(d) Tubes: The plate is attached to a series of parallel tubes or one serpentine tube through which water or other liquid passes. The tubes are made of copper, aluminum or steel in the diameter 1 to 1.5 cm and are brazed, soldered on top/bottom of the absorber water equally in all the tubes and collect it back from the other end. The header pipe is made of same material as tube and of larger diameter. Now-a-days the tubes are made of plastic buttheyhavelowthermalconductivityandhighercoefficientofexpansionthanmetals.

Copper and aluminum are likely to get corroded with saline liquids and steel tubes within hibitors are used at such places.

Removal of Heat: These systems are best suited to applications that require low temperatures. Once the heat is absorbed on the absorber plate it must be removed fast and delivered to the place of storage for further use. As the liquid circulates through the tubes, it absorbs the heat from absorber plate of the collectors. The heated liquid moves slowly and the losses from collector will increase because of rise of high temperature of collector and will lower the efficiency. Flat-plate solar collectors are less efficient in cold weather than in warm weather. Factors affecting the Performance of Flat Plate Collector.

The different factors affecting the performance of system are:

(a) Incident Solar Radiation: The efficiency of collector is directly related with solar radiation falling onit and increases with rise intemperature.

(b) Number of Cover Plate: The increase in number of cover plate reduces the internal convective heat losses but also prevents the transmission of radiation inside the collector. More than two cover plate should not be used to optimize thesystem.

(c) Spacing: The more space between the absorber and cover plate the less internal heat losses. The collector efficiency will be increased. However on the other hand, increase in space between them provides the shading by side wall in the morning and evening and reduces the absorbed solar flux by 2-3% of system. The spacing between absorber and cover plate is kept 2-3 cm to balance theproblem.

(d) Collector Tilt: The flat plate collectors do not track the sun and should be tilted at angle of latitude of the location for an average better performance. However with changing declination angle with seasons the optimum tilt angle is kept $\Phi \pm 15^o$.

The collector is placed with south facing at northern hemisphere to receive maximum radiation throughout the day.

(e) Selective Surface: Some materials like nickel black ($\alpha= 0.89$, $\varepsilon= 0.15$) and black chrome ($\alpha= 0.87$, $\varepsilon= 0.088$), copper oxide ($\alpha= 0.89$, $\varepsilon= 0.17$) etc. are applied chemically on the surface of absorber in a thin layer of thickness 0.1 μm. These chemicals have high degree of absorption (α) to short wave radiation (< 4 μm) and low emission (ε) of long wave radiations (> 4 μm). The higher absorption of solar energy increase the temperature of absorber plate and working fluid. The top losses reduce and the efficiency of the collector increases. The selective surface should be able to withstand high temperature of $300\text{-}400^o$C, cost less, should not oxidize and be corrosive resistant. The property of material should not change with time.

(f) Inlet Temperature: With increase in inlet temperature of working fluid the losses increase to ambient. The high temperature fluid absorbed the less heat from absorber plate because of low temperature difference and increases the top loss coefficient. Therefore the efficiency of collector get reduced with rise in inlettemperature.

(g) Dust on cover Plate: The efficiency of collector decreases with dust particles on the cover plate because the transmission radiation decreases by 1%. Frequent cleaning is required to get the maximum efficiency ofcollector.

Concentrating Collectors

Concentrating collector is a device to collect solar energy with high intensity of solar radiation on the energy absorbing surface. Such collectors use optical system in the form of reflectors or refractors.

These collectors are used for medium (100-300^o C) and high-temperature (above 300^{o}C) applications such as steam production for the generation of electricity. The high temperature is achieved at absorber because of reflecting arrangement provided for concentrating the radiation at required location using mirrors and lenses.

These collectors are best suited to places having more number of clear days in a year.

The area of the absorber is kept less than the aperture through which the radiation passes, to concentrate the solar flux. These collectors require tracking to follow the sun because of optical system. The tracking rate depends on the degree of concentration ratio and needs frequent adjustment for system having high concentration ratio. The efficiency of these collectors lies between 50-70%. The collectors need more maintenance than FPC because of its optical system. The concentrating collectors are classified on the basis of reflector used; concentration ratio and tracking methodadopted.

FPC with Reflectors

The mirrors are placed as reflecting surface to concentrate more radiations on FPC absorber. The fluid temperature is higher by 30^{o}C than achieved in FPC. These collections utilize direct and diffuseradiation.

Lens Focusing Type

The fresnel lenses are used to concentrate the radiation at its focus. The lower side of lenses is grooved so that radiation concentrates on a focus line.

Compound Parabolic Collectors

These collectors are line focusing type. The compound parabolic collectors have two parabolic surfaces to concentrate the solar radiation to the absorber placed at bottom.

These collectors have high concentration ratio and concentrator is moving to track the sun.

Cylindrical Parabolic Collectors

The troughs concentrate sunlight onto a receiver tube, placed along the focal line of the trough. The temperature at the absorber tube is obtained at nearly 400^o C. The absorber in these collectors is moving to receive the reflected radiations by reflector, while the concentrators (trough) remains fixed. Because of its parabolic shape, it can focus the sun at 30 to 100 times its normal intensity (concentration ratio) on a receiver. The heat transfer medium carries the heat at one central place for furtherutilization.

Parabolic Dish Collector

The collectors have mirror-like reflectors and an absorber at the focal point. These collectors are point focusing type. The concentrating ratio of these collectors is 100 and temperature of the receiver can reach up to 2000^o C. These collectors have higher efficiency for converting solar energy to electricity in the small-power plant. In some systems, a heat engine, such as a Stirling engine, is connected to the receiver to generate electricity.

Center Receiver Type (Solar Power Tower)

These collectors are used to collect the large solar energy at one point. This system uses 100-10000 of flat tracking mirror scaled heliostats to reflect the solar energy to central receiver mounted on tower. The energy can be concentrated as much as 1,500 times than that of the energy coming in, from the sun. The losses of energy from the system are minimized as solar energy is being directly transferred by reflection from the heliostats to a single receiver where the sun’s rays heat a fluid to produce steam.

Advantages of concentrating collector over flat collector

- The size of the absorber can be reduced that gives high concentrationratio.
- Thermal losses are less than FPC. However small losses occur in the concentrating collector because of its optical system as well as by reflection, absorption by mirrors and lenses.
- The efficiency increases at hightemperatures.
- In these collectors the area intercepting the solar radiation is greater than the absorber area.
- These collectors are used for high-temperatureapplications.
- Reflectors can cost less per unit area than flat platecollectors.

- Focusing or concentrating systems can be used for electric power generation when not used for heating orcooling
- Little or no anti freeze is required to protect the absorber in a concentrator system whereas the entire solar energy collection surface requires anti freeze protection in a flat platecollector

Disadvantages

- Out of the beam and diffuse solar radiation components, only beam component is collected in case of focusing collectors because diffuse component cannot be reflected and is thuslost.
- 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 thesun.
- Additional requirements of maintenance particular to retain the quality of reflecting surface against dirt, weather, oxidationetc.
- Non –uniform flux on the absorber whereas flux in flat-plate collectors inuniform.
- Additional optical losses such as reflectance loss and the intercept loss, so they introduce additional factors in energybalances.
- High initialcost.

Solar Air Heaters

Air stream is heated by the back side of the collector plate in flat plate collector. 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. If the size of collector is large, a blower is used to draw air into the collector and transmit the hot air to dryer.

The most favorable orientation of a collector for heating only is facing due south at an inclination angle to the horizontal equal to the latitude plus 150. The use of air as the heat transport fluid eliminates both freezing and corrosion problems and small air leaks are of less concern than water leaks

Disadvantages:

1. Need of handling larger volumes of air than liquids due to low density of air as workingsubstance.
2. Thermal capacity of the air islow.

3. They have relatively high fluid circulation costs (especially if the rock heat storage unit is not carefullydesigned)
4. They have relatively large volumes of storage (roughly three times as much volume as for waterheat-storage)
5. They have a higher noiselevel.
6. The system has difficulty of adding conventional absorption air-conditioners to air systems
7. The space is required forducting.

Types of Air Heaters

1. Non porous absorber in which air stream does not flow through the absorberplate

2. Porous absorber that includes slit and expanded material, transpired honey comb and over lapped glass plate

1. Non-porous absorber plate type collectors: A non-porous absorber may be cooled by the air stream flowing over both sides of the plate. In most of the designs, the air flows behind the absorbing surface. Air flow above the upper surface increases the convection losses from the cover plate and therefore is not recommended if the air inlet temperature rise at the collector arelarge.

Transmission of the solar radiation through the transparent cover system and its absorption is identical to that of a liquid type flat-plate collector. To improve collection efficiency selective coating maybeapplied provided there is no much cost.

Due to low heat transfer rates, efficiencies are lower than liquid solar heaters under the same radiation intensity and temperature conditions. Performance of air heaters is improved by:

(a) Roughening the rear of the plate to promote turbulence and improve the convective heat transfercoefficient

(b) Adding fins to increase heat transfer surface. Usually turbulence is also increased which enhances the convective heat transfer. Absorption of solar radiation is improved due to surface radioactive characteristics and the geometry of the corrugations, which help in trapping the reflectedradiation.

2. Collectors with porous absorbers: The main drawback of the non-porous absorber plate is the necessity of absorbing all incoming radiation over the projected area from a thin layer over the surface, which is in the order of a few microns. Unless selective coatings areused,radiativelossesfromtheabsorberplateareexcessive,therefore,thecollection

efficiency cannot be improved. Too many surfaces and too much restriction to air flow will require a larger fan and a larger amount of energy to push the air through. The energy required for this cancels out saving from using solar energy, particularly if fan is electrical and if the amount of energy which is burned at the power plant to produce the electrical energy is included.

The solar air heating utilizing a transpired honey comb is also favorable since the flow cross section is much higher. Crushed glass layers can be used to absorb solar radiation and heat the air. A porous bed with layers of broken bottles can be readily used for agricultural drying purposes with minimum expenditure. The overlapped glass plate air heater can be considered as a form of porous matrix, although overall flow direction is along the absorber plates instead of being across the matrix.

Applications of Solar air heaters

- Heatingbuildings.
- Drying agricultural produce andlumber.
- Heating greenhouses.
- Air conditioning building sutilizing desiccant beds or a absorption refrigerationprocess.
- Heat sources for a heat engine such as a Brayton or Stirlingcycle.

Flat platecollector:

Flat plate collector absorbs both beam and diffuse components of radiant energy. The absorber plate is a specially treated blackened metal surface. Sun rays striking the absorber plate are absorbed causing rise of temperature of transport fluid. Thermal insulation behind the absorber plate and transparent cover sheets (glass or plastic) prevent loss of heat tosurroundings.

Applications of flat plate collector:

1. Solar water heating systems for residence, hotels,industry.
2. Desalination plant for obtaining drinking water from seawater.
3. Solar cookers for domesticcooking.

4. Dryingapplications.

5. Residenceheating.

Losses in flat plate collector:

1. *Shadow effect*: Shadows of some of the neighbor panel fall on the surface ofthe collectorwhere

the angle of elevation of the sun is less than 15°(sun-rise and sunset).

Shadow factor = $\frac{surface\ of\ thecollectorrecieving\ light}{Total\ surface\ of\ thecollector}$

Shadow factor is less than 0.1 during morning and evening. The effective hours of solar collectors

are between 9AM and5PM.

2. *Cosine loss factor:*For maximum power collection, the surface of collector should receivethe

sun rays perpendicularly. If the angle between the perpendicular to the collector surface and the direction of sun rays is θ, then the area of solar beam intercepted by the collector surface is proportional to cosθ.

3. *Reflective loss factor:*The collector glass surface and the reflector surface collect dust, dirt, moisture etc. The reflector surface gets rusted, deformed and loses the shine. Hence, the efficiency of the collector is reduced significantly with passage oftime.

Maintenance of flat plate collector:

1. Dailycleaning
2. Seasonal maintenance (cleaning, touch-up paint)
3. Yearly overhaul (change of seals, cleaning afterdismantling)

Parabolic trough collector:

Parabolic trough with line focusing reflecting surface provides concentration ratios from 30 to 50.Hence, temperature as high as 300^{o}C can be attained. Light is focused on a central line of the parabolic trough. The pipe located along the centre line absorbs the heat and the working fluid iscirculatedtrough the pipe.

Paraboloid dishcollectors:

The beam radiation is reflected by paraboloid dish surface. The point focus is obtained with CR (above 1000) and temperatures around 1000^{o}C.

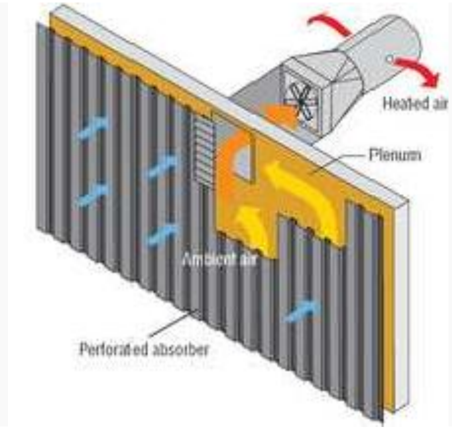
Based on the temperature:

- Low temperaturecollector
- Medium temperaturecollector
- High temperaturecollector

Low temperature collector:

Low-temperature collectors[edit]
Main article: Solar thermal collector

Glazed solar collectors are designed primarily for space heating. They re-circulate building air through a solar air panel where the air is heated and then directed back into the building. These solar space heating systems require at least two penetrations into the building and only perform when the air in the solar collector is warmer than the building room temperature. Most glazed collectors are used in the residential sector.



Unglazed, "transpired" air collector

Unglazed solar collectors are primarily used to pre-heat make-up ventilation air in commercial, industrial and institutional buildings with a high ventilation load. They turn building walls or sections of walls into low cost, high performance, unglazed solar collectors. Heat conducts from the absorber surface to the thermal boundary layer of air 1 mm thick on the outside of the absorber and to air that passes behind the absorber. The boundary layer of air is drawn into a nearby perforation before the heat can escape by convection to the outside air. The heated air is then drawn from behind the absorber plate into the building's ventilationsystem.

A Trombe wall is a passive solar heating and ventilation system consisting of an air channel sandwiched between a window and a sun-facing thermal mass. During the ventilation cycle, sunlight stores heat in the thermal mass and warms the air channel causing circulation through vents at the top and bottom of the wall. During the heating cycle the Trombe wall radiates stored heat.

Solar roof ponds are unique solar heating and cooling systems developed by Harold Hay in the 1960s. A basic system consists of a roof-mounted water bladder with a movable insulating cover. This system can control heat exchange between interior and exterior environments by covering and uncovering the bladder between night and day. When heating is a concern the bladder is uncovered during the day allowing sunlight to warm the water bladder and store heat for evening use. When cooling is a concern the covered bladder draws heat from the building's interior during the day and is uncovered at night to radiate heat to the cooler atmosphere.

Solar space heating with solar air heat collectors is more popular in the USA and Canada than heating with solar liquid collectors since most buildings already have a ventilation system for heating and cooling. The two main types of solar air panels are glazed and unglazed.

Medium temperature collector:

Solar drying

Solar thermal energy can be useful for drying wood for construction and wood fuels such as wood chips for combustion. Solar is also used for food products such as fruits, grains, and fish. Crop drying by solar means is environmentally friendly as well as cost effective while improving the quality. The less money it takes to make a product, the less it can be sold for, pleasing both the buyers and the sellers. Technologies in solar drying include ultra low cost pumped transpired plate air collectors based on black fabrics. Solar thermal energy is helpful in the process of drying products such as wood chips and other forms of biomass by raising the temperature while allowing air to pass through and get rid of the moisture.

Cooking

Solar cookers use sunlight for cooking, drying and pasteurization. Solar cooking offsets fuel costs, reduces demand for fuel or firewood, and improves air quality by reducing or removing a source of smoke. The simplest type of solar cooker is the box cooker first built by Horace de Saussure in 1767. A basic box cooker consists of an insulated container with a transparent lid. These cookers can be used effectively with partially overcast skies and will typically reach temperatures of 50–100 °C. Concentrating solar cookers use reflectors to concentrate solar energy onto a cooking container. The most common reflector geometries are flat plate, disc and parabolic trough type. These designs cook faster and at higher temperatures (up to 350 °C) but require direct light to function properly. The Solar Kitchen in Auroville, India uses a unique concentrating technology known as the solar bowl. Contrary to conventional tracking reflector/fixed receiver systems, the solar bowl uses a fixed spherical reflector with a receiver which tracks the focus of light as the Sun moves across the sky. The solar bowl's receiver reaches temperature of 150 °C that is used to produce steam that helps cook 2,000 dailymeals.

High temperature collector

Where temperatures below about 95 °C are sufficient, as for space heating, flat-plate collectors of the non-concentrating type are generally used. Because of the relatively high heat losses through the glazing, flat plate collectors will not reach temperatures much above 200 °C even when the heat transfer fluid is stagnant. Such temperatures are too low for efficient conversion to electricity.

The efficiency of heat engines increases with the temperature of the heat source. To achieve this in solar thermal energy plants, solar radiation is concentrated by mirrors or lenses to obtain higher temperatures – a technique called Concentrated Solar Power (CSP). The practical effect of HIGH EFFICIENCIES is to reduce the plant's collector size and total land use per unit power generated, reducing the environmental impacts of a power plant as well as itsexpense.

As the temperature increases, different forms of conversion become practical. Up to 600 °C, steam turbines, standard technology, have an efficiency up to 41%. Above 600 °C, gas turbines can be more efficient. Higher temperatures are problematic because different materials and techniques are needed. One proposal for very high temperatures is to use liquid fluoride salts operating between 700 °C to 800 °C, using multi-stage turbine systems to achieve 50% or more thermal efficiencies.[25] The higher operating temperatures permit the plant to use higher-temperature dry heat exchangers for its thermal exhaust, reducing the plant's water use – critical in the deserts where large solar plants are practical. High temperatures also make heat storage more efficient, because more watt-hours are stored per unit offluid.

Commercial concentrating solar thermal power (CSP) plants were first developed in the 1980s. The world’s largest solar thermal power plants are now the 370 MW Ivanpah Solar Power Facility, commissioned in 2014, and the 354 MW SEGS CSP installation both located in the Mojave Desert of California, where several other solar projects have been realized as well. With the exception of the Shams solar power station, built in 2013 near Abu Dhabi, the United Arab Emirates, all other 100 MW or larger CSP plants are either located in the United States or inSpain.

The principal advantage of CSP is the ability to efficiently add thermal storage, allowing the dispatching of electricity over up to a 24-hour period. Since peak electricity demand typically occurs at about 5 pm, many CSP power plants use 3 to 5 hours of thermal storage.[26] With current technology, storage of heat is much cheaper and more efficient than storage of electricity. In this way, the CSP plant can produce electricity day and night. If the CSP site has predictable solar radiation, then the CSP plant becomes a reliable power plant. Reliability can further be improved by installing a back-up combustion system. The back-up system can use most of the CSP plant, which decreases the cost of the back-up system.

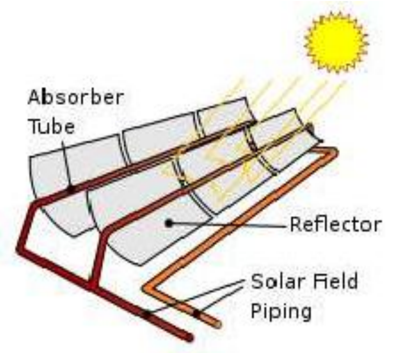
CSP facilities utilize high electrical conductivity materials, such as copper, in field power cables, grounding networks, and motors for tracking and pumping fluids, as well as in the main generator and high voltage transformers.

With reliability, unused desert, no pollution, and no fuel costs, the obstacles for large deployment for CSP are cost, aesthetics, land use and similar factors for the necessary connecting high tension lines. Although only a small percentage of the desert is necessary to meet global electricity demand, still a large area must be covered with mirrors or lenses to obtain a significant amount of energy. An important way to decrease cost is the use of a SIMPLEdesign.

When considering land use impacts associated with the exploration and extraction throughtotransportationandconversionoffossilfuels,whichareusedformostofour electrical power, utility-scale solar power compares as one of the most land-efficient energy resources available.

System designs

During the day the sun has different positions. For low concentration systems (and low temperatures) tracking can be avoided (or limited to a few positions per year) if non-imaging optics are used. For higher concentrations, however, if the mirrors or lenses do not move, then the focus of the mirrors or lenses changes (but also in these cases non-imaging optics provides the widest acceptance angles for a given concentration). Therefore it seems unavoidable that there needs to be a tracking system that follows the position of the sun (for solar photovoltaic a solar tracker is only optional). The tracking system increases the cost and complexity. With this in mind, different designs can be distinguished in how they concentrate the light and track the position of thesun.



Parabolic trough designs

Parabolic troughpower plants use a curved, mirrored trough which reflects the direct solar radiation onto a glass tube containing a fluid (also called a receiver, absorber or collector) running the length of the trough, positioned at the focal point of the reflectors. The trough is parabolic along one axis and linear in the orthogonal axis. For change of the daily position of the sun perpendicularto the receiver, the trough tilts east to west so that the direct radiation remains focused on the receiver. However, seasonal changes in the in angle of sunlight parallelto the trough does not require adjustment of the mirrors, since the light is simply concentrated elsewhere on the receiver. Thus the trough design does not require tracking on a second axis. The receiver may be enclosed in a glass vacuum chamber. The vacuum significantly reduces convective heat loss.

A fluid (also called heat transfer fluid) passes through the receiver and becomes very hot. Common fluids are synthetic oil, molten salt and pressurized steam. The fluid containing the heat is transported to a heat engine where about a third of the heat is converted to electricity.

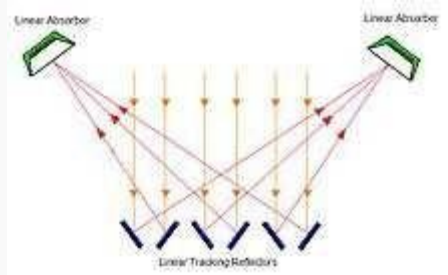
Full-scale parabolic trough systems consist of many such troughs laid out in parallel over a large area of land. Since 1985 a solar thermal system using this principle has been in full operation in California in the United States. It is called the Solar Energy Generating Systems(SEGS) system.[29] Other CSP designs lack this kind of long experience and therefore it can currently be said that the parabolic trough design is the most thoroughly proven CSP technology.

Power tower designs

Power towers (also known as 'central tower' power plants or 'heliostat' power plants) capture and focus the sun's thermal energy with thousands of tracking mirrors (called heliostats) in roughly a two square mile field. A tower resides in the centre of the heliostat field. The heliostats focus concentrated sunlight on a receiver which sits on top of the tower. Within the receiver the concentrated sunlight heats molten salt to over 1,000°F (538°C). The heated molten salt then flows into a thermal storage tank where it is stored, maintaining 98% thermal efficiency, and eventually pumped to a steam generator. The steam drives a standard turbine to generate electricity. This process, also known as the "Rankine cycle" is similar to a standard coal-fired power plant, except it is fueled by clean and free solar energy.

The advantage of this design above the parabolic trough design is the higher temperature. Thermal energy at higher temperatures can be converted to electricity more efficiently and can be more cheaply stored for later use. Furthermore, there is less need to flatten the ground area. In principle a power tower can be built on the side of a hill. Mirrors can be flat and plumbing is concentrated in the tower. The disadvantage is that each mirror must have its own dual-axis control, while in the parabolic trough design single axis tracking can be shared for a large array ofmirrors.

Dish designs



A parabolic solar dish concentrating the sun's rays on the heating element of a Stirling engine.

Fresnel reflector

CSP-Stirling is known to have the highest efficiency of all solar technologies around 30% compared to solar PV approximately 15%, and is predicted to be able to produce the cheapest energy among all renewable energy sources in high scale production and hot areas, semi deserts etc. A dish Stirling system uses a large, reflective, parabolic dish (similar in shape to satellite television dish). It focuses all the sunlight that strikes the dish up onto a single point above the dish, where a receiver captures the heat and transforms it into a useful form. Typically the dish is coupled with a Stirling engine in a Dish-Stirling System, but also sometimes a steam engine is used. These create rotational kinetic energy that can be converted to electricity using an electric generator.

Fresnel technologies

A linear Fresnel reflector power plant uses a series of long, narrow, shallow-curvature (or even flat) mirrors to focus light onto one or more linear receivers positioned above the mirrors. On top of the receiver a small parabolic mirror can be attached for further focusing the light. These systems aim to offer lower overall costs by sharing a receiver between several mirrors (as compared with trough and dish concepts), while still using the simple line-focus geometry with one axis for tracking. This is similar to the trough design (and different from central towers and dishes with dual-axis). The receiver is stationary and so fluid couplings are not required (as in troughs and dishes). The mirrors also do not need to support the receiver, so they are structurally simpler. When suitable aiming strategies are used (mirrors aimed at different receivers at different times of day), this can allow a denser packing of mirrors on available landarea.

Rival single axis tracking technologies include the relatively new linear Fresnel reflector (LFR) and compact-LFR (CLFR) technologies. The LFR differs from that of the parabolic trough in that the absorber is fixed in space above the mirror field. Also, the reflector is composed of many low row segments, which focus collectively on an elevated long tower receiver running parallel to the reflector rotationalaxis.

Prototypes of Fresnel lens concentrators have been produced for the collection of thermal energy by International Automated Systems. No full-scale thermal systems using Fresnel lenses are known to be in operation, although products incorporating Fresnel lenses in conjunction with photovoltaic cells are already available.[41]

Micro-CSP

Micro-CSP is used for community-sized power plants (1 MW to 50 MW), for industrial, agricultural and manufacturing 'process heat' applications, and when large amounts of hot water are needed, such as resort swimming pools, water parks, large laundry facilities, sterilization, distillation and other such uses.

Enclosed parabolic trough

The enclosed parabolic trough solar thermal system encapsulates the components within an off-the-shelf greenhouse type of glasshouse. The glasshouse protects the components from the elements that can negatively impact system reliability and efficiency. This protection importantly includes nightly glass-roof washing with optimized water-efficient off-the-shelf automated washing systems.[42] Lightweight curved solar-reflecting mirrors are suspended from the ceiling of the glasshouse by wires. A single-axis tracking system positions the mirrors to retrieve the optimal amount of sunlight. The mirrors concentrate the sunlight and focus it on a network of stationary steel pipes, also suspended from the glasshouse structure.[43] Water is pumped through the pipes and boiled to generate steam when intense sun radiation is applied. The steam is available for process heat. Sheltering the mirrors from the wind allows them to achieve higher temperature rates and prevents dust from building up on the mirrors as a result from exposure tohumidity.[42]

Heat collection and exchange:

More energy is contained in higher frequency light based upon the formula of $E = h\upsilon$,where h is the Planck constant and v is frequency. Metal collectors down convert higher frequency light by producing a series of Compton shifts into an abundance of lower frequency light. Glass or ceramic coatings with high transmission in the visible and UV and effective absorption in the IR (heat blocking) trap metal absorbed low frequency light from radiation loss. Convection insulation prevents mechanical losses transferred through gas. Once collected as heat, thermos containment efficiency improves significantly with increased size. Unlike Photovoltaic technologies that often degrade under concentrated light, Solar Thermal depends upon light concentration that requires a clear sky to reach suitabletemperatures.

Heat in a solar thermal system is guided by five basic principles: heat gain; heat transfer; heat storage; heat transport; and heat insulation. Here, heat is the measure of the amount of thermal energy an object contains and is determined by the temperature, mass and specific heat of the object. Solar thermal power plants use heat exchangers that are designed for constant working conditions, to provide heat exchange. Copper heat exchangers are important in solar thermal heating and cooling systems because of copper’s high thermal conductivity, resistance to atmospheric and water corrosion, sealing and joining by soldering, and mechanical strength. Copper is used both in receivers and in primary circuits (pipes and heat exchangers for water tanks) of solar thermal water systems.

Heat gain is the heat accumulated from the sun in the system. Solar thermal heat is trapped using the greenhouse effect; the greenhouse effect in this case is the ability of a reflective surface to transmit short wave radiation and reflect long wave radiation. Heat and infrared radiation (IR) are produced when short wave radiation light hits the absorber plate, which is then trapped inside the collector. Fluid, usually water, in the absorber tubes collect the trapped heat and transfer it to a heat storagevault.

Heat is transferred either by conduction or convection. When water is heated, kinetic energy is transferred by conduction to water molecules throughout the medium. These molecules spread their thermal energy by conduction and occupy more space than the cold slow moving molecules above them. The distribution of energy from the rising hot water to the sinking cold water contributes to the convection process. Heat is transferred from the absorber plates of the collector in the fluid by conduction. The collector fluid is circulated through the carrier pipes to the heat transfer vault. Inside the vault, heat is transferred throughout the medium throughconvection.

Heat storage enables solar thermal plants to produce electricity during hours without sunlight. Heat is transferred to a thermal storage medium in an insulated reservoir during hours with sunlight, and is withdrawn for power generation during hours lacking sunlight. Thermal storage mediums will be discussed in a heat storage section. Rate of heat transfer is related to the conductive and convection medium as well as the temperature differences. Bodies with large temperature differences transfer heat faster than bodies with lower temperaturedifferences.

Heat transport refers to the activity in which heat from a solar collector is transported to the heat storage vault. Heat insulation is vital in both heat transport tubing as well as the storage vault. It prevents heat loss, which in turn relates to energy loss, or decrease in the efficiency of the system.

As solar power has low density (kW/m^2), therefore large area on the ground is covered by collectors. Flat plate collectors are used for low temperature applications. For achieving higher temperature of transport fluid, the sun rays must be concentrated and focused.

Concentration Ratio (CR):

$$CR = \frac{\text{solar radiation surfaces(kW/m}^2\text{)}}{\text{solar radiation at focus on surfaces of collector(kW/m}^2\text{)}}$$

CR = For flat plate collectors, CR = 1. Using heliostats with sun-tracking in two planes, we obtain CR of the order of 1000. CR up to 100 can be achieved by using parabolic trough collectors with sun tracking in one plane.

The performance of a collector is evaluated in terms of its collector efficiency which is given as constant solar radiation (kW/m^2), the collector efficiency decreases with the increasing difference between the collector temperature and the outside temperature.

PHOTO VOLTAIC TECHNOLOGY:

The Kyoto agreement on global reduction of greenhouse gas emissions has prompted renewed interest in renewable energy systems worldwide. Many renewable energy technologies today are well developed, reliable, and cost competitive with the conventional fuel generators. The cost of renewable energy technologies is on a falling trend and is expected to fall further as demand and production increases. There are many renewable energy sources such as biomass, solar, wind, mini-hydro, and tidal power. One of the advantages offered by renewable energy sources is their potential to provide sustainable electricity in areas not served by the conventional powergrid.

The growing market for renewable energy technologies has resulted in a rapid growth in the need for power electronics. Most of the renewable energy technologies produce DC power, and hence power electronics and control equipment are required to convert the DC into AC power.

Inverters are used to convert DC to AC. There are two types of inverters: stand-alone and grid-connected. The two types have several similarities, but are different in terms of control functions.

A stand-alone inverter is used in off-grid applications with battery storage. With backup diesel generators (such as PV–diesel hybrid power systems), the inverters may have additional control functions such as operating in parallel with diesel generators and bidirectional operation (battery charging and inverting). Grid-interactive inverters must follow the voltage and frequency characteristics of the utility-generated power presented on the distribution line. For both types of inverters, the conversion efficiency is a very important consideration. Details of stand-alone and grid-connected inverters for PV and wind applications are discussed in thischapter.

The density of power radiated from the sun (referred to as the ‘‘solar energy constant’’) at the outer atmosphere is 1.373kW/m^2. Part of this energy is absorbed and scattered by the earth’s atmosphere. The final incident sunlight on earth’s surface hasapeakdensityof1kW/m^{2}atnooninthetropics.Thetechnologyofphotovoltaic

(PV) is essentially concerned with the conversion of this energy into usable electrical form. The basic element of a PV system is the solar cell.

Solar cells can convert the energy of sunlight directly into electricity. Consumer appliances used to provide services such as lighting, water pumping, refrigeration, telecommunications, and television can be run from photovoltaic electricity.

Solar cells rely on a quantum-mechanical process known as the ‘‘photovoltaic effect’’ to produce electricity. A typical solar cell consists of a p n junction formed in a semiconductor material similar to a diode. Figure 1 shows a schematic diagram of the cross section through a crystalline solar cell. It consists of a 0.2–0.3mm thick mono-crystalline or polycrystalline silicon wafer having two layers with different electrical properties formed by ‘‘doping’’ it with other impurities (e.g., boron and phosphorus). An electric field is established at the junction between the negatively doped (using phosphorus atoms) and the positively doped (using boron atoms) silicon layers. If light is incident on the solar cell, the energy from the light (photons) creates free charge carriers, which are separated by the electrical field. An electrical voltage is generated at the external contacts, so that current can flow when a load is connected. The photocurrent (I_{ph}), which is internally generated in the solar cell, is proportional to the radiation intensity.

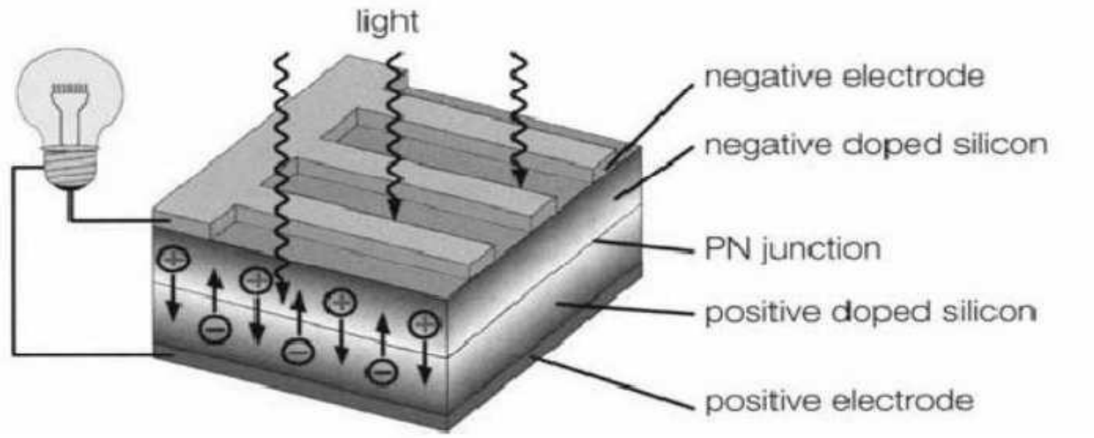


Figure 1: Solar Cell

A simplified equivalent circuit of a solar cell consists of a current source in parallel with a diode as shown in Fig. 2a. A variable resistor is connected to the solar cell generator as a load. When the terminals are short-circuited, the output voltage and also the voltage across the diode are both zero. The entire photocurrent (I_{ph}) generated by the solar radiation then flows to the output. The solar cell current has its maximum (I_{sc}). If the load resistance is increased, which results in an increasing voltage across the p n junction of the diode, a portion of the current flows through the diode and the output current decreases by the same amount. When the load resistor is open circuited, the output current is zero and the entire photocurrent flows through the diode. The relationship between current and voltage may be determined from the diode characteristicequation:

$$I = I_{ph} - I_0 \left(e^{\frac{qv}{kt}} - 1\right) = I_{ph} - I_d$$

where q is the electron charge, k is the Boltzmann constant, I_{ph} is photocurrent, I_0 is the reverse saturation current, Id is diode current, and T is the solar cell operating temperature (K). The current versus voltage (I-V) of a solar cell is thus equivalent to an ‘‘inverted’’diode

characteristic curve shown in Fig.2.

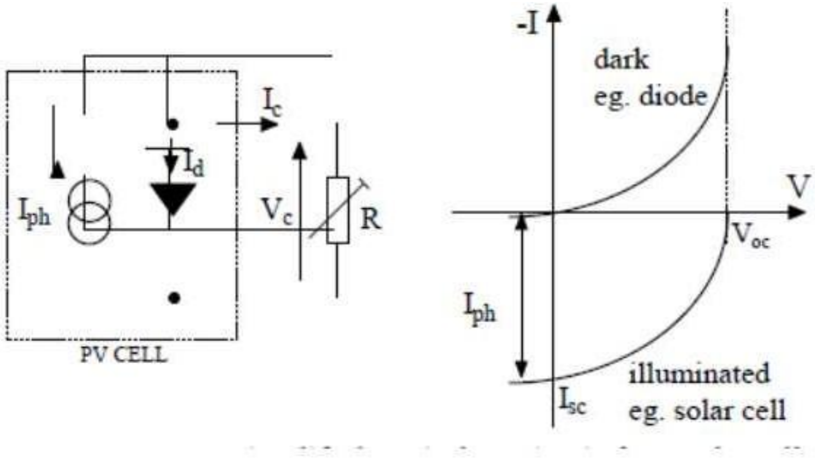


Figure 2: Equivalent circuit of a solar cell

A number of semiconductor materials are suitable for the manufacture of solar cells. The most common types using silicon semiconductor material (Si) are:

- Monocrystalline Sicells
- Polycrystalline Sicells
- Amorphous Sicells

A solar cell can be operated at any point along its characteristic current–voltage curve, as shown in Fig. 3. Two important points on this curve are the open circuit voltage (V_{oc}) and short-circuit current (I_{sc}). The open-circuit voltage is the maximum voltage at zero current, whereas the short circuit current is the maximum current at zero voltage. For a silicon solar cell under standard test conditions, V_{oc} is typically 0.6–0.7 V, and $I_{sc}$is typically 20–40mA for every square centimeter of the cell area. To a good approximation, I_{sc} is proportional to the illumination level, whereas V_{oc} is proportional to the logarithm of the illuminationlevel.

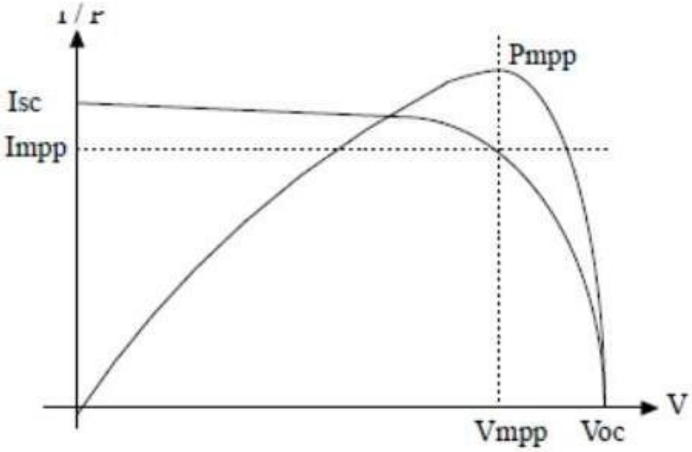


Figure 3: I vs. V characteristics of a solar cell

A plot of power (P) against voltage (V) for this device (Fig. 3) shows that there is a unique point on the I-V curve at which the solar cell will generate maximum power. This is known as the maximum power point (V_{mp}, I_{mp}). To maximize the power output, steps are usually taken during fabrication to maximize the threebasic cell parameters: open-circuit voltage, short-circuit current, and fill factor (FF)—a term describing how ‘‘square’’ the I-V curve is, given by

$$Fill\ Factor = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}$$

For a silicon solar cell, FF is typically 0.6–0.8.

Because silicon solar cells typically produce only about 0.5 V, a number of cells are connected in series in a PV module. A panel is a collection of modules physically and electrically grouped together on a support structure. An array is a collection of panels (see Fig. 4).

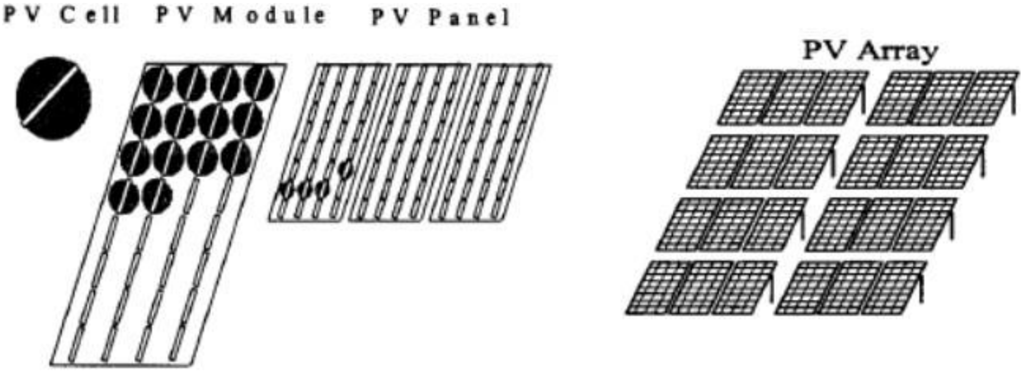


Figure 4: Elements of SPV system

The effect of temperature on the performance of a silicon solar module is illustrated in Fig.6.5.

Note that I_{sc} slightly increases linearly with temperature, but V_{oc} and the maximum power P_m

decrease with temperature.

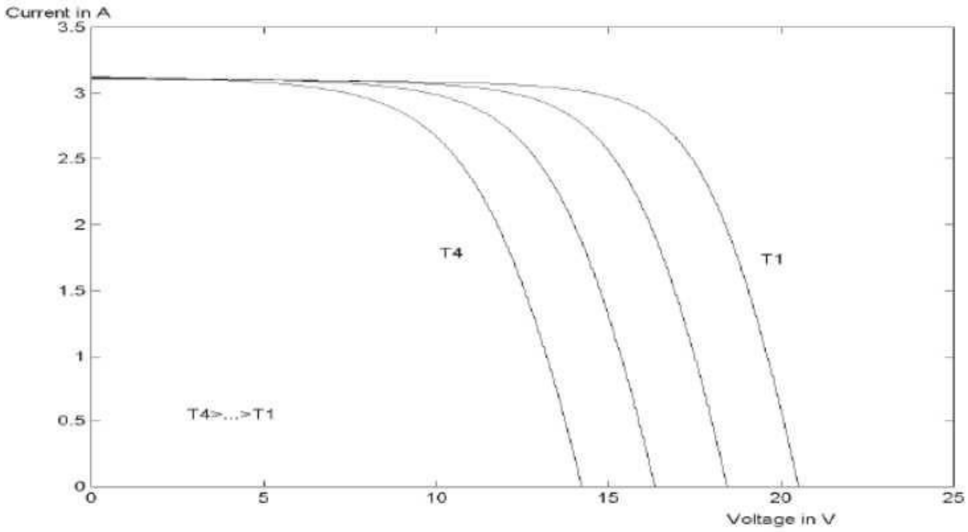


Figure 5: Effect of temperature on the performance of Silicon solar module

Figure 6 shows the variation of PV current and voltages at different insolation levels. From Figs. 5 and 6, it can be seen that the I V characteristics of solar cells at a given insolation and temperature consist of a constant-voltage segment and a constant-current segment. The current is limited, as the cell is short-circuited. The maximum power condition occurs at the knee of the characteristic where the two segmentsmeet.

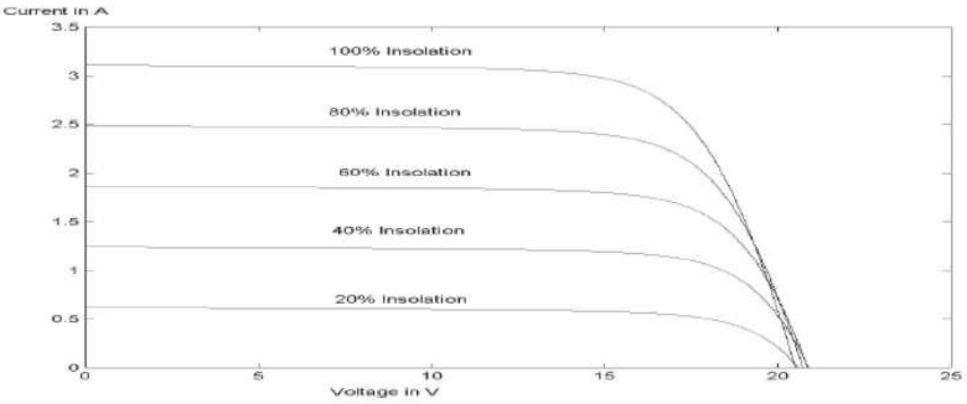


Figure 6: I-V characteristics for different insolation levels

ARRAY DESIGN

The major factors influencing the electrical design of the solar array are as follows:

- The sunintensity
- The sunangle
- The load matching for maximumpower
- The operatingtemperature

These factors are discussed in the following subsections.

SUN INTENSITY:

The magnitude of the photocurrent is maximum under a full bright sun (1.0 sun). On a partially sunny day, the photocurrent diminishes in direct proportion to the sun intensity. At a lower sun intensity, the I-V characteristic shifts downward as shown above. On a cloudy day, therefore, the short-circuit current decreases significantly. The reduction in the open-circuit voltage, however, is small. The photo conversion efficiency of the cell is insensitive to the solar radiation in the practical working range. This means that the conversion efficiency is the same on a bright sunny day as on a cloudy day. We get a lower power output on a cloudy day only because of the lower solar energy impinging on thecell.

SUN ANGLE:

The cell output current is given by $I = I_o\cos\theta$, where I_o is the current with normal sun (reference), and θ is the angle of the sun line measured from the normal. This cosine law holds well for sun angles ranging from 0 to about 50°. Beyond 50°, the electrical output deviates significantly from the cosine law, and the cell generates no power beyond 85°, although the mathematical cosine law predicts 7.5% power generation.

SHADOW EFFECT:

The array may consist of many parallel strings of series-connected cells. Two such strings are shown in Figure 9.13. A large array may get partially shadowed due to a structure interfering with the sun line. If a cell in a long series string gets completely shadowed, it loses the photo-voltage but still must carry the string current by virtue of its being in series with all other cells operating in full sunlight. Without internally generated voltage, the shadowed cell cannot produce power. Instead, it acts as a load, producing local I^2R loss and heat. The remaining cells in the string must work at higher voltage to make up the loss of the shadowed cell voltage.

TEMPERATURE EFFECTS:

With increasing temperature, the short-circuit current of the cell increases, whereas the open-circuit voltage decreases. The effect of temperature on PV power is quantitatively evaluated by examining the effects on the current and the voltage separately.

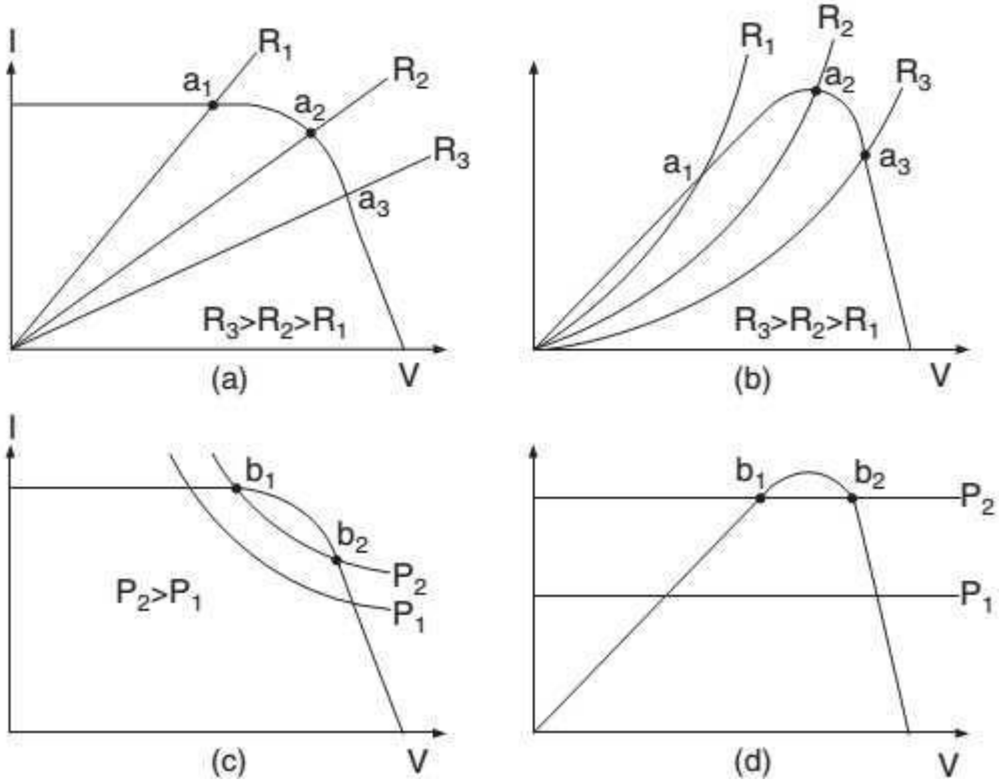
EFFECT OF CLIMATE:

On a partly cloudy day, the PV module can produce up to 80% of its full sun power. It can produce about 30% power even with heavy clouds on an extremely overcast day. Snow does not usually collect on the module, because it is angled to catch the sun. If snow does collect, it quickly melts. Mechanically, the module is designed to withstand golf-ball-size hail.

ELECTRICAL LOAD MATCHING:

The operating point of any power system is the intersection of the source line and the load line. If the PV source having the I-V and P-V characteristics shown in

Figure is supplying power to a resistive load R_1, it will operate at point A_1.If the load resistance increases to R_2 or R_3, the operating point moves to A_2 or A_3, respectively. The maximum power is extracted from the module when the load resistance is R_2. Such a load that matches with the source is always necessary for the maximum power extraction from a PV source.



Operating stability and electrical load matching with constant-resistive load and constant-power load.

SUN TRACKING:

More energy is collected by the end of the day if the PV module is installed on a tracker with an actuator that follows the sun. There are two types of sun trackers:

- One-axis tracker, which follows the sun from east to west during theday.
- Two-axis tracker, which follows the sun from east to west during the day, and from north to south during the seasons of theyear.

PEAK POWER OPERATION:

The sun tracker drives the module mechanically to face the sun to collect the maximum solar radiation. However, that in itself does not guarantee the maximum power output from the module. As was seen in Figure, the module must operate electrically at a certain voltage that corresponds to the peak power point under a given operating condition. First we examine the electrical principle of peak-power operation.

If the array is operating at any point at voltage V and current I on the I-V curve, the power generation is P = VI watts. If the operation moves away from the preceding point such that the current is now I + ΔI, and the voltage is V + ΔV, then the new power is as follows:

$$P + \Delta P = (V + \Delta V)(I+\Delta I) \qquad \text{(i)}$$

which, after ignoring a small term, simplifies to the following:

$$\Delta P = \Delta V\cdot I+\Delta I\cdot V \qquad \text{(ii)}$$

ΔP would be zero if the array were operating at the peak power point, which necessarily lies on a locally flat neighborhood. Therefore, at the peak power point, the preceding expression in the limit becomes:

$$\frac{\mathrm{d}V}{\mathrm{d}I} = -\frac{V}{I} \qquad \text{(iii)}$$

We note here that dV/dI is the dynamic impedance of the source, and V/I the static impedance. Thus, at the peak power point, the following relation holds:

$$\text{Dynamic impedance } Z_d = -\text{staticimpedance} Z_s \qquad \text{(iv)}$$

There are three electrical methods of extracting the peak power from a PV source, as described in the followingtext:

1. In the first method, a small signal current is periodically injected into the array bus, and the dynamic bus impedance (Z_d = dV/dI) and the static bus impedance (Z_s = V/I) are measured. The operating voltage is then increased or decreased until Z_d equals $-Z_s$. At this point, the maximum power is extracted from thesource.
2. In another method, the operating voltage is increased as long as dP/dV is positive.Thatis,thevoltageisincreasedaslongaswegetmorepower.If

dP/dV is sensed negative, the operating voltage is decreased. The voltage stays the same if dP/dV is near zero within a preset deadband.

3. The third method makes use of the fact that for most PV cells, the ratio of the voltage at the maximum power point to the open-circuit voltage (i.e., V_{mp}/V_{oc}) is approximately constant, say K. For example, for high quality crystalline silicon cells, K = 0.72. An unloaded cell is installed on the array and kept in the same environment as the power-producing cells, and its open-circuit voltage is continuously measured. The operating voltage of the power-producing array is then set at $K \cdot V_{oc}$, which will produce the maximumpower.

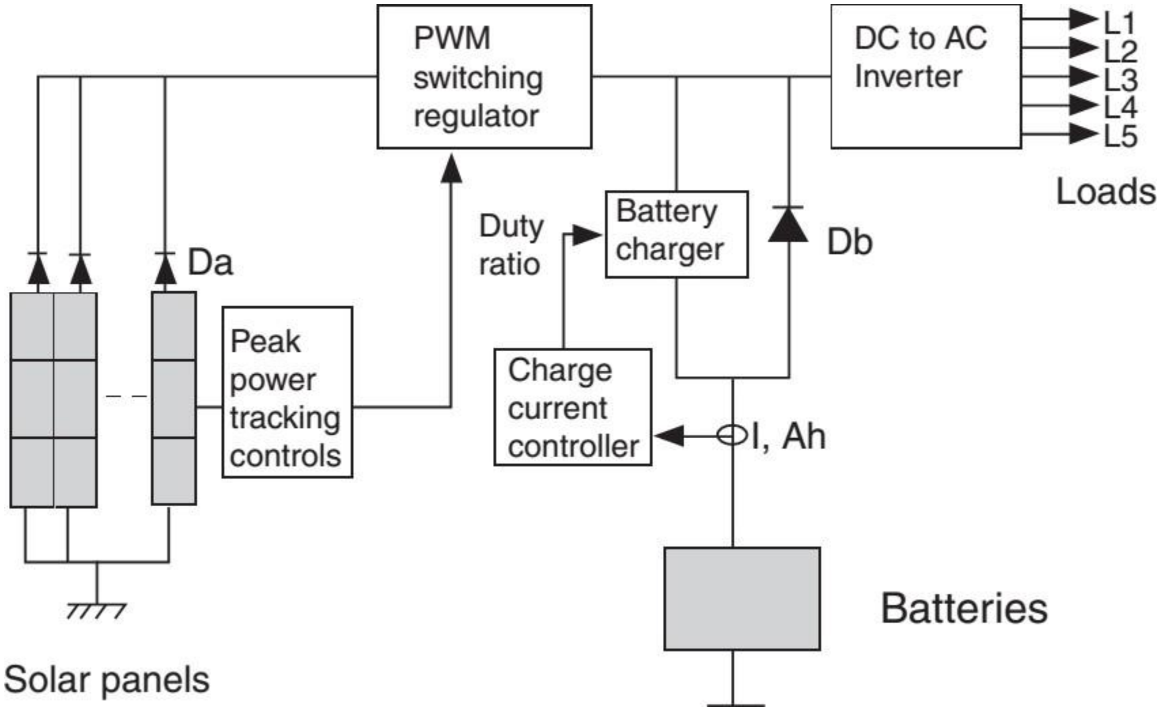
SYSTEM COMPONENTS:

The array by itself does not constitute the PV power system. We may also need a structure to mount it, a sun tracker to point the array to the sun, various sensors to monitor system performance, and power electronic components that accept the DC power produced by the array, charge the battery, and condition the remaining power in a form that is usable by the load. If the load is AC, the system needs an inverter to convert the DC power into AC at 50 or 60 Hz.

Figure shows the necessary components of a stand-alone PV power system. The peak-power tracker senses the voltage and current outputs of the array and continuously adjusts the operating point to extract the maximum power under varying climatic conditions. The output of the array goes to the inverter, which converts the DC into AC. The array output in excess of the load requirement is used to charge the battery. The battery charger is usually a DC–DC buck converter. If excess power is still available after fully charging the battery, it is shunted in dump heaters, which may be a room or water heater in a stand-alone system. When the sun is not available, the battery discharges to the inverter to power the load. The battery discharge diode Db is to prevent the battery from being charged when the charger is opened after a full charge or for other reasons. The array diode Da is to isolate the array from the battery, thus keeping the array from acting as the load on the battery at night. The mode controller collects system signals, such as thearray and the battery currents and voltages, and keeps track of the battery state of charge by bookkeeping the charge/discharge ampere-hours. It uses this information to turn on or off the battery charger, discharge converter, and dump loads as needed. Thus, the mode controller is the central controller of the entire system.

In the grid-connected system, dump heaters are not required, as all excess power is always fed to the grid lines. The battery is also eliminated, except for a few small critical loads, such as the start-up controller and the computer. DC power is first converted into AC by the inverter, ripples are filtered, and only then is the filtered power fed into the grid lines.

In the PV system, the inverter is a critical component, which converts the array DC power into AC for supplying the loads or interfacing with the grid. A new product line recently introduced into the market is the AC PV module, which integrates an inverter directly into module design. It is presently available in a few hundred watts capacity. It provides utility-grade 60-Hz power directly from the module junction box. This greatly simplifies PV system design.



Peak-power-tracking PV power system showing major components

Types of PV Power Systems

Photovoltaic power systems can be classified as follows:

- Stand-alone
- Hybrid
- Gridconnected

Stand-alone PV systems, shown in Fig. 7a, are used in remote areas with no access to a utility grid. Conventional power systems used in remote areas often based on manually controlled diesel generators operating continuously or for a few hours. Extended operation of diesel generators at low load levels significantly increases maintenance costs and reduces their useful life. Renewable energy sources such as PV can be added to remote area power systems using diesel and other fossil fuel powered generators to provide 24-hour power economically and efficiently. Such systems are called ‘‘hybrid energy systems.’’ Figure 7a shows a schematic of a PV–diesel hybrid system. In grid-connected PV systems, as shown in Fig.7c, PV panels are connected to a grid through inverters without battery storage. These systems can be classified as small systems, such as residential rooftop systems or large grid-connected systems. The grid interactive inverters must be synchronized with the grid in terms of voltage andfrequency.

Stand-Alone PV Systems

The two main stand-alone PV applications are:

- Batterycharging
- Solar waterpumping

(a) Batterycharging

Battery manufacturers specify the nominal number of complete charge and discharge cycles as a function of the depth-of-discharge (DOD), as shown in Fig. 23.8. Although this information can be used reliably to predict the lifetime of lead-acid batteries in conventional applications, such as uninterruptable power supplies or electric vehicles, it usually results in an overestimation of the useful life of the battery bank in renewable energysystems.

Two of the main factors that have been identified as limiting criteria for the cycle life of batteries in photovoltaic power systems are incomplete charging and prolonged operation at a low state of charge (SOC). The objective of improved battery control strategies is to extend the lifetime of lead-acid batteries to achieve the typical number of cycles shown in Fig. 8. If this is achieved, an optimum solution for the required storage capacity and the maximum depth-of-discharge of the battery can be found by referring to the manufacturer’s information.

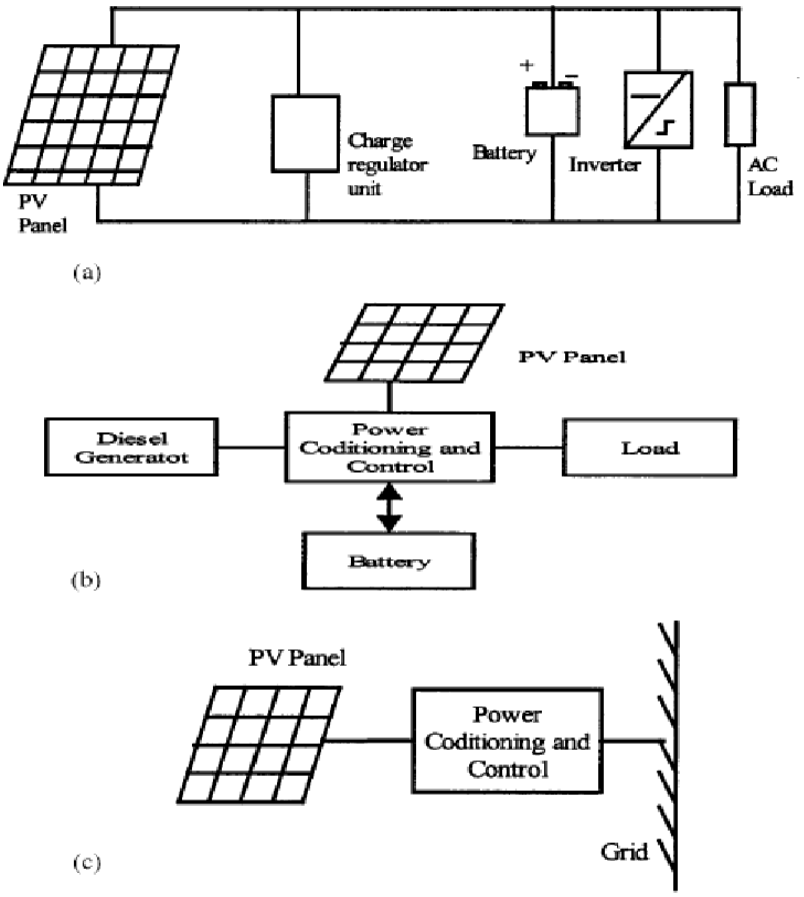


Figure 7: (a) Stand Alone PV system (b) PV-diesel hybrid system (c) Grid-connected PV system

Increasing the capacity will reduce the typical depth-of discharge and therefore prolong the battery lifetime. Conversely, it may be more economic to replace a smaller battery bank morefrequently.

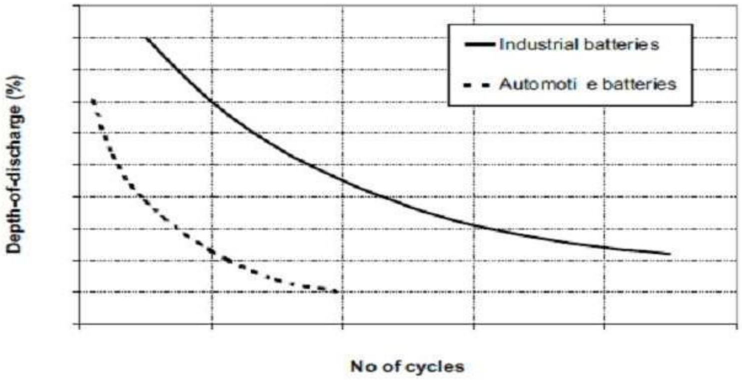


Figure 8: No. of battery cycles and Depth of discharge

(b) Solar WaterPumping:

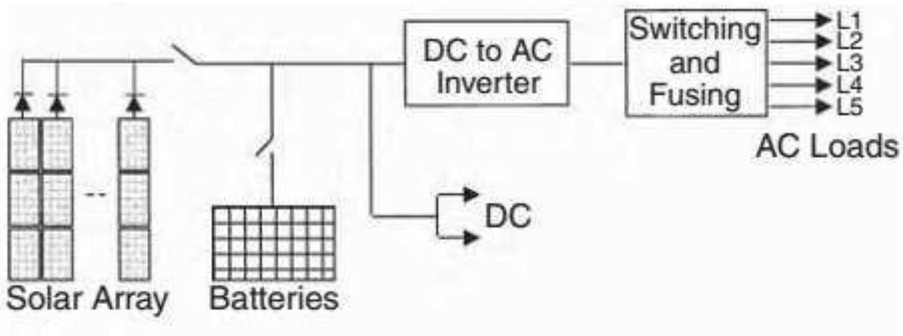
In many remote and rural areas, hand pumps or diesel driven pumps are used for water supply. Diesel pumps consume fossil fuel, affect the environment, need more maintenance, and are less reliable. Photovoltaic (PV)-powered water pumps have received considerable attention because of major developments in the field of solar-cell materials and power electronic systemstechnology.

Two types of pumps are commonly used for water-pumping applications: Positive displacement and centrifugal. Both centrifugal and positive displacement pumps can be further classified into those with motors that are surface mounted, and those that are submerged into the water(‘‘submersible’’).

Displacement pumps have water output directly proportional to the speed of the pump, but almost independent of head. These pumps are used for solar water pumping from deep wells or bores. They may be piston-type pumps or use a diaphragm driven by a cam or rotary screw, or use a progressive cavity system. The pumping rate of these pumps is directly related to the speed, and hence constant torque isdesired.

The typical PV stand-alone system consists of a solar array and a battery connected as shown in Figure. The PV array supplies power to the load and charges the battery when there is sunlight. The battery powers the load otherwise. An inverter converts the DC power of the array and the battery into 60 or 50 Hz power. Inverters are available in a wide range of power ratings with efficiencies ranging from 85 to 95%. The array is segmented with isolation diodes for improving reliability. In such a design, if one string of the solar array fails, it does not load or short the remaining strings. Multiple inverters are preferred for reliability. For example, three inverters, each with a 35% rating, are preferred to one with a 105% rating. If one such inverter fails, the remaining two can continue supplying most loads until the failed one is repaired or replaced. The same design approach also extends to using multiplebatteries.

Most stand-alone PV systems are installed in developing countries to provide basic necessities such as lighting and pumping water.

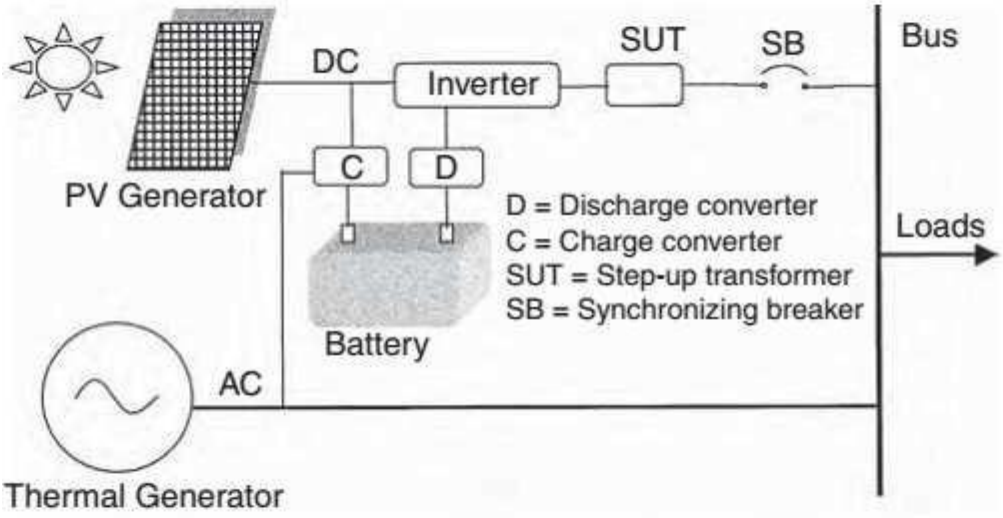


PV stand-alone power system with battery.

A traveling clinic uses photovoltaic electricity to keep vaccines refrigerated in the African desert area.

Photovoltaic (PV) power systems have made a successful transition from small stand-alone sites to large grid-connected systems. The utility interconnection brings a new dimension to the renewable power economy by pooling the temporal excess or the shortfall in the renewable power with the connecting grid that generates base-load power using conventional fuels. This improves the overall economy and load availability of the renewable plant site — the two important factors of any power system. The grid supplies power to the site loads when needed or absorbs the excess power from the site when available. A kilowatthour meter is used to measure the power delivered to the grid, and another is used to measure the power drawn from the grid. The two meters are generally priced differently on a daily basis or on a yearly basis that allows energy swapping and billing the net annual difference.

In the below figure is a typical circuit diagram of the grid-connected PV power system. It interfaces with the local utility lines at the output side of the inverter as shown. A battery is often added to meet short-term load peaks. In the U.S., the Environmental Protection Agency sponsors grid-connected PV programs in urban areas where wind towers would be impractical. In recent years, large building-integrated PV installations have made significant advances by adding grid connections to the system design. For example, Figure shows the building-integrated PV system on the roof of the Northeastern University Student Center in Boston. The project was part of the EPA PV DSP program. The system produces 18 kW power and is connected to the grid. In addition, it collects sufficient research data using numerous instruments and computer data loggers. The vital data are sampled every 10 sec, and are averaged and stored every 10 min. The incoming data includes information about air temperature and wind speed. The performance parameters include direct current (DC) voltage and current generated by the PV roof and the alternating current (AC) power at the inverter outputside.



Electrical schematic of the grid-connected PV system

Planck’s formula in wavelength unit

Planck’s radiation law, a mathematical relationship formulated in 1900 by German physicist Max Planck to explain the spectral-energy distribution of radiation emitted by a blackbody (a hypotheticalbody that completely absorbs all radiant energy falling upon it, reaches some equilibriumtemperature, and then reemits that energy as quickly as it absorbs it). Planck assumed that the sources of radiation are atoms in a state of oscillation and that the vibrational energy of each oscillator may have any of a series of discrete values but never any value between. Planck further assumed that when an oscillator changes from a state of energy E_1 to a state of lower energy E_2, the discrete amount of energy $E_1 - E_2$, or quantum of radiation, is equal to the product of the frequency of the radiation, symbolized by the Greek letter ν and a constant *h*, now called Planck’s constant, that he determined

Planck’s law for the energy E_λ radiated per unit volume by a cavity of a blackbody in the wavelength interval λ to λ + Δλ (Δλ denotes an increment of wavelength) can be written in terms of Planck’s constant (*h*), the speed of light (*c*), the Boltzmann constant (*k*), and the absolute temperature (*T*):

$$E_\lambda = \frac{8\pi hc}{\lambda^5} \times \frac{1}{\exp(hc/kT\lambda) - 1}.$$

The wavelength of the emitted radiation is inversely proportional to its frequency, or $\lambda = c/\nu$. The value of Planck’s constant is found to be $6.62606957 \times 10^{-34}$ joule·second, with a standard uncertainty of $0.00000029 \times 10^{-34}$ joule·second.

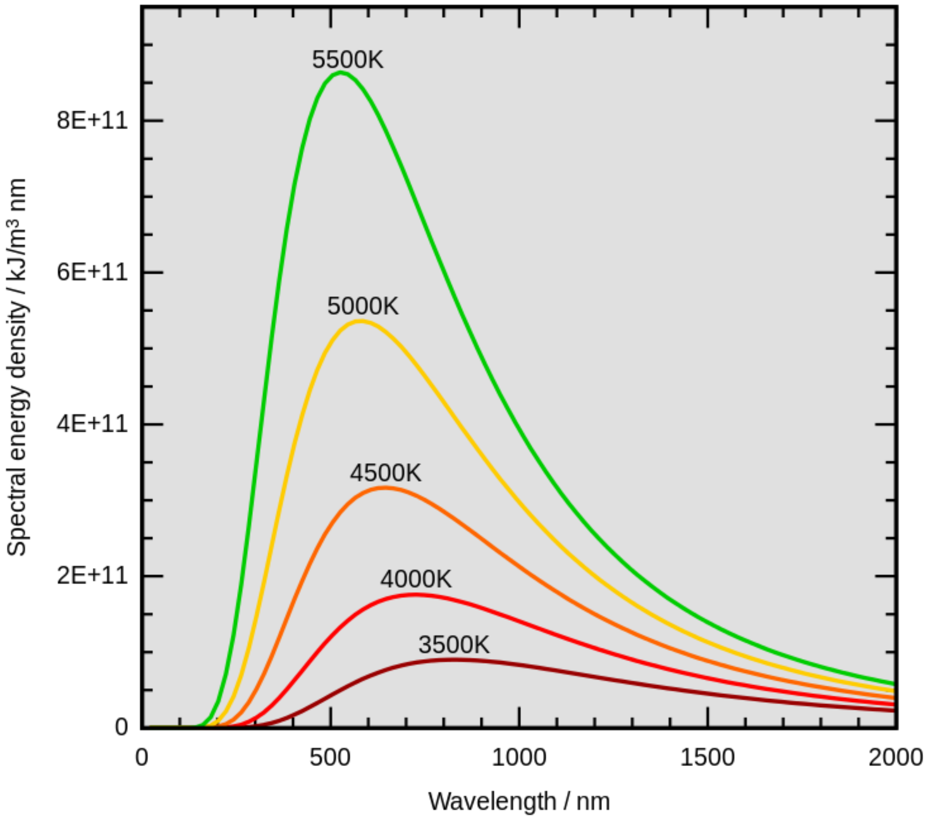
For a blackbody at temperatures up to several hundred degrees, the majority of the radiation is in the infrared radiation region of the electromagnetic spectrum. At higher temperatures, the total radiated energy increases, and the intensity peak of the emitted spectrum shifts to shorter wavelengths so that a significant portion is radiated as visible light.

Wien's displacement law states that the black body radiation curve for different temperature peaks at a wavelength is inversely proportional to the temperature. The shift of that peak is a direct consequence of the Planck radiation law, which describes the spectral brightness of black body radiation as a function of wavelength at any given temperature. However, it had been discovered by Wilhelm Wien several years before Max Planck developed that more general equation, and describes the entire shift of the spectrum of black body radiation toward shorter wavelengths as temperature increases.

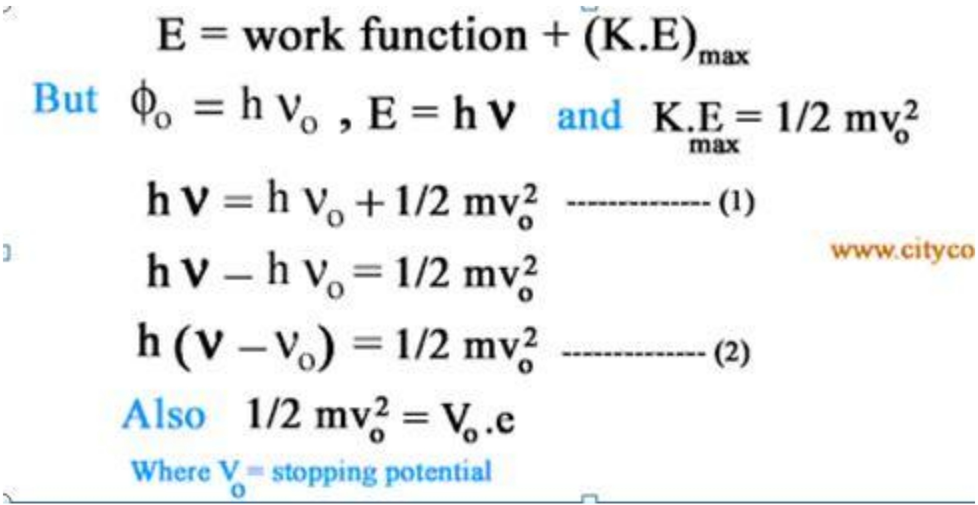
Formally, Wien's displacement law states that the spectral radiance of black body radiation per unit wavelength, peaks at the wavelength $\lambda_{\max}$ given by:

where *T* is the absolute temperature in kelvins. *b* is a constant of proportionality called Wien's displacementconstant, equal to $2.8977729(17)\times10^{-3}$ m·K,[1] or to obtain wavelength in micrometers, $b \approx 2900$ μm·K. If one is considering the peak of black body emission per unit frequency or per proportional bandwidth, one must use a different proportionality constant. However, the form of the law remains the same: the peak wavelength is inversely proportional to temperature, and the peak frequency is directly proportional to temperature.

Wien's displacement law may be referred to as "Wien's law", a term which is also used for the Wien approximation.



According to Plank's quantum theory, light is emitted from a source in the forms of bundles of energy called photons Energy of each photon is $E = h\nu$.
Einstein made use of this theory to explain how photo electric emission takes place.
According to Einstein, when photons of energy $E = h\nu$ fall on a metal surface, they transfer their energy to the electrons of metal. When the energy of photon is larger than the minimum energy required by the electrons to leave the metal surface, the emission of electrons take place instantaneously.
He proposed that an electron absorbs one whole photon or none. The chance that an electron may absorb more then one electron is negligible because the number of photons is much lower than the electron. After absorbing the photon, an electron either leaves the surface or dissipates its energy within the metal in such a short interval that it has almost no chance to absorb second photon. An increase in intensity of light source simply increases the number of photon and the number of photo electrons but no increase in the energy of photo electron.
However, increase in frequency increases the energy of photons and photo electrons.
According to Einstein's explanation of photoelectric emission, a photon of energy 'E' performs two operations:
1. Removes the electron from the surface of metal
2. Supplies some part of energy to move photo electron towards anode
Since minimum amount of energy to remove electron from a surface is equal to work function, we can write Einstein equation as:
Energy Supplied = Energy Consumed in ejecting an electron + maximum Kinetic energy of electron



$$E = \text{work function} + (K.E)_{max}$$

But $\phi_o = h\nu_o$, $E = h\nu$ and $K.E_{max} = 1/2\, mv_o^2$

$$h\nu = h\nu_o + 1/2\, mv_o^2 \quad \text{-------------- (1)}$$

$$h\nu - h\nu_o = 1/2\, mv_o^2$$

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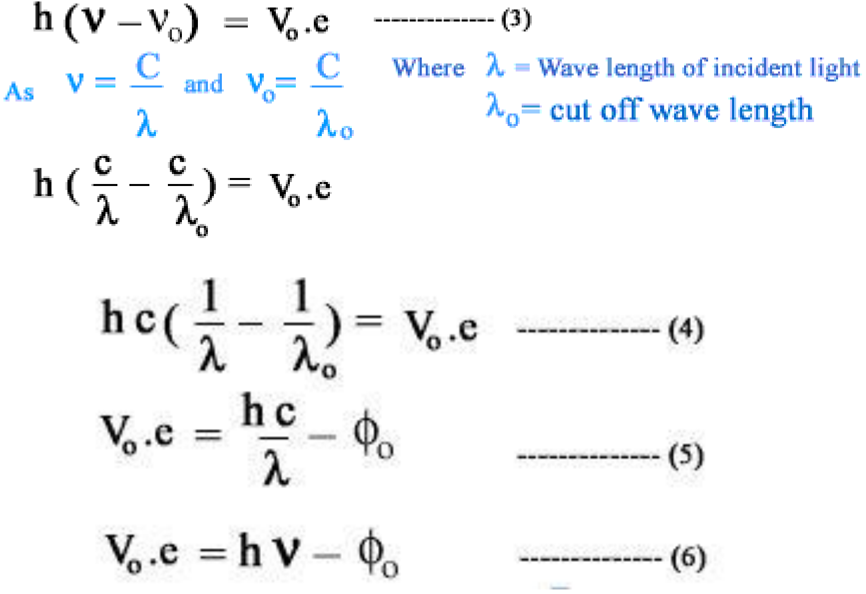
$$h(\nu - \nu_o) = 1/2\, mv_o^2 \quad \text{-------------- (2)}$$

Also $1/2\, mv_o^2 = V_o.e$

Where V_o = stopping potential



$$h(\nu - \nu_o) = V_o.e \quad \text{-------------- (3)}$$

As $\nu = \frac{C}{\lambda}$ and $\nu_o = \frac{C}{\lambda_o}$

Where λ = Wave length of incident light

λ_o = cut off wave length

$$h\left(\frac{c}{\lambda} - \frac{c}{\lambda_o}\right) = V_o.e$$

$$hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_o}\right) = V_o.e \quad \text{-------------- (4)}$$

$$V_o.e = \frac{hc}{\lambda} - \phi_o \quad \text{-------------- (5)}$$

$$V_o.e = h\nu - \phi_o \quad \text{-------------- (6)}$$

Equations from (1) to (6) are identical and are known as Einstein's photoelectric equations.

UNIT-II

ORIGIN OF SOLAR ENERGY,TRACKING SUNLIGHT AND ATMOSPHERIC INTERACTION

Absorption of radiant energy by the atmosphere:

Absorption is mainly caused by three different atmospheric gases. Contrary to popular belief, water vapor causes the most absorption, followed by carbon dioxide and then ozone. In the picture below, one can see how much of the total incoming radiation the atmosphere typicallyabsorbs.

The second way in which absorption helps the earth is as a heat source for it. If one were to take a vertical cross section of the entire atmosphere, one would note that the temperature generally increases with height. This increase in temperature is caused by an increase in absorption of electromagnetic radiation with height due to higher concentrations of high energy wavelength (low wavelength a and high frequency) absorbing gases present at higher atmospheric levels.

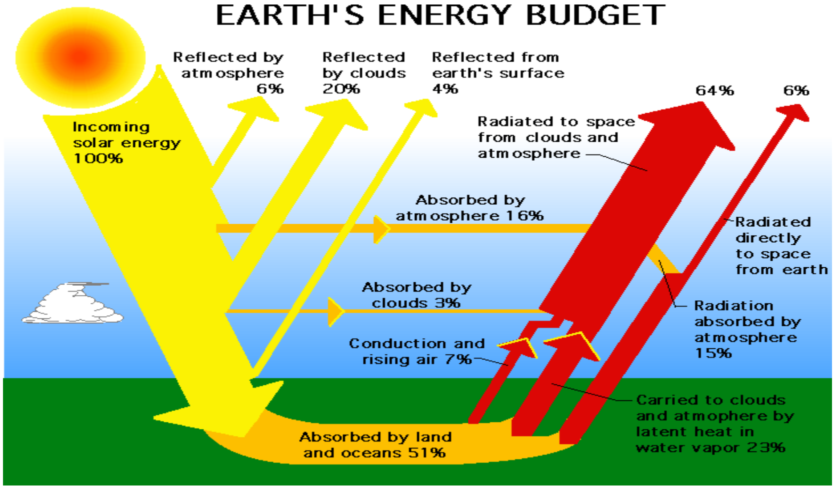


Fig: The Earth Radiation Budget is the balance between incoming energy from the sun and the outgoing longwave(thermal) and reflected *shortwave* energy from the Earth.

Sunlight is *reflected* by surfaces and *absorbed* by gases and surfaces. Greenhouse gases *do not* reflect sunlight. Infrared energy is *emitted* and absorbed by surfaces and greenhouse gases. Radiation refers to radiant energy, not nuclear radiation.

Notice also that the amount of infrared energy emitted at the top of the atmosphere (235 W/m2) must equal almost exactly the amount of solar energy absorbed by earth (342–107 W/m2). The small difference, about a watt per square meter, leads to global warming or cooling.

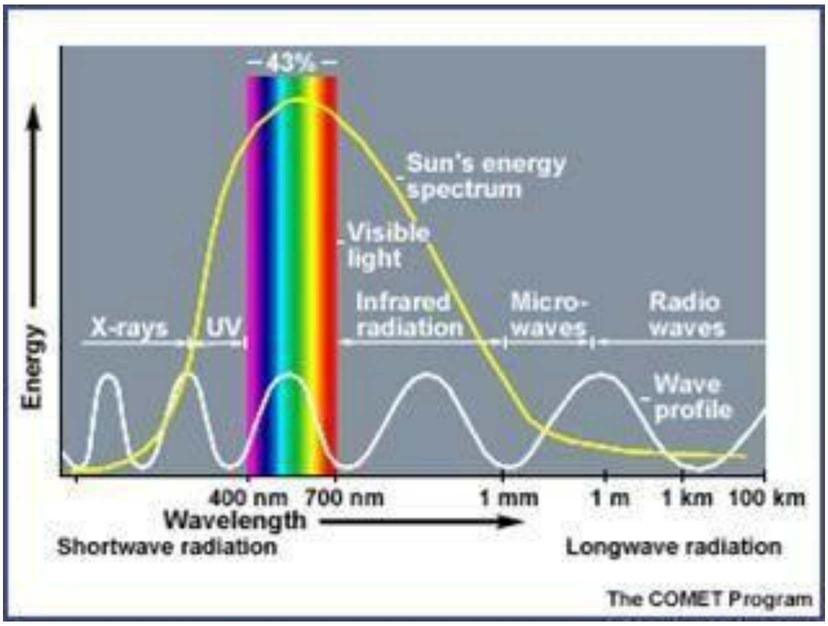


Fig: The solar spectrum.

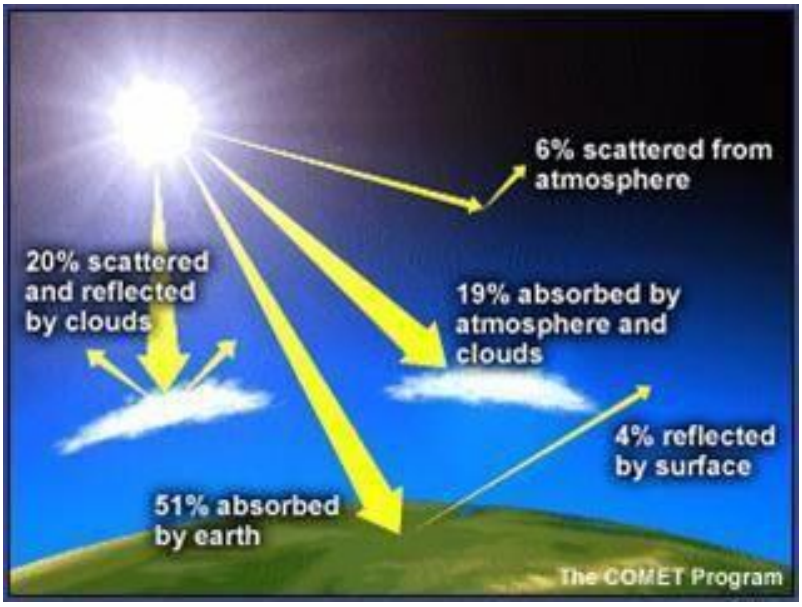


Fig : This figure gives approximate percentages for solar radiation

Measuring the temperature of a glowing material:

Physicists and engineers use a pyrometer (see figure 26). The illustration below shows a very simple type of radiation pyrometer. Part of the thermal radiation emitted by a hot object is intercepted by a lens and focused onto a thermopile. The resultant heating of the thermopile causes it to generate an electrical signal (proportional to the thermal radiation) which can be displayed on a recorder.

The optical pyrometer should more strictly be called the disappearing-filament pyrometer. In operation, an image of the target is focused in the plane of a wire that can be heated electrically. A rheostat is used to adjust the current through the wire until the wire blends into the image of the target (equal brightness condition), and the temperature is then read from a calibrated dial on the rheostat. See problem 1below.

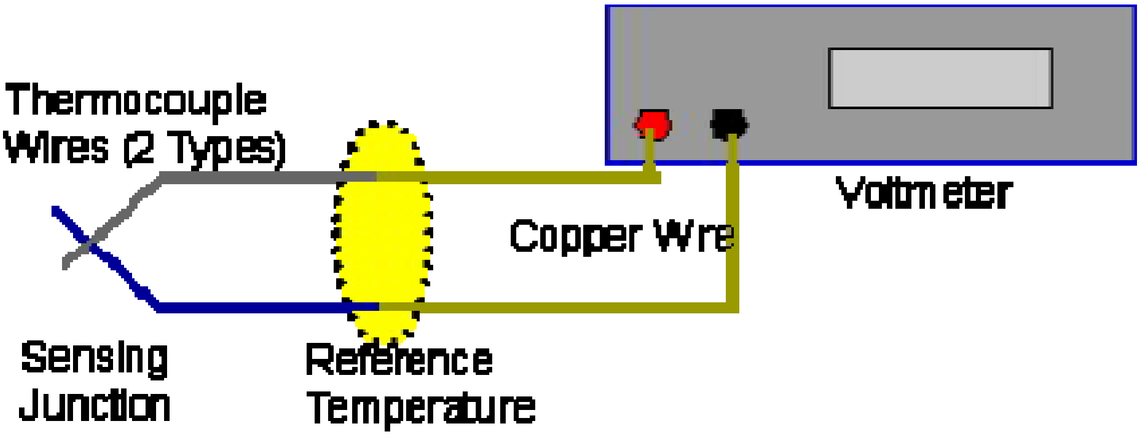


Fig: Thermocouple

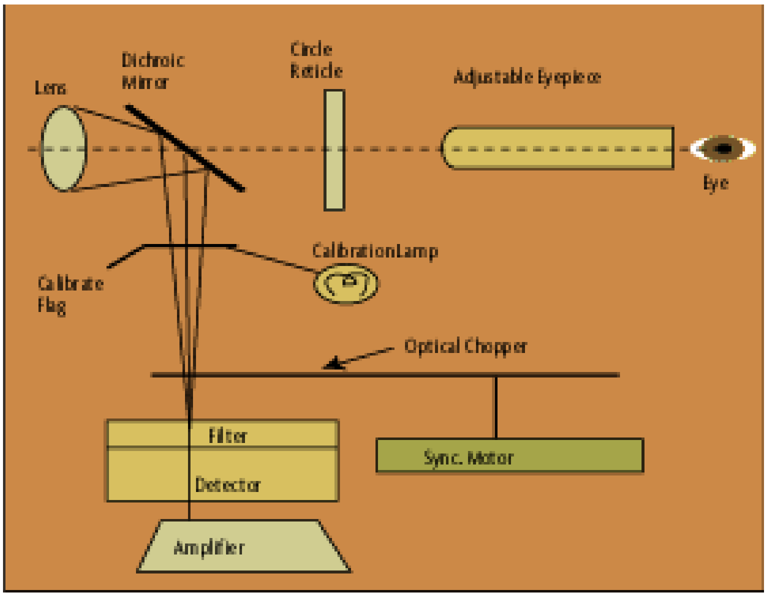


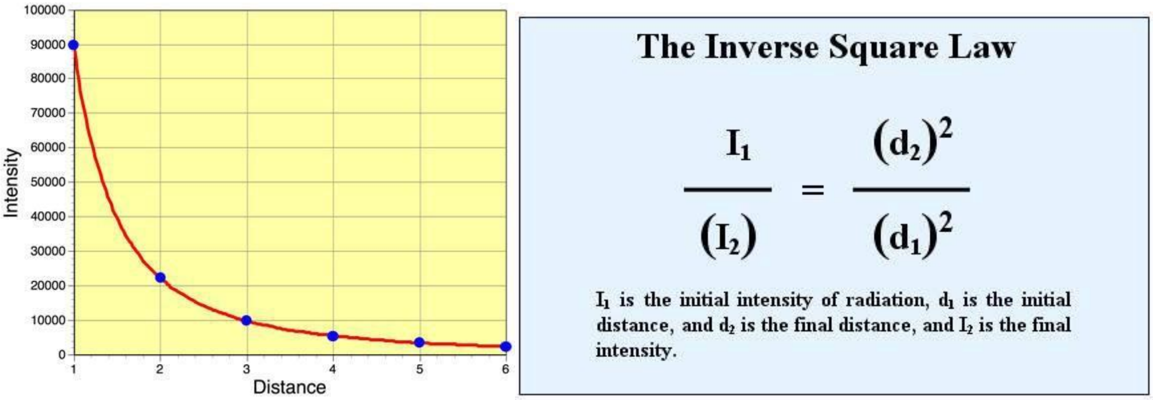
Fig: Automatic optical pyrometer

The energy output of the sun

We will first discuss how the energy output of the sun can be measured and then show how the surface temperature can be estimated. To estimate the energy output of the sun, we need to know:

1. The distance between the earth and the sun,and
2. 2. The amount of radiant energy the sun provides at the top of the atmosphere (about 100 km from the surface of theearth).

In addition, we must assume that the radiation is given out evenly (isotropic) in all direction. See Fig. below.We could, of course measure the amount of radiation energy the sun provides on the surface of the earth by simply measuring the energy required to heat up an object that is exposed to the sun for a certain time. Unfortunately, we can only guess the amount of solar energy that the atmosphere absorbs or reflects The distance to the sun was well known already in the 19th century, about 1.5x1011 m. We must then know the radiation energy of the sun striking the Earth, or find the value of the *solarconstant*



The Inverse Square Law

$$\frac{I_1}{(I_2)} = \frac{(d_2)^2}{(d_1)^2}$$

I_1 is the initial intensity of radiation, d_1 is the initial distance, and d_2 is the final distance, and I_2 is the final intensity.

Fig. 27: The inverse square law of radiation, with three representations: visual, graphical and mathematical all showing intensity reduction with distance travelled.

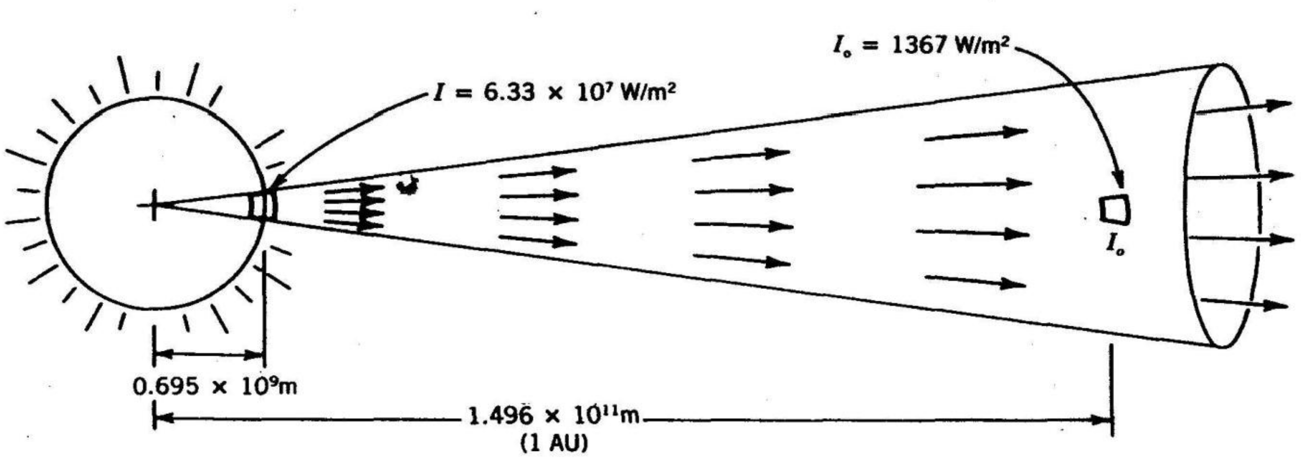


Fig : The inverse square law of radiation from the sun.

The solar constant and its determination.

The *solar constant* is defined as the amount of heat energy received per second per unit area (J/s/m^2, or W/m^2)andcompletelyabsorbedbya–perfectblackbody‖atthesurfaceoftheEarthwiththesurfacebeingheld perpendicular to the direction of the sun's rays. One instrument used for measuring the solar constant is called Pyroheliometer. In the middle of the 19th century, a very good measurement was made by the French physicist Pouillet. Later, the Swedish physicist Angstrom developed an improved version, called a compensation pyro heliometer, is describedbelow.

Various scientists had tried to calculate the Sun's energy output, but the first attempts at a direct measurement were carried out independently and more or less simultaneously by the French physicist Claude Pouillet (1790-1868) and British astronomer John Herschel (1792- 1871). Although they each designed different apparatus, the underlying principles were the same: a known mass of water is exposed to sunlight for a fixed period of time, and the accompanying rise in temperature recorded with a thermometer. The energy input rate from sunlight is then readily calculated, knowing the heat capacity of water. Their inferred value for the solar constant was about half the accepted modern value of 1367 ± 4 Watts per square meter, because they failed to account for of absorption by the Earth's atmosphere.

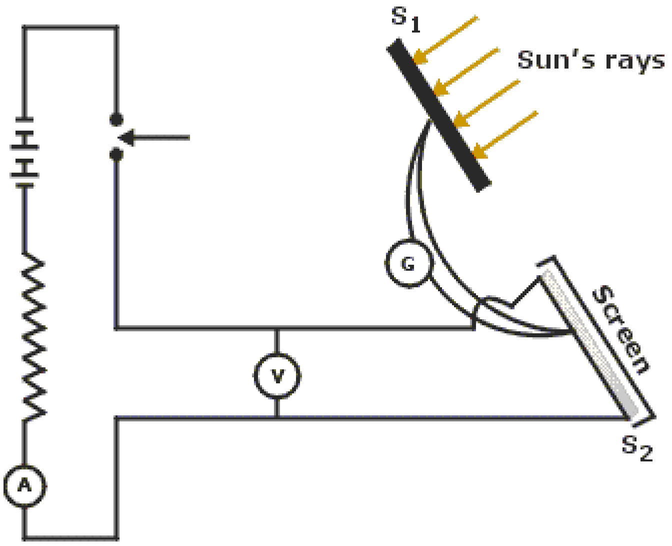


Fig. 30: Angstrom's compensation pyroheliometer

The total energy output of the sun.

We are now ready to estimate the total energy output of the sun, assuming that the inverse square law is applicable. We know the following:

1. The value of the solar constant. We will take it as approximately 1400W/m2.
2. The distance to the sun: approximately 1.5x1011m.
3. The inverse square law: The radiation, measured in W/m2 from a pointsource (Consider the sun‘s energy to come from a point source (see Fig. above)) is inversely proportional to the distance from the source squared.
4. The area of the surface of a sphere is 4πr2.

The following then is a guide for solving this problem:

First show that the inverse square law requires that the radiation energy from the sun intercepted by 1 m on the earth‘s surface is the solar constant, or about 1400 W/m2. Secondly, calculate the total energy going through the surface of the giant sphere with a radius of the distance to the sun, namely 1.5x1011 m. Finally, show that this is equal to about 3.9x1026 J/s.

This is an enormous amount of energy given out each second. See problem xx for moredetail.

Determining the temperature of the surface of the sun:

Having estimated the energy output of the sun to be 3.9x1026 J/s, it is now possible to estimate the temperate of the surface of the sun. We have already suggested that the temperature of the surface of the sun by a measurement using a pyrometer, or more precisely, a pyro heliometer.

The temperature of the sun is found to be about 6000 K.

However, it is also possible to confirm this value with a theoretical approach by using the physics of black body radiation. See discussion of black body radiation and Fig. xx below. According the theory of black body radiation, the sun is radiating energy, given by the Stephan-Boltzmann law R = δ A T4(see detail below). R is the radius of the sun, A the area of the surface of the sun, **δ** an experimentally determined constant (5.67x -8 watts / m2 x T4.), and T the temperature of the surface of the radiating black body object. You can now show that the temperature of the sun, according to this approach, is about 5900 K.

Although the sun is millions of degrees in its core, pyrometric measurement of the surface of the sun produces a black body temperature of about 6000 degrees K and the maximum power wavelength of the black body curve, shown below, is: Wavelength (max) = (0.0029)/T = .0029/6000 = 483 nanometers(nm).

Thus the sun appears white hot because the peak radiation output is in the blue/green portion of the visible spectrum.

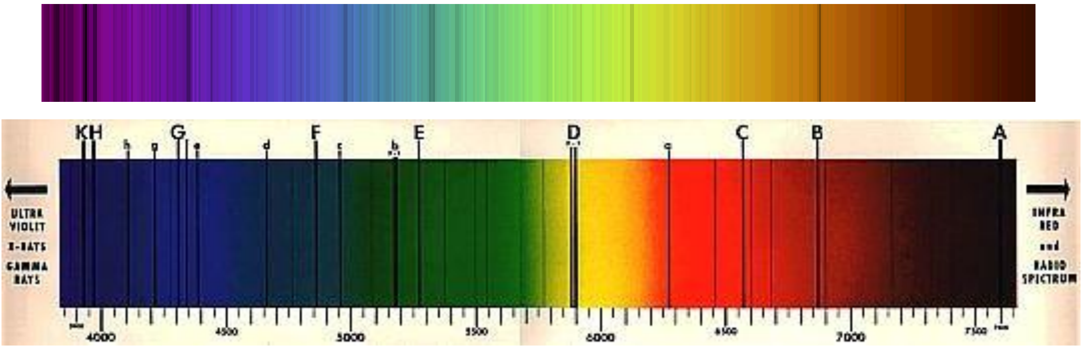


Fig : The SolarSpectrum

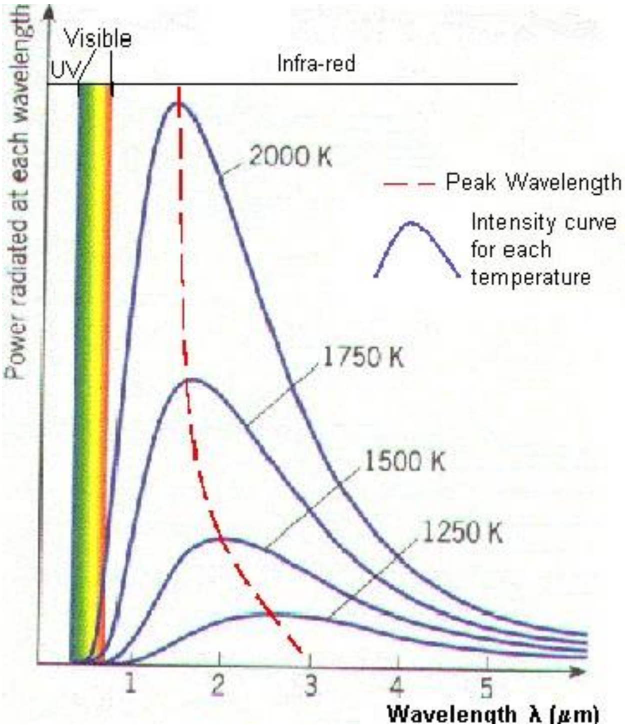


Fig: Black bodyradiation

Commercial Energy and Non CommercialEnergy:

Commercial Energy:

The energy sources that are available in the market for a definite price are known as commercial energy.By far the most important forms of commercial energy are electricity, coal and refined petroleum products. Commercial energy forms the basis of industrial, agricultural, transport and commercial development in the modern world. In the industrialized countries, commercialized fuels are predominant source not only for economic production, but also for many household tasks of general population.
Examples: Electricity, lignite, coal, oil, natural gas etc.

UNIT-III

SOLAR CELLS, PHOTOVOLTAIC BASICS

Diode:

A pure silicon crystal or germanium crystal is known as an intrinsic semiconductor. There are not enough free electrons and holes in an intrinsic semi-conductor to produce a usable current. The electrical action of these can be modified by doping means adding impurity atoms to a crystal to increase either the number of free holes or no of free electrons.

When a crystal has been doped, it is called a extrinsic semi-conductor

. They are of two types

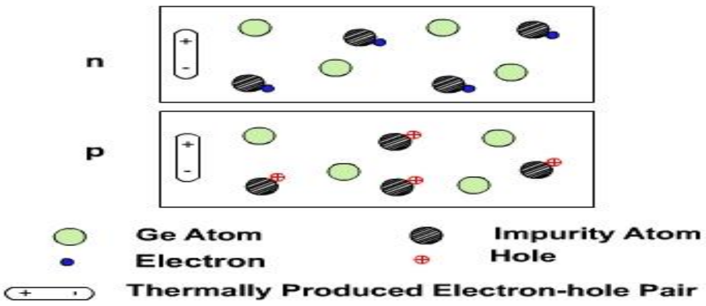
1. n-type semiconductor having free electrons as majority carriers
2. p-type semiconductor having free holes as majority carriers

By themselves, these doped materials are of little use. However, if a junction is made by joining p-type semiconductor to n-type semiconductor a useful device is produced known as diode. It will allow current to flow through it only in one direction. The unidirectional properties of a diode allow current flow when forward biased and disallow current flow when reversed biased. This is called rectification process and therefore it is also called rectifier.

Consider first the condition of p-type and n-type germanium just prior to joining fig. 1. The majority and minority carriers are in constant motion.

The minority carriers are thermally produced and they exist only for short time after which they recombine and neutralize each other. In the mean time, other minority carriers have been produced and this process goes on and on.

The number of these electron hole pair that exist at any one time depends upon the temperature. The number of majority carriers is however, fixed depending on the number of impurity atoms available. While the electrons and holes are in motion but the atoms are fixed in place and do not move.



As soon as, the junction is formed, the following processes are initiated fig. 2.

Holes from the p-side diffuse into n-side where they recombine with free electrons.

Free electrons from n-side diffuse into p-side where they recombine with free holes.

The diffusion of electrons and holes is due to the fact that large no of electrons are concentrated in one area and large no of holes are concentrated in another area.

When these electrons and holes begin to diffuse across the junction then they collide each other and negative charge in the electrons cancels the positive charge of the hole and both will lose their charges.

The diffusion of holes and electrons is an electric current referred to as a recombination current. The recombination process decay exponentially with both time and distance from the junction. Thus most of the recombination occurs just after the junction is made and very near to junction.

A measure of the rate of recombination is the lifetime defined as the time required for the density ofcarriers to decrease to 37% to the original concentration.

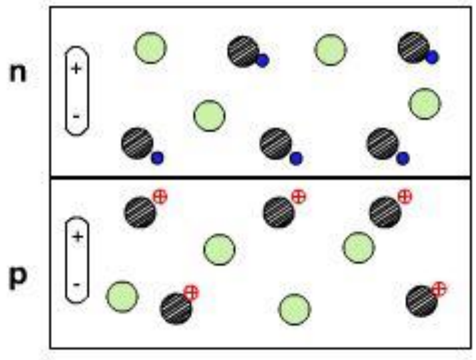


Figure-2

The impurity atoms are fixed in their individual places. The atoms itself is a part of the crystal and so cannot move. When the electrons and hole meet, their individual charge is cancelled and this leaves the originating impurity atoms with a net charge, the atom that produced the electron now lack an electronic and so becomes charged positively, whereas the atoms that produced the hole now lacks a positive charge and becomes negative.

The electrically charged atoms are called ions since they are no longer neutral. These ions produce an electric field as shown in fig. 3. After several collisions occur, the electric field is great enough to repel rest of the majority carriers away of the junction. For example, an electron trying to diffuse from n to p side is repelled by the negative charge of the p-side. Thus diffusion process does not continue indefinitely but continues as long as the This region is produced immediately surrounding the junction that has no majority carriers. The majority carriers have been repelled away from the junction and junction is depleted from carriers. The junction is known as the barrier region or depletion region. The electric field represents a potential difference across the junction also called space charge potential or barrier potential . This potential is 0.7v for Si at 25^o Celsius and 0.3v for Ge.

The physical width of the depletion region depends on the doping level. If very heavy doping is used, the depletion region is physically thin because diffusion charge need not travel far across the junction before recombination takes place (short life time). If doping is light, then depletion is more wide (long life time).

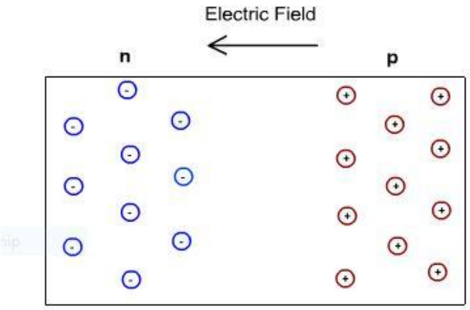


Fig.3

Space charge:

Space charge is a concept in which excess electric charge is treated as a continuum of charge distributed over a region of space (either a volume or an area) rather than distinct point-like charges. This model typically applies when charge carriers have been emitted from some region of a solid—the cloud of emitted carriers can form a space charge region if they are sufficiently spread out, or the charged atoms or molecules left behind in the solid can form a space charge region. Space charge usually only occurs in dielectric media (including vacuum) because in a conductive medium the charge tends to be rapidly neutralized or screened. The sign of the space charge can be either negative or positive. This situation is perhaps most familiar in the area near a metal object when it is heated to incandescence in a vacuum. This effect was first observed by Thomas Edison in light bulb filaments, where it is sometimes called the Edison effect, but space charge is a significant phenomenon in many vacuum and solid-state electronic devices.

When a metal object is placed in a vacuum and is heated to incandescence, the energy is sufficient to cause electrons to "boil" away from the surface atoms and surround the metal object in a cloud of free electrons. This is called thermionic emission. The resulting cloud is negatively charged, and can be attracted to any nearby positively charged object, thus producing an electric current which passes through the vacuum.

Space charge can result from a range of phenomena, but the most important are:

1. Combination of the current density and spatially inhomogeneous resistance
2. Ionization of species within the dielectric to form heterocharge
3. Charge injection from electrodes and from a stress enhancement
4. Polarization in structures such as water trees. "Water tree" is a name given to a tree-like figure

It has been suggested that in alternating current (AC) most carriers injected at electrodes during a half of cycle are ejected during the next half cycle, so the net balance of charge on a cycle is practically zero. However, a small fraction of the carriers can be trapped at levels deep enough to retain them when the field is inverted. The amount of charge in AC should increase slower than in direct current (DC) and become observable after longer periods of time.

If the "vacuum" has a pressure of 10^{-6} mmHg or less, the main vehicle of conduction is electrons. The emission current density *(J*) from the cathode, as a function of its thermodynamic temperature *T*, in the absence of space-charge, is given by Richardson's law:

where

$\mathrm{A\ m^{-2}\ K^{-2}}$

e = elementary positive charge (i.e., magnitude of electron charge),
m_e = electron mass,
k = Boltzmann's constant = 1.38 x 10^{-23}J/K,
h = Planck's constant = 6.62 x 10^{-34} J s,
φ = work function of the cathode,
$\check{r}$ = mean electron reflection coefficient.

The reflection coefficient can be as low as 0.105 but is usually near 0.5. For Tungsten, $(1 - \check{r})A_0 = 0.6$ to $1.0 \times 10^6\ \mathrm{A\ m^{-2}\ K^{-2}}$, and $\varphi = 4.52$ eV. At 2500 °C, the emission is 28207 A/m^2.

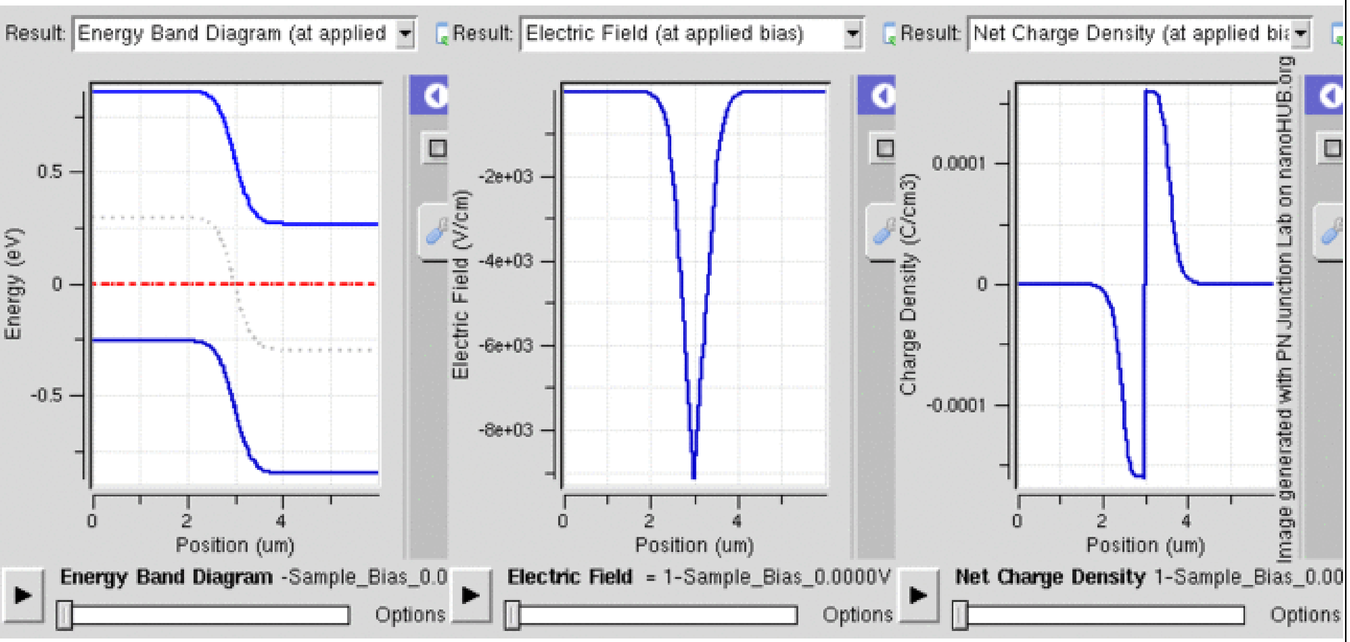
The emission current as given above is many times greater than that normally collected by the electrodes, except in some pulsed valves such as the cavity magnetron. Most of the electrons emitted by the cathode are driven back to it by the repulsion of the cloud of electrons in its neighborhood. This is called the space charge effect. In the limit of large current densities, J is given by the Child-Langmuir equation below, rather than by the thermionic emission equation above.

QUASI FERMI LEVEL:

A quasi Fermi level (also called imref, which is "fermi" spelled backwards) is a term used in quantum mechanics and especially in solid state physics for the Fermi level (chemical potential of electrons) that describes the population of electrons separately in the conduction band and valence band, when their populations are displaced from equilibrium. This displacement could be caused by the application of an external voltage, or by exposure to light of energy , which alter the populations of electrons in the conduction band and valence band. Since recombination rate (the rate of equilibration between bands) tends to be much slower than the energy relaxation rate within each band, the conduction band and valence band can each have an individual population that is internally in equilibrium, even though the bands are not in equilibrium with respect to exchange of electrons. The displacement from equilibrium is such that the carrier populations can no longer be described by a single Fermi level, however it is possible to describe using concept of separate quasi-Fermi levels for each band.

When a semiconductor is in thermal equilibrium, the distribution function of the electrons at the energy level of E is presented by a Fermi–Dirac distribution function. In this case the Fermi level is defined as the level in which the probability of occupation of electron at that energy is ½. In thermal equilibrium, there is no need to distinguish between conduction band quasi-Fermi level and valence band quasi-Fermi level as they are simply equal to the Fermi level.

When a disturbance from a thermal equilibrium situation occurs, the populations of the electrons in the conduction band and valence band change. If the disturbance is not too great or not changing too quickly, the bands each relax to a state of quasi thermal equilibrium. Because the relaxation time for electrons within the conduction band is much lower than across the band gap, we can consider that the electrons are in thermal equilibrium in the conduction band. This is also applicable for electrons in the valence band (often understood in terms of holes). We can define a quasi Fermi level and quasi temperature due to thermal equilibrium of electrons in conduction band, and quasi Fermi level and quasi temperature for the valence band similarly.



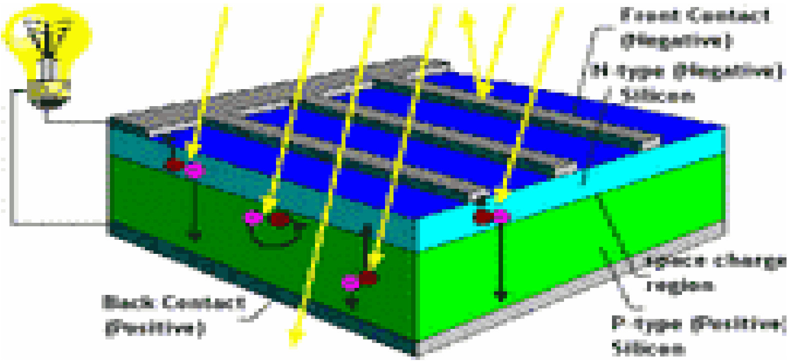
Structure of solar cell

Solar cells are structured in layers with different functions. The working principle is the same as in semiconductors.

The main part of a silicon (Si) solar cell generating solar power is formed by two differently doped (n- and p-) silicon layers. A physical barrier is created between them along the p-/n-junction, with electrons and holes diffusing into regions of lower concentration.
This depleted region or space charge region can only be overcome with the help of photons i.e. sunlight.

To be able to channel electrones and holes and generate electric power, metal contacts need to be printed onto the front and rear side. Generally, a full aluminium or silver layer is screenprinted onto the rear. A thin grid forms the front contact keeping the impact on light entering the silicon cells as low as possible.

To reduce light reflection, a thin film of silicon nitride or titanium dioxide is coated onto the surface.



Copper Indium Gallium Selenide:

A **copper indium gallium selenide solar cell** (or **CIGS cell**, sometimes CI(G)S or CIS cell) is a thin-film solar cell used to convert sunlight into electric power. It is manufactured by depositing a thin layer of copper, indium, gallium and selenium on glass or plastic backing, along with electrodes on the front and back to collect current. Because the material has a high absorption coefficient and strongly absorbs sunlight, a much thinner film is required than of other semiconductor materials.

CIGS is one of three mainstream thin-film PV technologies, the other two being cadmium telluride and amorphous silicon. Like these materials, CIGS layers are thin enough to be flexible, allowing them to be deposited on flexible substrates. However, as all of these technologies normally use high-temperature deposition techniques, the best performance normally comes from cells deposited on glass, even though advances in low-temperature deposition of CIGS cells have erased much of this performance difference. CIGS outperforms polysilicon at the cell level, however its module efficiency is still lower, due to a less mature upscaling.

Thin-film market share is stagnated at around 15 percent, leaving the rest of the PV market to conventional solar cells made of crystalline silicon. In 2013, the market share of CIGS alone was about 2 percent and all thin-film technologies combined fell below 10 percent. CIGS cells continue being developed, as they promise to reach silicon-like efficiencies, while maintaining their low costs, as is typical for thin-film technology. Prominent manufacturers of CIGS photovoltaics were the now-bankrupt companies Nanosolar and Solyndra. Current market leader is the Japanese company Solar Frontier, Global Solar and GSHK Solar producing solar modules free of any heavy metals such as cadmium or lead.

Properties of CIGS:

CIGS is a I-III-VI$_2$ compound semiconductor material composed of copper, indium, gallium, and selenium. The material is a solid solution of copper indium selenide (often abbreviated "CIS") and copper gallium selenide, with a chemical formula of CuIn$_x$Ga$_{(1-x)}$Se$_2$, where the value of x can vary from 1 (pure copper indium selenide) to 0 (pure copper gallium selenide). It is a tetrahedrally bonded semiconductor, with the chalcopyrite crystal structure. The bandgap varies continuously with *x* from about 1.0 eV (for copper indium selenide) to about 1.7 eV (for copper gallium selenide).

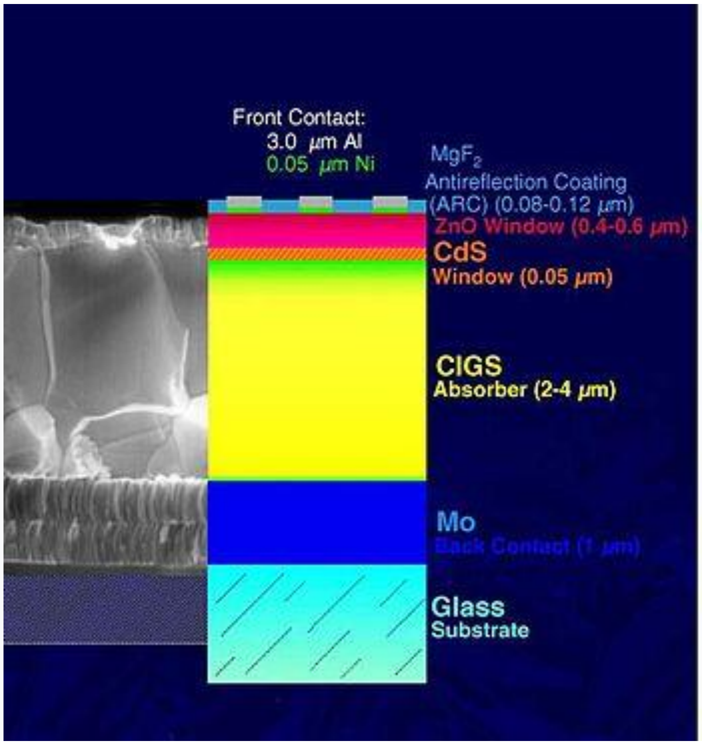


Figure : Structure of a CIGS device. CdS is used optionally and some CIGS cells contain no cadmium at all.

CIGS has an exceptionally high absorption coefficient of more than 10^5/cm for 1.5 eV and higher energy photons. CIGS solar cells with efficiencies around 20% have been claimed by the National Renewable Energy Laboratory(NREL), the Swiss Federal Laboratories for Materials Science and Technology (Empa),

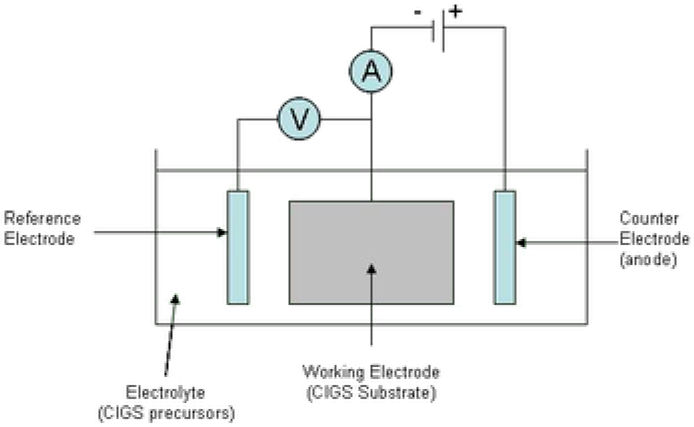


Fig: CIGS electrodeposition apparatus

Organic solar cell: An organic solar cell or plastic solar cell is a type of photovoltaic that uses organic electronics, a branch of electronics that deals with conductive organic polymers or small organic molecules, for light absorption and charge transport to produce electricity from sunlight by the photovoltaic effect. Most organic photovoltaic cells are polymer solar cells.

The molecules used in organic solar cells are solution-processable at high throughput and are cheap, resulting in low production costs to fabricate a large volume. Combined with the flexibility of organic molecules, organic solar cells are potentially cost-effective for photovoltaic applications. Molecular engineering (e.g. changing the length and functional group of polymers) can change the band gap, allowing for electronic tunability. The optical absorption coefficient of organic molecules is high, so a large amount of light can be absorbed with a small amount of materials, usually on the order of hundreds of nanometers. The main disadvantages associated with organic photovoltaic cells are low efficiency, low stability and low strength compared to inorganic photovoltaic cells such as silicon solar cells.

Organic photovoltaics are made of electron donor and electron acceptor materials rather than semiconductor p-n junctions. The molecules forming the electron donor region of organic PV cells, where exciton electron-hole pairs are generated, are generally conjugated polymers possessing delocalized π electrons that result from carbon p orbital hybridization. These π electrons can be excited by light in or near the visible part of the spectrum from the molecule's highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO), denoted by a π -π^* transition. The energy bandgap between these orbitals determines which wavelength(s) of light can be absorbed.

Unlike in an inorganic crystalline PV cell material, with its band structure and delocalized electrons, excitons in organic photovoltaics are strongly bound with an energy between 0.1 and 1.4 eV. This strong binding occurs because electronic wave functions in organic molecules are more localized, and electrostatic attraction can thus keep the electron and hole together as an exciton. The electron and hole can be dissociated by providing an interface across which the chemical potential of electrons decreases. The material that absorbs the photon is the donor, and the material acquiring the electron is called the acceptor. In Fig. 2, the polymer chain is the donor and the fullerene is the acceptor. Even after dissociation, the electron and hole may still be joined as a "geminate pair", and an electric field is then required to separate them. The electron and hole must be collected at contacts. If charge carrier mobility is insufficient, the carriers will not reach the contacts, and instead recombine at trap sites or remain in the device as undesirable space charges that oppose the flow of new carriers. The latter problem can occur if electron and hole mobilities are not matched. In that case, space-charge limited photocurrent (SCLP) hampers device performance.

Organic photovoltaics can be fabricated with an active polymer and a fullerene-based electron acceptor. Illumination of this system by visible light leads to electron transfer from the polymer to a fullerene molecule. As a result, the formation of a photoinduced quasiparticle, or polaron (P^+), occurs on the polymer chain and the fullerene becomes a radical anion (C_{60}). Polarons are highly mobile and can diffuse away.

Single layer:

single layer organic photovoltaic cells are the simplest form. These cells are made by sandwiching a layer of organic electronic materials between two metallic conductors, typically a layer of indium tin oxide (ITO) with high work function and a layer of low work function metal such as Aluminum, Magnesium or Calcium. The basic structure of such a cell is illustrated in Fig 2.

The difference of work function between the two conductors sets up an electric field in the organic layer. When the organic layer absorbs light, electrons will be excited to the LUMO and leave holes in the HOMO, thereby forming excitons. The potential created by the different work functions helps to split the exciton pairs, pulling electrons to the positive electrode (an electrical conductor used to make contact with a non-metallic part of a circuit) and holes to the negative electrode.

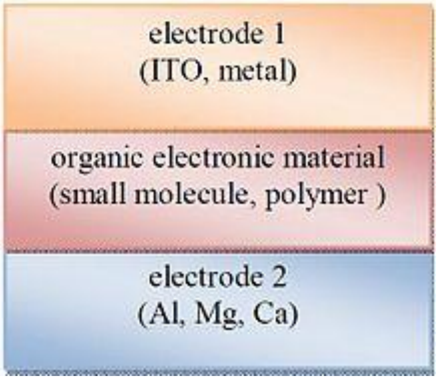


Fig: single layer organic photovoltaic cell

Bilayer organic cell:

Bilayer cells contain two layers in between the conductive electrodes (Fig 3). The two layers have different electron affinity and ionization energies, therefore electrostatic forces are generated at the interface between the two layers. Light must create excitons in this small charged region for an efficient charge separation and collecting. The materials are chosen to make the differences large enough that these local electric fields are strong, which splits excitons much more efficiently than single layer photovoltaic cells. The layer with higher electron affinity and ionization potential is the electron acceptor, and the other layer is the electron donor. This structure is also called a planar donor-acceptor heterojunction.

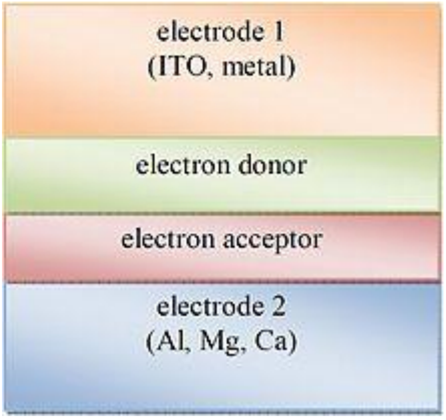


Fig:: Bilayer organic photovoltaic cell

Example:

C_{60} has high electron affinity, making it a good acceptor. A C_{60}/MEH-PPV double layer cell had a relatively high fill factor of 0.48 and a power conversion efficiency of 0.04% under monochromatic illumination.PPV/C_{60} cells displayed a monochromatic external quantum efficiency of 9%, a power conversion efficiency of 1% and a fill factor of 0.48.

Perylene derivatives display high electron affinity and chemical stability. A layer of copper phthalocyanine (CuPc) as electron donor and perylenetetracarboxylic derivative as electron acceptor, fabricating a cell with a fill factor as high as 0.65 and a power conversion efficiency of 1% under simulated AM2 illumination.[23] Halls et al. fabricated a cell with a layer of bis(phenethylimido) perylene over a layer of PPV as the electron donor. This cell had peak external quantum efficiency of 6% and power conversion efficiency of 1% under monochromatic illumination, and a fill factor of up to 0.6.

Tandem Cells:

One method to increase the efficiency of a solar cell is to split the spectrum and use a solar cell that is optimised to each section of the spectrum.

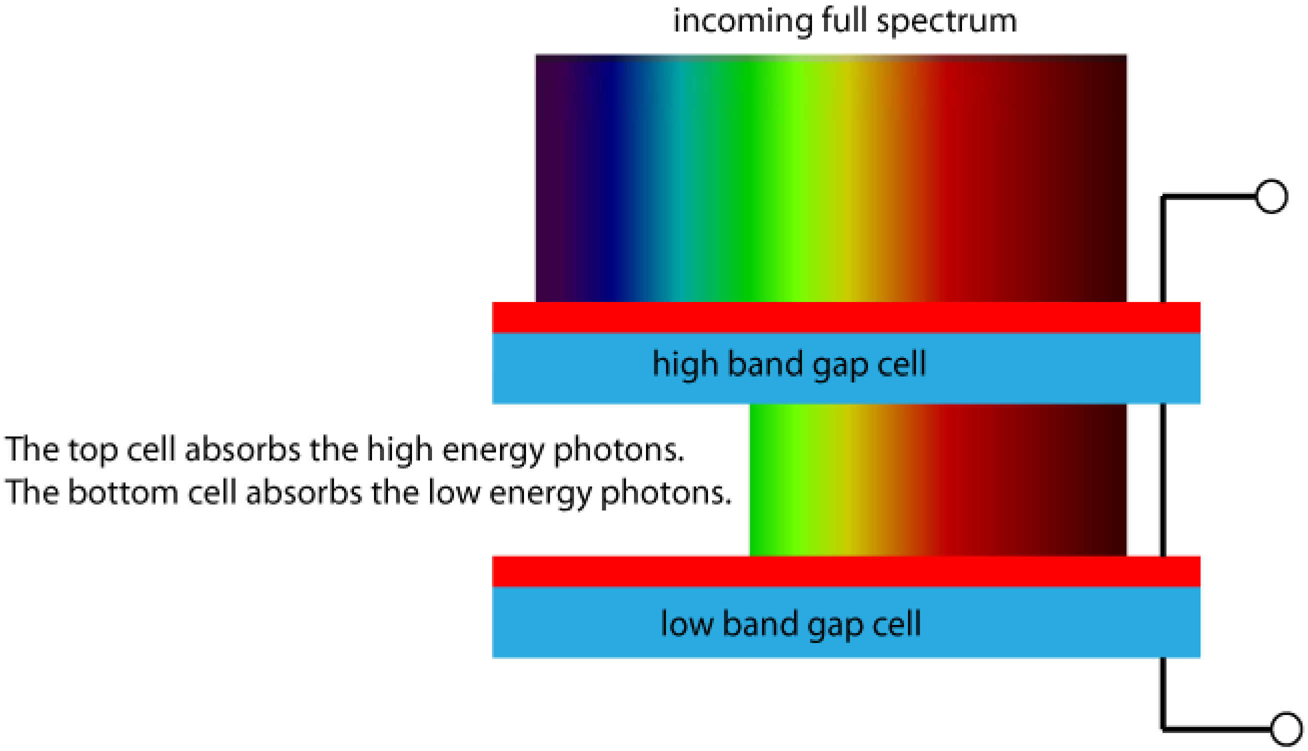
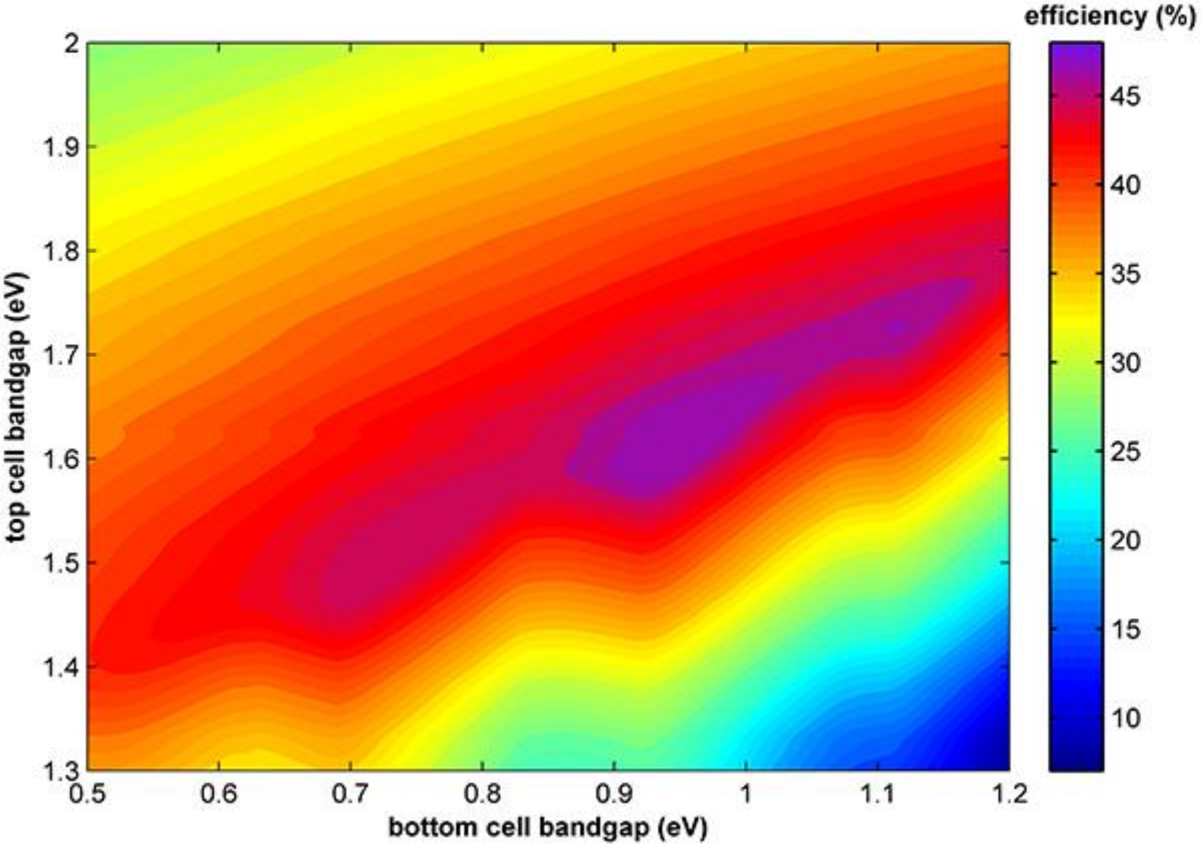


Fig: Tandem Cells

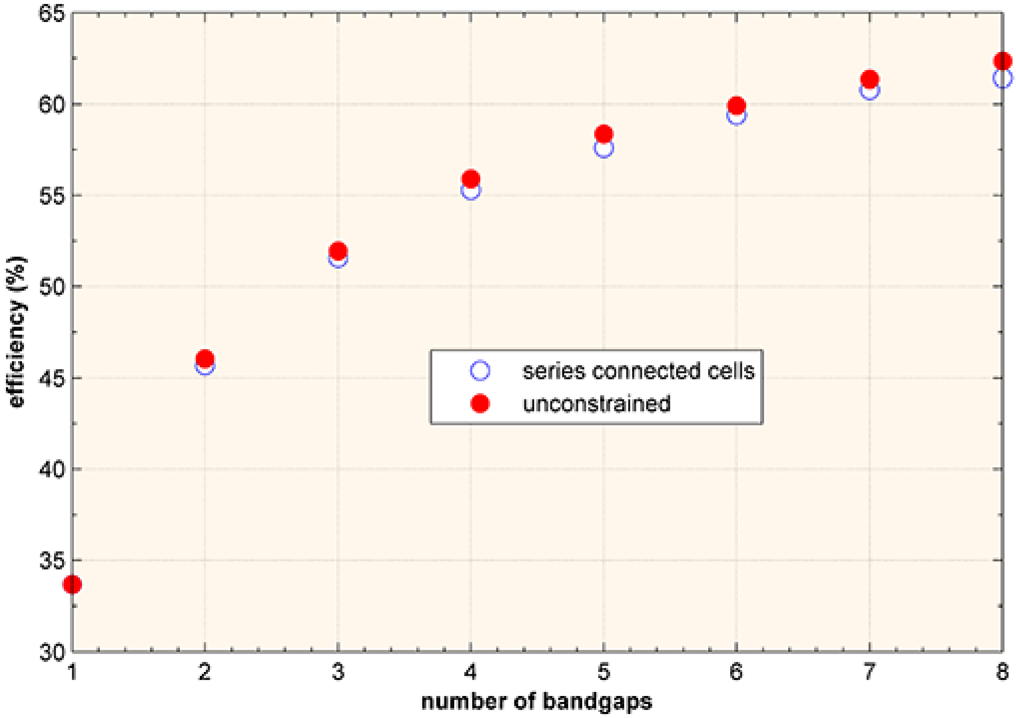
Series connected tandem solar cell. Adding more devices allows for each device to be optimized to a narrower spectrum giving a higher overall efficiency.

Tandem solar cells can either be individual cells or connected in series. Series connected cells are simpler to fabricate but the current is the same though each cell so this contrains the band gaps that can be used. The most common arrangement for tandem cells is to grow them monolithically so that all the cells are grown as layers on the on substrate and tunnel junctions connect the individual cells.



The maximum efficiency for a two junction tandem under the AM1.5G spectrum and without concentration is 47 %. At the peak efficiency the top cell has a bandgap of 1.63 eV and the bottom cell has a bandgap of 0.96 eV.

As the number of bandgaps increases the efficiency of the stack also potentially increases. In reality, the semiconductor materials do not exist to allow for arbitrary materials with a specific bandgap and of high quality.



Efficiency of a an ideal stack of solar cells as a function of the number of bandgaps.

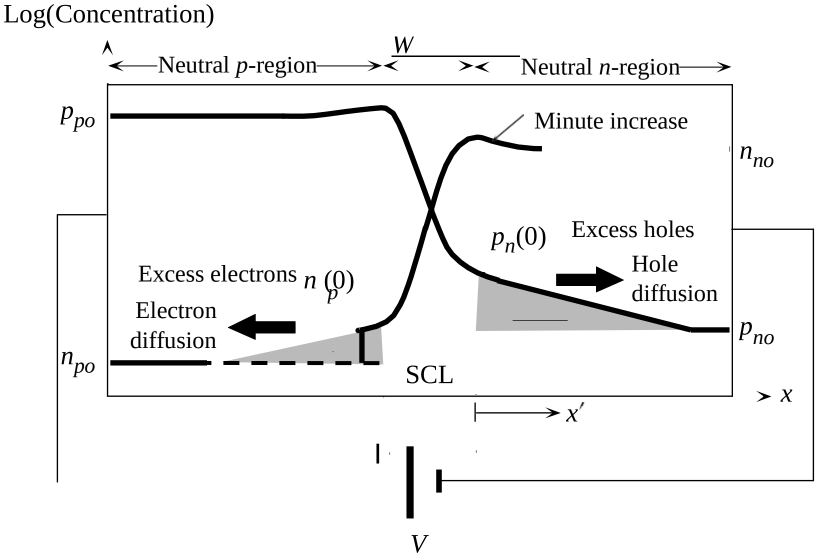
The spectrum used here is the direct spectrum (AM 1.5D) where the diffuse radiation is excluded.

***pn* Junction *I–V* Characteristics**

The current density in a forward biased *pn* junction is generally described by the Shockley equation,

$$J = \left(\frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a}\right) n_i^2 \left[\exp\left(\frac{eV}{kT}\right) - 1\right] \qquad \textit{Shockley equation} \qquad (1)$$

where e is the electronic charge, k is Boltzmann’s constant, T is temperature (K), V is the voltage across the *pn* junction, n_i is the intrinsic concentration, D is the diffusion coefficient, L is the diffusion length and N_a and N_d are the acceptor and donor doping concentrations respectively. The subscripts e and h refer to electrons and holes, respectively, as minority carriers; that is, holes in the *n*-side and electrons in the *p*-side. If τ is the charge carrier lifetime (recombination time) then $L = \sqrt{D\tau}$. The Shockley expression neglects the current component that is due to recombination in the depletion region, that is in the space charge layer (SCL). The electron and hole concentrations across the device are depicted (in an exaggerated way) in Figure 1. The application of a forward bias leads to the injection of minority carriers into the neutral regions of the diode. The minority carrier concentrations (*e.g.* holes and electron concentrations) at the space charge layer (SCL) boundaries in the neutral regions (*n*- and *p*-regions respectively) are represented as $p_n(0)$ and $n_p(0)$. In a long diode the minority carrier concentration profile falls exponentially towards the electrode, which means that there is a concentration gradient and hence diffusion. The minority carriers therefore diffuse towards the bulk giving rise to a diode current. These arguments lead to the Shockley equation stated in Equation (1) for a p^+n junction long diode.



Forward biased *pn* junction and the injection of minority carriers. Carrier concentration profiles across the device under forward bias. Note: SCL = space charge layer and *W* = width of the SCL with forward bias. Other symbols have their usual meanings.

Figure 1

The reverse current density component due to thermal generation of electron-hole pairs (EHPs) within the depletion region, as depicted in Figure 2, is given by

$$J_{gen} = \frac{eWn_i}{\tau_g} \qquad \textit{Thermal generation} \tag{2}$$

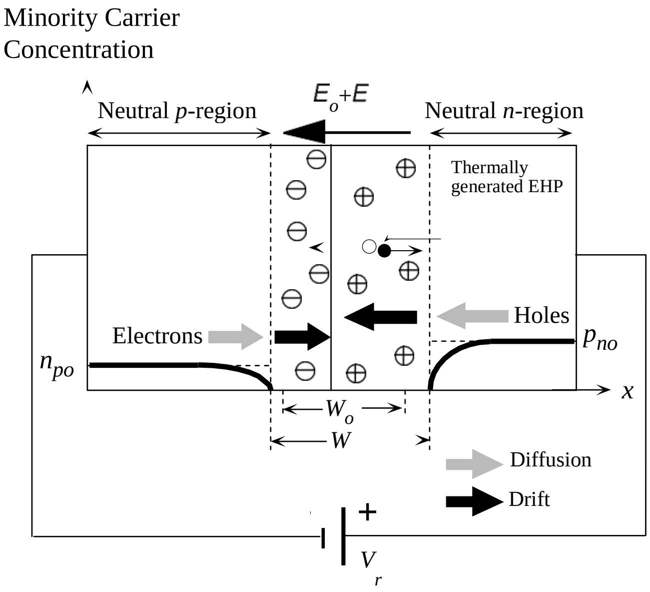
where *W* is the width of the depletion region and τ_g is the *mean* thermal generation time. Thermal generation of EHPs in the depletion region occurs through generation-recombination centers and depends on carrier concentrations, crystal defects and impurities. τ_g in Equation (2) represents a *mean* thermal generation time calculated by integrating the rate of thermal generation across the depletion region.

There is also a contribution to the reverse current arising from the thermal generation of minority carriers in the neutral regions within a diffusion length to the SCL, their diffusion to the SCL, and subsequent drift through the SCL (Figure 2). This is essentially the Shockley model with a negative voltage, that is Equation (1) with a reverse bias. The battery replenishes the minority carriers that are lost in this way from the neural regions. Stated differently, there is a reverse current due to the diffusion of minority carriers in neutral regions towards the SCL.

The width of the depletion region with a reverse bias $V = -V_r$ is given by

$$W = \left[\frac{2\varepsilon(N_a+N_d)(V_o+V_r)}{eN_aN_d}\right]^{1/2} \qquad \text{Depletion layer(SCL)width} \qquad (3)$$

where $V_o = (kT/e)\ln[(N_aN_d)/n_i^2]$ is the built-in voltage, $\varepsilon = \varepsilon_o\varepsilon_r$ is the permittivity of the semiconductor material. Equation (3) assumes an abrupt *pn* junction.



Reverse biased *pn* junction. Minority carrier concentration profiles and the origin of the reverse current. Note: EHP = electron-hole pair, SCL = spacecharge layer, E = electric field, W = width of the SCL with reverse bias, V_r = reverse bias. Other symbols have their usual meanings. Subscript *o* refers to "no-bias" condition.

Figure 2

Problem: The *pn* junction

Consider a long Si diode made of an abrupt p^+n junction which has 10^{15} donors cm^{-3} on the *n*-side and 10^{18} acceptors on the *p*-side. The dependence of the hole and electron drift mobility on the dopant concentration is shown in Figure 3. The minority carrier recombination times are τ_h = 490 ns for holes in the *n*-side and τ_e = 23.8 ns for electrons in the *p*-side. The cross sectional area is 0.1 mm^2. Assume a long diode. The thermal generation time τ_g in the depletion region is ~1 ms. Assume that the reverse current is dominated by the thermal generation rate in the depletion region.

a Calculate the forward current at 27°C when the voltage across the diode is 0.6V.

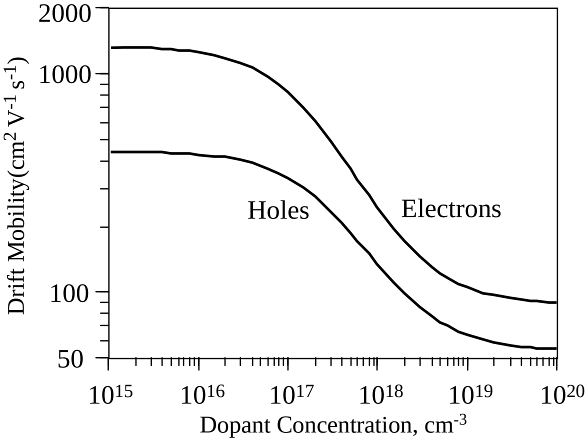
b Estimate the forward current at 57°C when the voltage across the diode is still 0.6V.

c Calculate the voltage across the diode at 57 °C if the forward current in **a** above at 27 °C is kept constant.

d Whatisthereversecurrentat27°Cwhenthediodevoltageis−5V?

e Estimatethereversecurrentat57°Cwhenthediodevoltageis−5V.

Note: Assume thatthe forward currentis determinedby the Shockley equation (minority carrier diffusion).



The variation of the drift mobility with dopant concentration in Si for electrons and holes.

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