GETTING OUT OF THE DARKNESS: THE SOLAR ENERGY SOLUTION

BAYERO UNIVERSITY KANO
PROFESSORIAL INAUGURAL LECTURE

NO. 45

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12TH DECEMBER 2019

BAYERO
UNIVERSITY PRESS

Published 2019 by:
Bayero University Press,
Main Library Building,
Bayero University, Kano,
New Site, Gwarzo Road
P.M.B.3011, Kano.

Website: *www:buk.edu.ng*

Email: *info.bukpress@buk.edu.ng*

ISBN 978 - 978 - 57092 - 9 - 2

PRODUCED BY BAYERO UNIVERSITY PRESS KANO

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PRESENTER'S BIODATA

Professor Dalhatu Balarabe Yahaya, former Rector, Nuhu Bamalli Polytechnic, Zaria, was born in Zaria, Kaduna State on the 25th September, 1963. He obtained his B.Eng., M.Sc. Degrees from Technical University of Russe in Bulgaria and his PhD from Bayero University, Kano. Bench work for the PhD was conducted in the University of Leeds, United Kingdom for a period of nine months. His area of specialization is Energy Engineering. He began his career as an Assistant Lecturer in the Department of Mechanical Engineering, Faculty of Technology of Bayero University, Kano in December 1988 and rose to become a Professor in October 2012.

In the course of his career, he has held various academic positions like: Head of Department, Mechanical Engineering; Sub-Dean, Faculty of Technology; Deputy Dean, School of Postgraduate Studies all in BUK and was the pioneer Dean, School of Postgraduate Studies, Kano University of Science and Technology (KUST), Wudil. Other aspects of his responsibilities in Bayero University, Kano included:

i. Chairman, Minor Works Committee

ii. Chairman, Technical Sub-Committee of University Transport System.

iii. Chairman, Committee on Unutilized Fuel Station in the University.

iv. Chairman, Student Entry Qualifications Irregularities Committee.

v. Member of over 60 University Committees and Task Forces including some as Chairman.

vi. Served in over 20 committees, prominent among which was member, committee of Revitalization of Industries in Kano State in 2003.

Professor Yahaya has supervised more than ninety (90) PhD theses, M.Eng. dissertations and B.Eng projects in different areas of Mechanical Engineering and has also served as external examiner to ten (10) universities and polytechnics. He is an assessor, technical reviewer and editorial member to ten research journals. Also, he has to his credit, more than sixty (60) articles in journals, conference proceedings and technical reports. Professor Yahaya has authored three (3) books on Engineering Mechanics, Solid Mechanics and Energy Conversion with Combustion.

He has received more than ten (10) distinguished awards and certificate of honours. Professor Yahaya is a COREN registered engineer and member of Nigeria Society of Engineers (NSE). He is also a member of AfricaFirstNigeria project and Fellow Institute of Human and Natural Resource (FHNR).

GETTING OUT OF THE DARKNESS: THE SOLAR ENERGY SOLUTION

PREAMBLE

Nigeria has been bedevilled with the problem of generation, transmission and distribution of electricity for a long period of time. Almost all past governments did their best to improve the generation of electricity. For example, in 2005, former president Olusegun Obasanjo signed into law the Electric Power Reform Bill which transformed the former National Electric Power Authority into Power Holding Company of Nigeria (PHCN). Licences were given to six semi-autonomous power generating companies with a mandate to generate electric power and sell it to the Transmission Company of Nigeria in bulk unit. The companies that were given licences were:

1. Kainji/Jebba Hydro Power Business Unit
2. Sapele Electric Power Business Unit
3. Delta Electric Power Business Unit and
4. Afam Electric Power Business Unit
5. Shiroro Hydro Power Business Unit
6. Egbin Electric Power Business Unit

Billions of dollars was spent between 1999 and 2007 by the former regime of President Olusegun Obasanjo with the intention of increasing electric power generation by 10,000mW at the end of his tenure in 2007. However, by the time he left office that year, power generation was less than 3000MW.

The present administration is also doing its best in terms of generating power for the country;, there has been some remarkable improvement in the last four years. There was a time when 9,931MW of electricity was generated before it went down to almost an average of 6, 841MW. For Nigeria to develop economically, it has to produce enough energy to cater for the need of industries and other uses. There is a need for government to pay more attention to generating electricity from alternative energy sources like solar, geothermal, hydroelectric, wind, etc. instead of using only fossil fuels.

Electricity production in Nigeria reached 8,441MWh in March, 2019, compared with 5,908 MWh in the premiums quarter. Electricity production data of Nigeria is updated quarterly, averaging at 6,841 MWh from March 2005 to March 2019. The data reached an all-time high of 9,936 MWh in September 2015 and reached an all-time low of 3,247 MWh in June 2009. CEIC calculates the Electricity Generation Average per Hour by multiplying it by the number of hours in the quarter. The number of hours used is 24×90. The Central Bank of Nigeria Provides Electricity Generation Average Per Hour. (CBN, 2019).

Solar energy is available in abundance; it is clean and can be converted into required form through thermal and photovoltaic methods. But it does have its own drawbacks, some of which are listed below (Iqbal, 1983).

i. The area of collection required per unit power output is very large

ii. For high temperature system, the fluids used are glycol mixture and sulphate when power is generated through thermal system. This may be hazardous to health, especially in densely populated areas.

iii. Solar photovoltaic system is expensive and its waste products are difficult to dispose due to the presence of arsenic and cadmium in them.

iv. Solar power generators require batteries and inverters as storage is essential.

v. Solar thermal collectors (water heaters) and photovoltaic system have become an integral part of high-rise building. Therefore, large scale use in densely populated areas limits the exposure of people to daylight.

SOLAR RADIATION SOFTWARE

The solar radiation software currently being used today in the world include International Satellite Cloud Climatology Project (ISCCP), Solar Radiation Budget (SRB), National Aeronautical and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), Geostationary Operational Environmental Satellite (GOES) and European Solar Radiation Atlas (ESRA). Both NOAA and GOES use alternative to surface measurement (Domkundwar, 2010).

Bayero University is one of the leading universities doing research on renewable energy, especially solar energy. The Department of Mechanical Engineering, Bayero University, runs master’s and doctoral degrees in Energy Engineering leading to the awards of M.Eng and PhD in Energy Engineering. Many researches carried out by undergraduates, postgraduates and staff of the department in this field have been published in reputable journals both nationally and internationally. The recent commissioning of 7.1 megawatts solar hybrid power plant (the largest in Africa) in New Campus, Bayero University, Kano by the Vice President, Prof. Yemi Osinbajo on 3rd September, 2019 as well as the installation of 1megawatt solar station in Old Campus of the university will go a long way in solving the perennial power problems of the university; it also fits well into its current research focus on renewable energy. The university electrical bills will go down drastically and the whole school will have improved power supply. This is a great achievement by the university, I commend the present administration under the leadership of Prof. Muhammad Yahuza Bello, the current Vice Chancellor for the exemplary and visionary leadership displayed in the university (*BUK Bulletin*, September, 2019).

Table 1: *Estimated Life of Fossil Fuels Reserves of the World*

Country/Region	**Life (Years)**	**Country/Region**	**Life (Years)**
Canada	27	Africa	81
USA	62	China	97
L. America	27	Japan	12.5
W. Europe	58	Australia	76
E. Europe	-	S.E. Asia	-
F. USSR	76	Middle East	127.6

The above figures do not include hydro, nuclear and other sources and have also omitted the imports of fossil fuels by a particular country. The largest importer is Japan for coal and oil. The individual country will show different lifespan for their reserves. For example, in the U.K., the coal reserves are estimated to last for 300 years instead of 58 years as shown, by grouping it with other West-European countries. However, it is clear that the fossil fuels in the world may only sustain the requirement of power for 50 to 80 years and it is essential to use alternative sources of energy (Domkundwar, 2010).

GLOBAL ENERGY CONSUMPTION PATTERN

The rising population of the world, the constant increase in power consumption and the simultaneous decline in fuel resources have made energy problem one of the most complicated that mankind has to face today. The global consumption of electrical energy is currently increasing by a factor of 4 to 5 after every 20 years, whereas the corresponding increase in the consumption of all forms of energy is by a factor of 2 to 2.5. The rate of increase in the consumption of power must eventually decline and it seems that by the year 2100, this will be the situation as characterised by the data given in Table 2 (Domkundwar, 2010).

Fig. 1 shows the world energy consumption between 1960 - 1990. There is a remarkable increase in the consumption of electricity during this period; in fact, it more than double the 1960 world energy consumption.

Table 2: *World Consumption Pattern*

Parameter	Year							
	1960	1980	2000	2020	2040	2060	2080	2100
Electric power consumption in units of 10^{12} kWh/yr	2	8	27	78	187	374	600	900
Factor by which consumption increases during stated period	4.6	4.0	3.4	2.9	2.4	2.0	1.6	1.5
Annual fuel consumption in units of 10^{12} tons	5	15	39	86	163	277	416	582
Factor by which it increases during the stated period	1.7	3.0	2.6	2.2	1.9	1.7	1.5	1.4
Fuel consumption in units of 10^{9} tons/20 years	100	220	540	1240	2500	4460	6920	10000
Since the beginning of the period, tons	100	300	840	2080	4580	8930	15900	25900

Source: (Domkundwar, 2010)

Fig. 1 below gives a pictorial representation of the rate of increase of energy consumption.

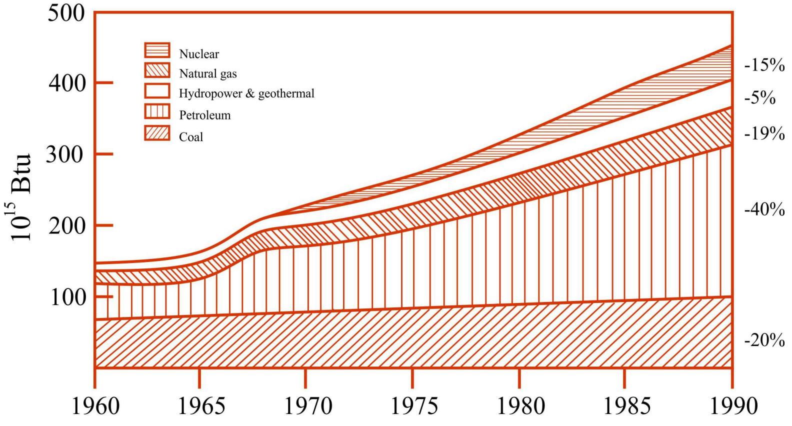


Fig. 1: *World Energy Consumption*

If possible, other existing sources which are not yet developed to economic viability should be used, for example, hydroelectric power as shown in Fig. 2.

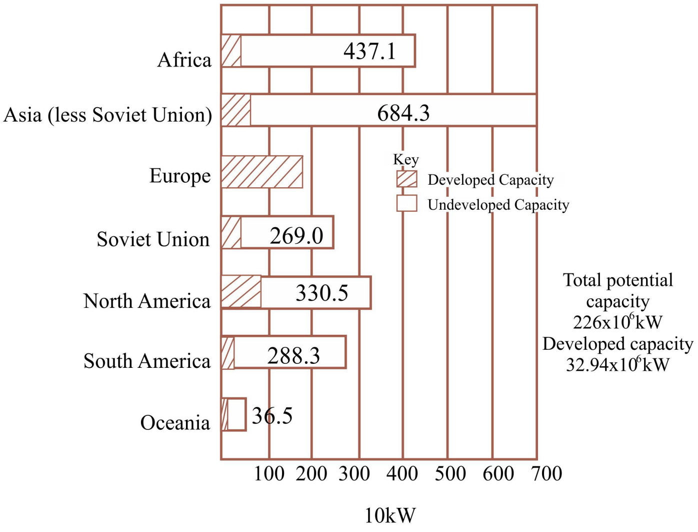


Fig. 2: *World Hydroelectric Power, Developed and Undeveloped (1973)*

It is obvious from the above data that by the end of the 21st century, the rate of increase in the consumption of power and fuel will probably fall from 2.1 to 1.7 %. Moreover, there will be scope for finding new ways of using fossil fuels and reduction in its specific consumption.

Under these conditions, the consumption of electric power and energy will increase by the factors of 33 and 15 over 100 years period (in proportion of 2:1) and the high rate of increase in electric power will persist. Moreover, the technological progress will ensure that the specific fuel consumption for generating electrical power will fall substantially (in USSR, it fell from 0.894 to 0.645 kg/kWh) and, because of the saturation of the market with industrial products, the demand for primary energy sources for technological purposes will be limited. The demand for primary energy sources will also be restricted by the expansion in the industrial utilisation of secondary sources. It is estimated that annual consumption of primary energy (apart from energy used to generate electrical power) will increase from 28 to 220 billion tons over the 100 years period.

The predictions made above are somewhat arbitrary. They may be too high for highly developed countries and too low for the developing countries. It is also predicted that in continents like Africa and Asia, the rate of increase in power consumption will be the highest. If the rate of increase in population falls during the next 250 years (from 2.5 to 2.1 times during 100 years), then by the year 2100, the global population will be 30 billion and ratio of the population and power growth factors over the 100 years period will be 1:6.6 for electrical power and 1:3 for energy consumption.

Looking into the future , the renewable energies have already entered into the market but on a very small basis as shown in Fig. 3.

Market share of renewables

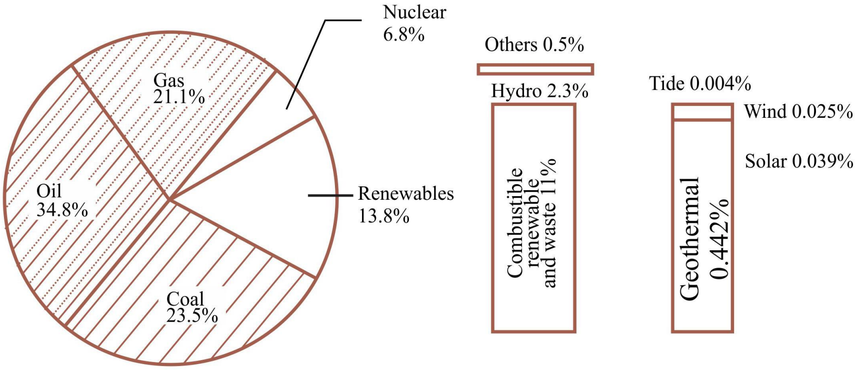


Fig. 3: *Renewables in Global Energy Supply as at 2002*

Tables 3 and 4 show energy primary energy consumptions and consumption of fuel in 2002 of China, India USA and Japan (International Energy Agency IEA).

Table 3: *Primary Energy Consumption*

Country	**Energy (MTOE)**	**Population (Million)**	**Per Capital Consumption (Kg)**	**% Increase from 2001**
India	325.1	148	310	3.4
China	997.8	1,281	779	19.7
US	2293	288	7,861	1.9
Japan	509.4	127	4,011	-1.1

Note: MTOE (Million tonnes of oil equivalent)

Table 4: *Consumption of Fuel (2002)*

MTOE						
Country	**Coal**	**Oil**	**Natural Gas**	**Hydel**	**Nuclear**	**Total**
India	180.8	97.7	25.4	16.9	4.4	325.2
China	663.4	245.7	27	55.8	5.9	997.8
US	553.8	894.3	600	58.2	185.8	2,292.8
Japan	105.3	242.6	69.7	20.5	71.8	509.4

1. Coal

China (2002) excelled in coal production with an increase of 28.3 % and achieved first place in its production and consumption followed by the USA, Australia, India and Russian Federation. The EIA forecasts 45% increase in coal fired generating capacity (from 66 GW to 96 GW) in India between 2001 and 2025. This is far below their forecast of 60% for China from 232 GW to 321GW for the same period. India also has abundant reserve of coal but still lags behind many countries in consumption. Concerted efforts are needed in. this energy segment where the country has been successful in building total project capabilities.

2. Oil

Despite worldwide decline of 0.7% in 2002, oil production in China and India increased by 2.5% and 2% respectively in 2001. The international energy outlook of US Department of Energy predicted, in 2003, 4% growth rate every year to reach 5.5 million barrels by 2025.

3. Natural Gas

The Asia Pacific region achieved a growth of 6.5 % in natural gas production. The US and Russian Federation are the world's major natural gas producers and consumers. During 2002, the gas production increased by 7.7% in China and 4% in India.

The International Energy outlook forecast an increase of 6.7% annually between 2001 and an increase in consumption of gas from 22.7 billion m^3 to 96.3 billion m^3.

In the year 2002, supply of natural gas was 72 million m^3/day against a demand of 151 million m^3/ day. Demand projection for 2025 is 322 million m^3/day which is going to be 12% of total energy demand. Bulk of this demand will have to be met from increased domestic production and through imports.

4. Nuclear Energy

Nuclear energy grew by 48.3% in China, whereas the growth in India was only 2.6%. There was marginal decline (1.9%) in nuclear power in Japan because of public resistance. South Korea and Taiwan have registered substantial progress. According to EIA forecast, in India, installed nuclear power capacity is projected to increase from 2503 MW in 2001 to 6986 MW by 2025.

5. Hydro-Electric-Generation

Hydro-energy is clean and is ideal for peak demand. Only 20% available potential is used so far in India compared to 58% in Norway, 41% in Canada and 31% in Brazil. The share of hydro power in India has gradually decreased during the last 25 years. Therefore, earnest efforts are required to increase the share to higher level by 2025.

ENERGY ALTERNATIVES FOR THE FUTURE

The water sources available in the world are limited and fixed. Even if the water power is renewed by the Sun, this can only be used where there is large quantity of water and the area is considerably above the sea level (1 ton of water has to fall 360 m height to generate 1 kWh of electric power). The present developed capacity is 32.95×10^6 kW against available 226×10^6 kW (15% of total). Developing the water resources takes a long time (10 to 20 years) and is highly capital based. All the fossil fuels in the world are going to be exhausted, including Nigeria's, within 50 to 60 years (Domkundwar, 2010).

The sources may last 100 years in one country and 60 years in another country, as per the total resources available and rate of power development in that country. However, there is no doubt that fossil fuels in the world which are supporting 70% power generation are going to disappear within 100 years. Therefore, it is necessary to look for new resources which will support the present resources. During that period, there should be further development of new resources which will support complete power industry in the world. Such types of resources are presently known as non-conventional energy resources as they are not used on a very large scale.

In addition to the problem of non-availability of fossil fuels, the power industry pollutes the environment by emitting billion tons of $C0_2$ in the atmosphere.

Electric Power Generation Using Solar Energy

Solar pumps operating during period of insular are useful in providing a saving of both capital and running costs because they do not require the provision of power transmission lines which are essential for electric pumps. The capital investment in solar power station of 1 MW capacity is quite acceptable if the use is made of cheap reflecting surfaces and steam is not wasted.

The development of solar power stations in the southern part of Europe, the USSR, which has the maximum insulation in Transcaucasia, Kazakhstan and Republic of Central Asia, is very convenient. The area of these regions is nearly 5million km^2. If in this enormous area, the very hot desert receives solar radiation of 1 kW/m^2, one can build solar power station occupying about 1000 km^2 (0.02% of the total area) and with an efficiency of 20%, one can generate about 200 million kW (Tiwari, 2012).

There are equally suitable areas in many regions of Africa, non-Soviet Asia and USA. A particular desirable feature is that deserts which are unsuitable for industrial or agricultural purposes can be used, whereas conventional power stations occupy considerable area suitable for agricultural purposes. For example, a hydraulic power station with an output of 1 million kWh requires 12-18 hectares of area which is suitable for agriculture.

Moreover, solar installations do not violate any of the natural proportions in nature. They do not modify the internal balance of the Earth and do not have polluting effect on rivers and seawater. Therefore, this is exceptionally important for estimating the efficiency of solar energy utilisation from a nation's economy point of view.

Applications of solar technology should be given priority in areas with high rate of insulation, limited fossil fuels and water resources and where transport of traditional fuels or electric power along transmission lines is expensive. One can think of developing a belt of solar power stations located in the tropical. This will substantially reduce the effect of the periodic character of insolation, because, as the Earth rotates, some of the stations will be switched on whereas others will be switched off. Relatively constant electric power generation will be possible through the availability of long-distance power transmission system.

Solar installations will even be more effective when they are used as a component of a grid of electric power stations using conventional sources of energy and having operational radius governed by the limitations of power transmission systems along the parallels and meridian of the globe. In this way, it is possible to shift the insolation maximum in the northerly direction.

Presently, scientists are examining the possibility of launching solar power satellites in space, each of one hundred squares kilometres of solar cells. These satellites would gather energy from the Sun and beam it through microwaves to the receiving stations on Earth. Scientists predict that about 15% of the total power needs of the world will be met by the Sun by 2025.

A young German agriculture degree holder developed a solar power plant over 200 acres of land fitting 10,050 solar panels in 2003 and power generated is supplied to the surrounding villages for different purposes (Domkundwar, 2010).

To overcome both the difficulties mentioned above, the scientists throughout the world are thinking of the use of non-conventional energy sources such as solar, wind, sea thermal, tide, wave energies and geothermal. These resources were not tapped on large scale as conventional energy sources were easily available.

The above-mentioned resources have long life as the Sun has very long-life and other sources (tide, wind, and sea thermal) are continuously generated by the Sun only.

Detailed Considerations for Alternative Sources

In the face of the dwindling reserves of fossil fuels and the increase in price, efforts are being made world-wide to harness the alternative sources of energy. The challenges for the energy problems lies essentially in finding and developing new, preferably infinite sources of energy for future. Apart from emphasising the conservation and finding more efficient and economical sources, efforts are also made throughout the world for developing and harnessing inexhaustible new sources which were out of reach to the scientists till two decades before. It is also important to know how much of the light is diffused and how long the solar disc is unobstructed. A wide solar belt between latitudes 40° north and south exists, within which large amounts of solar radiation are available. It is important to note that, the less developed countries are situated 30° S to 30° N of the equator where sunshine is bountiful. Therefore, the people in this region can look for solar energy as a source of perennial bounty of nature (Tiwari, 2012).

Sun, being the basic source of energy for creating all the existing source of power (conventional and non-conventional), emits enormous amount of energy every day and fraction of that falls on the Earth surface. Out of that, a fraction of falling energy is used.

Man is trying for the last 50-years to avoid the intermediate step with an intention to increase efficiency from 40% to 60%. This will also extend the life of conventional energy resources. Extensive research is also going on throughout the world to develop different methods for Direct-Energy Conversion-Systems.

Irrespective of the difficulties mentioned above for developing the solar and non-conventional energy sources, the whole world is seriously thinking of developing these resources and extensive research is going on.

Solar Energy

It is always felt that since solar energy is periodic in character, as it depends upon cloud cover and has relatively low intensity (1.2 kW/m^2), it cannot satisfy the needs of industry. The output of solar installations is acceptable for low power purposes as relative number of such consumers is continuously increasing.

The use of solar energy is one non-exhausting source of energy. Because the total amount of solar energy received globally per year is equal to all the non-replenishable sources of the Earth. Our planet (Earth) receives an amount of radiant energy annually which is 20,000 times-the energy required in 2100. The corresponding factor by the year, 2100 is 500. Therefore, the only problem left is to utilise a small fraction of the solar energy falling on Earth, to convert it into electric-power.

The major barriers to widespread use of solar technology are its poor intensity and higher cost. The extent, to which this cost continues to be a barrier, depends on the cost of non-solar energy. Since this is uncertain, a confident forecast cannot be made about the rate at which the market for solar technology will expand. But it is very sure that the solar energy will be preferred as the cost of conventional energy systems increases.

Solar energy units that can supply individual houses, apartments, buildings and commercial and industrial units must be considered to the limited number of options available for meeting the world demand for energy. Solar equipment is technically capable of providing almost any kind of energy. It can be used to heat and cool the buildings, to provide heat for industrial processes, provide mechanical power to run the pumps and generate electricity. Moreover, it can meet these demands with minimal adverse effect on the environment.

Solar energy is universally used for heating and cooling but its use for power generation is yet at primary stage as the space required for thermal system is very large. The cost with direct conversion system (photocell) is very large as the conversion is very poor (<5%).

Solar technology is now capable of providing well tested and readily available installations that can be used in industry. They include water heaters, stills, dryers and refrigerators. They can ensure the supply of hot and cold water for domestic purposes, for light industry, farming and areas that suffer from water shortage. These installations can also be used for long-period storage of foods and fruits.

The further applications are solar pumps for irrigation purposes, for photosynthesis in chemical manufactures and for the growing of single-cell algae under artificial conditions. Other applications include high temp-concentrations, semi-conductor cells for direct conversion of solar energy into electric power and solar thermal power stations.

Scientists in the USA plan to ensure that solar energy utilisation contributes 9% to the overall power resources by 2050 and 30% by the year 2200. Over 40 scientific organisations in USA are conducting research work in solar technology. At present, USA annually produces 3 to 4 million solar water heaters while Japan produces 1 million. There are solar stills in Australia and Greece which produces 30,000 litres/day and a solar furnace generating 1000 kW has been built in France 30 years before.

Small scale power stations of 1 MW capacity are being planned using direct collection and focusing techniques. The first solar plant was built in Italy in 1988. This power station has 8000 m^2 of heliostat mirrors to focus the Sun on a steam boiler placed at the top of the tower. Another solar naval plant is at Crosbyton in USA which uses five 60 m diameter hemi-spherical reflectors which develop 5 MW. Israel is a world leader in the utilisation of solar energy. Still, only 12% of the nation energy is used to heat the water for domestic purpose. India receives a substantial amount of solar energy practically throughout the year, therefore there is good scope for India to use this energy on large scale in future.

Why the Sun?

The Sun emits very large amount of energy and has a long life; therefore, this is considered an eternal source of energy for mankind. The details of the Sun are given below; this will give an idea of the amount of energy emitted and its available period.

Radius of Sun = 6.96×10^5 km

Surface area of Sun = 6.087×10^{18} m^2

Mass of Sun = 1.96×10^{27} tonnes

= 33×10^4 times the mass of Earth

This means, if Earth weighs an ounce, Sun will be about 30 tons.

Energy Production = 9.22×10^{30} kcal/sec = 38.724×10^3 kW

Mass equivalent of this energy production = 4×10^6 tons/sec

Solar constant = 1353 W/m^2

Mean distance between Sun and Earth = 1.497×10^{11} meters

Sun consists of 2.2 octillions tonnes of gaseous mass (H_2 + He) and surface temperature of 10,000° F (5538°C)

Sun Life = A few billions of years.

The Sun emits 3.7×10^{23} units into the space, out of which, the whole solar system intercepts only (1/120) millionth fraction. The Earth intercepts only 5×10^{-10}th part of solar energy output.

It is obvious from this data that the Sun is an infinite source of energy that is available for infinite time; it is also totally non-polluting. The only problem with its use is low intensity, which creates a problem of collection, and its considerably high cost.

About the World (Earth)

Table 5 shows present and future global energy consumption.

Table 5: *Energy Consumption (Present and Future)*

	Billion tonnes of coal equivalent	
	1975	2025
World Total	9.4	25 - 30
Industrialised Nations	9.1	10 - 30
Developing Nations	3.3	15 - 40
India	0.41	2.8

The distribution of land use is given below in Table 6.

Table 6: *World Land Area*

	Area in km^2	%
		1
Total Earth surface	510×10^6	
Usable Land Area	148×10^6	100
Forests	74×10^6	50
Pastures	35.3×10^6	23.85
Arable Land	21.3×10^6	14.4
Usable but not used	13×10^6	0.78
Human settlements	0.4×10^6	0.3

Considering the present energy consumption of the world- 50 TW (1 TW = 10^6 MW = 1 billion tons of coal per year in thermal form)-, it is estimated that 20 W/m^2 of useful energy is obtained by solar radiation; the area required is about 2.5×10^6 km^2 against available 148×10^6 km^2 (1.69% only.)

PROS AND CONS OF SOLAR ENERGY

The onsite solar systems sharply differ from the present conventional systems used to provide most of the world energy. By definition onsite devices are intended to be located at the point of energy use and would be designed, manufactured, installed and operated like today's conventional air-conditioners, heating systems and process heat systems. In contrast, conventional energy systems have become increasingly large and centralised at locations remote from the point of use.

There are sound economic reasons for centralising units, such systems serve a variety of uses and make better utilisation of their equipment because the peak-to-average demand ratio is lower. The large generating units are less expensive, more efficient, can use a variety of fuels and sitting problems are minimised by single remote location. Owners of conventionally fuelled onsite systems are concerned about the cost of running and maintaining the equipment and the chance that a system failure might ruin the complete industry. As a result, most design improvements have occurred in the technology of larger generating units and onsite devices are frequently neglected.

It is clear from the above picture that the business of providing energy will change during the next two decades and fundamental assumptions will need to be reviewed carefully in the light of new circumstances. Solar devices which are attractive for onsite applications may add an interesting element in such analysis.

The possibility that energy can be generated economically in small systems raises a number of opportunities and problems which were never considered, as long as low cost supplies of oil and gas were easily available and electricity was generated at lowest cost in large centralized stations. A small system offers a much better design-alternative when the cost of centralized system becomes high or fuels required to run the system are not available adequately or available but at a very high cost.

Due to the grave consequences of not having reliable future sources of energy, onsite solar system must be regarded as an important option. The advantages and shortfalls of solar energy systems are listed below.

1. There are a large number of techniques for providing useful energy in different forms from sunlight whose technical feasibility is beyond serious question.
2. Useful thermal and electrical power can be provided onsite by solar devices which are as simple to install and maintain as domestic refrigerator.
3. The technology of energy storage is critical to the development of low cost solar energy.
4. Using new materials and improving the performance of existing devices will lower the cost of solar devices.
5. For most of the solar energy parts, dramatic change in the technology is not essential. Most of the cost of solar devices lies in necessary processes such as assembling components, installing devices, connecting, plumbing and

electrical fixtures and digging excavations for storage tanks.

6. Careful attention should be given in architecture of the house for the efficient use of solar energy. Intelligent building designs, building orientation and siting are most cost effective for the use of solar energy.
7. Only solar energy cannot be used economically to provide all the energy requirement of the customers. A supply of back-up power is almost always required. This complicates the task of determining the real cost of solar energy.
8. Providing energy from sunlight will have a much smaller environmental impact than conventional sources providing equivalent amount of energy.
9. Irrespective of the cost of solar power, it is the only source on long-term basis and considering this, solar energy is accepted as an alternative source of power for future.
10. Lack of suitable land close to populated area could place major constraints on the use of solar equipment onsite.

INTRODUCTION TO SEMICONDUCTORS

Mechanical engineering students are not very much aware of semiconductor materials, therefore, it is necessary to introduce the configuration and behaviour of semiconductors before going to working and analysis of photovoltaic systems as they are responsible for generating power by absorbing the solar photon energy. Semiconductors are classified as per their electrical conductivity as shown in Table 7.

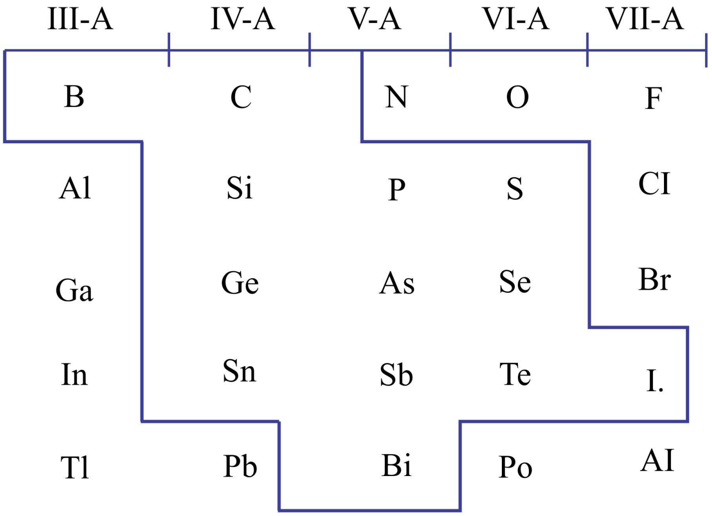
Table 7: *Electrical Resistivity of Various Material at 20^0C (in ohm-meter Ω-m)*

Metals		Semiconductors		Insulators	
Metal	**Resistivity**	**Semi-conductor**	**Resistivity**	**Insulator**	**Resistivity**
Ag	1.6×10^{-8}	Ge	0.47	Glass	10^{10} to 10^{11}
Cu	1.7×10^{-8}	Si	3000	Mica	9×10^{14}
At	2.8×10^{-8}	$Fe_3 O_4$	0.01	Diamond	1×10^{14}
Fe	10×10^{-8}	In Sb	2×10^{-4}		
Constantan	49×10^{-8}	Sn (grey)	2×10^{-6}		
Nichrome	100×10^{-8}				

Source: (Domkundwar, 2010)

The materials classified as semiconductors have a resistivity somewhere between metal and insulator. The electrical conductivity of semiconductor strongly depends on temperature. At high temperatures, semiconductors behave like insulators as their resistivity range comes near to insulators. Many semiconductors exhibit a negative temperature coefficient of resistivity over part of the temperature range. Insulators also have negative dp/dT (p is resistivity) and in this respect, they behave as semiconductors. Therefore, the difference between semiconductors and insulators is only of a quantitative nature.

Among many, silicon (Si) and Gallium (Ge) are the most popular semiconductors. The elements shown in Fig. 4 are the elemental semiconductors.



Source: (Domkundwar, 2010)

Fig. 4: *Elemental Semiconductors*

There are also many compounds which behave like semiconductors, such as PbS, BaO and few others.

Chemical Bond in Si and Ge

Silicon and Germanium are the elements in the fourth column of the periodic table. They are tetravalent atoms. Their outer shell contains four electrons which are available to react with electrons of other atoms. In solid state, they have diamond structure with two-dimensional lattice as shown in Fig. 5.

The bonds between a given atom in this structure and its neighbours are called electron-pairs bonds because bonds of this type are accomplished by pairs of electrons. Thus, each atom has four valence electrons, it has just enough to provide for electron pair bonds with four other atoms. There are no free electrons since all the available electrons are bound firmly to the atoms. If we supply some energy to the lattice in the form of heat or light, then some electrons will receive enough energy to become free.

In pure Si and Ge at absolute zero temperature, all the valence electrons have no freedom to move through the crystal. This is in contrast with the metals in which there is a constant number of free electrons at all temperatures. Therefore, Si and Ge are insulators because there are no charge carriers at absolute zero. If we supply some energy to the lattice, then some electrons will receive enough energy to become free. The energy supplied will allow some electrons to jump from valence band to conduction band. These free electrons can move from one atom to another and wander through the lattice at random. If an electric field is applied to the lattice, the random movement will stop and electrons will move against the field, they become directional and the current flows.

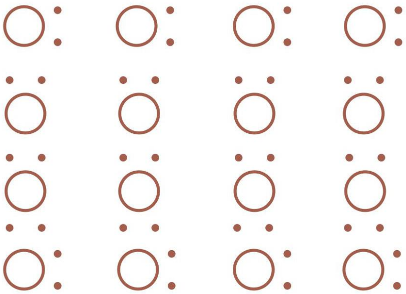


Fig 5: *Two dimensional representation of the electron pair bonds in the diamond structure. The dot represents the electron*

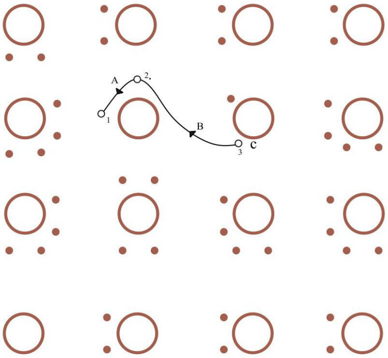


Fig. 6: *Effect of breaking an electron pair-bond A. The open circle at A represents a hole*

Suppose an electron is taken away from a particular bond A as shown in Fig. 6, then we are left with a bond which contains only one electron instead of two electrons. Now suppose, the material is subjected to an electrical field, then an electron from bond B tends to move into the vacant electronic state A, under the influence of the field. This leaves a vacant electronic state in bond B and electron from another bond C may fill this vacant state: By repeating this process, a charge is transported under influence of an electric field by virtue of the absence of an electron in an electron-pair bond. The vacant electronic state moves in the same direction as would a positive charge carrier. For this reason, these vacant electronic states are called positive holes (or simply holes).

As the temperature of the semiconductor material is increased above 0 K, a number of bonds will be broken and conduction may be observed as a result of the motion of electrons and holes under the influence of an external field.

In case of Si and Ge, the number of free electrons must be equal to number of mobile holes. Semiconductor of this type is called intrinsic semiconductor. An intrinsic semiconductor has negligible conductivity which is of little use. To increase the conductivity of an intrinsic semiconductor, a controlled quantity of selected impurity atoms is added to obtain an extrinsic semiconductor. The process of adding the impurity atoms is known as doping.

When the free electron moves, it may encounter one of the broken bonds. Then, it is possible that the electron recombines with the hole and consequently, two charge carriers are lost for the conduction process. At a given temperature, there will be a certain number of electrons and equal number of holes in the material. As the temperature is increased, the number of free charge carriers increases.

$$\text{Bond electron} \longleftrightarrow \text{Free electron + hole} \qquad (1)$$

The rate of reaction towards the right at a given temperature depends on the chemical bond of the material. If the electrons are bound strongly, then the number of charge carriers will be relatively small. Where C_1 is constant and *–ve* sign indicates decrease in *n* due to recombination. The rate at which the electron-hole pairs are created by the absorption of thermal energy is proportional to the density of electrons which are available for excitation (N - n) and Boltzmann (Tiwari, 2012).

Factor $(e)\frac{Es}{KT}$ where K is Boltzman constant and T is absolute temperature

$$\left(\frac{dn}{dt}\right)_{\cdot recombination=C_{1n}{}^{2}} \qquad (2)$$

where C, is constant and - ve sign indicates decrease in n due to recombination.

The rate at which the electron-hole pairs are created by the absorption of thermal energy is proportional to the density of electrons which are available for excitation (N - n) and Boltzmann

$$\left(\frac{dn}{dt}\right)_{\cdot excitation} = C_2\,(N-n)(e)^{-\frac{E_g}{KT}} \qquad (3)$$

$$\left(\frac{dn}{dt}\right)_{\cdot excitation} + \left(\frac{dn}{dt}\right)_{\cdot recombination} = 0 \qquad (4)$$

$$--c_1 n^2 + c_2(N - n)(e)^{\frac{E_g}{KT}} = 0 \qquad (5)$$

$$n^2 c_3(N - n)(e)^{\frac{E_g}{KT}} \qquad (6)$$

$$n = c_3\left(\frac{N}{n} - 1\right)(e)^{\frac{E_g}{KT}}$$

As long as n<<N (which is usually the case), then

$$n = C(e)^{\frac{E_g}{KT}} \qquad (7)$$

The value of n is given by:

$$n=5 \times 10^{21}(e) - \frac{Eg}{2kT} (T)^{3/2}/m^3 \qquad (8)$$

Table 7: *Energy gap for different materials*

Material	Energy Gap (eV)	Material	Energy Gap (eV)
Si	1.11	InP	1.2 7
SiC	2.60	In$_2$Te$_3$	1.20
Cd As$_2$	1.00,	^2°2-	2.80
CdTe	1.44	ZnO	3.30
CdSe	1.74	Zn$_3$P$_2$	1.60
CdS	2.42	ZnTe	2.20
Cd Sn0$_4$	2.90	Zn Se	2.60
Ga As	1.40	A1P ,	2.43
GaP	2.24	AlSb	1.63
Cu$_2$S	1.80	SnO,	1.80
CuO	2.00	AS$_2$ Se$_3$	1.60
Cu$_2$ Se	1.40	Sb$_2$Se$_3$	1.20
		Ge	0.67
		Se	1.60

Source: (Domkundwar, 2010)

INTRINSIC SEMICONDUCTOR AND ENERGY GAP

The valence electron may become free after absorbing sufficient amount of energy. This states that the energy of free electron is higher than that of a bound valence electron as shown in Fig. 2.3.

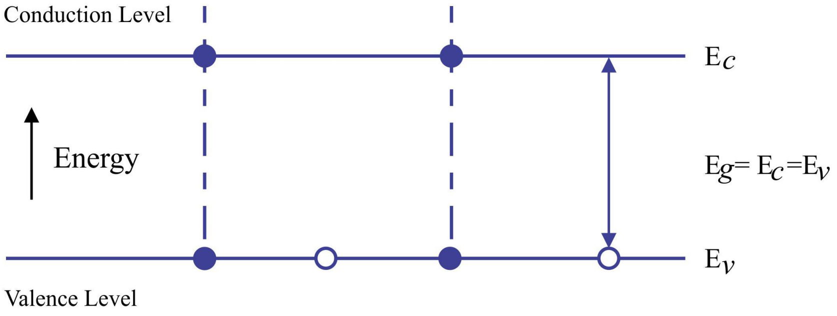


Fig. 7: *Valence and conduction electron level* (The shaded dots represent electrons and open circles represent holes.)

The E_e and E_v are the energy of an electron in the conduction and valence levels respectively. The energy gap between two levels is given by:

$$E_g = E_t - E_p \qquad (9)$$

Assume there are n conduction electrons per m^3 and equal number of holes in an intrinsic semiconductor material at a temperature T. Also assume there are N electrons per m^3 in the valence level at 0°K (absolute zero Temp). The Conduction electrons may recombine with holes. The probability of such recombination per m^3 of material is proportional to the density of electrons (n) and density of holes (n). Consider a semiconductor whose $E = 1$ eV (which is typical for Si and Ge),

$$\frac{E_g}{2kt} = \frac{1}{2\,x\,0.025} = 20$$

Substituting these values in equation, we get:

$$n = 5 \text{ x } 10^{16}/m^3$$

where number of atoms is approximately 5 × $10^{28}/m^3$. This indicates that only a small fraction of valence electrons is excited into the conduction band at this temperature.

The above equation indicates that the number of charge carriers (conductivity of the material) strongly depends upon the values of T and E_g. It is seen that ρ of the material increases very rapidly with increase in E_g, as the conductivity of semiconductor depends strongly on the magnitude of E_g. This can be seen from Table 8.

Table 8: *Density of the material and the energy gap band*

	C (diamond)	Si	Ge	Sn(grey)	Pb
ρ(ohm-m)	10^{14}	3000	0.49	2 x 10^6	2 x 10^{-7}
E_g	5.2	1.21	0.75	0.08	No gap

The above method can also be applied to an elemental semiconductors as well as to intrinsic- compound semiconductors such as ZnO and PbS.

The conductivity (σ) of an intrinsic semiconductor is generally given by:

$$\sigma_{intricsic} = A\,(e)^{-\frac{E_g}{2KT}} \qquad (10)$$

where A is constant and its value is dependent on the type of semiconductor.

Fig. 8 shows the variation of $\log_e(\sigma)$ with $1/T$ for Si and Ge. The graph permits to evaluate the value of E_g from the slope.

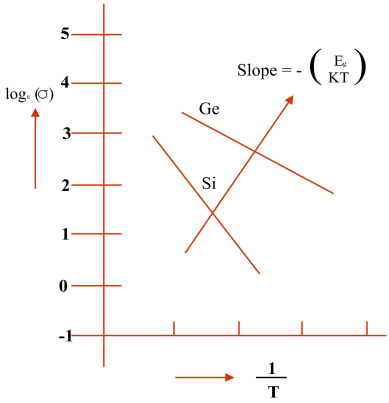


Fig. 8: *Variation of* $\log_e(\sigma)$ *with* $1/T$ *for Si and Ge*

Extrinsic Semiconductors

Electrical conductivity of pure semiconductor is primarily of electron type. The hole conductivity effect (positive charge conductivity) is comparatively weak. Therefore, such semiconductors are exceptionally sensitive to the presence of impurity.

Most of the engineering applications involve semiconductors which are doped intentionally with specific impurities rather than using intrinsic semiconductors. An influence of an impurity on the conductivity of a semiconductor is the result of charge in the energy band spectrum. In case of Si and Ge, the doping elements are either from the III or V column of the periodic table. The elements used from column III are boron, gallium and indium and from column V are phosphorus, antimony and arsenic. Addition of these elements in very small quantities increases the conductivity by several powers of ten. The temperature dependence of the conductivity is also strongly affected by these impurities.

TYPES OF SEMICONDUCTORS

1. n-type Semi-conductors: When pure silicon crystal (with n-valence electrons) is doped with atoms having five valence electrons, for example, phosphorus, arsenic or antimony, the doped crystal carries excess electrons which can move freely. Silicon doped with such atoms is known as n-type semiconductor. Addition is so small, one atom per million atoms of silica.

These impurity atoms are comparable in size to silicon atom, therefore, they take positions normally occupied by silicon atoms as shown in Fig. 9 (a). Fig. 9 (b) shows when Sb is added to Ge.

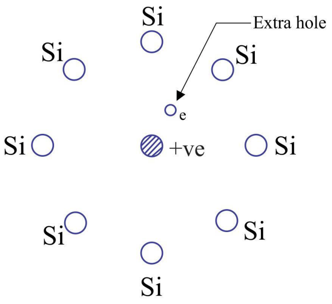


Fig. 9 (a): *Silicon lattice with donor substituent Arsenic*

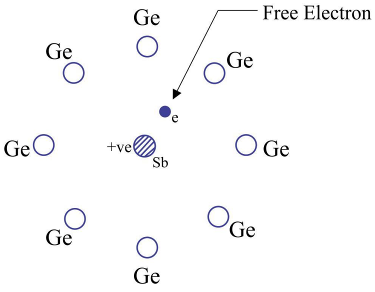


Fig. 9 (b):Ge- *Lattice with donor substituent Sb*

Because the impurity atoms are very few in number, each will be entirely surrounded by silicon atoms. The nearest silicon atoms form a covalent bond with four of the five valence electrons of the arsenic atoms. This ties these four electrons into the crystal structure with forces that require a considerable amount of energy to disrupt. However, no such binding force holds the fifth valence electron. In the energy band diagram, the energy level of this electron will be close to the conduction band level as shown in Fig. 9 (a). Being almost free, it can be removed from the parent impurity atom using very little energy E. (0.01 eV for Ge and 0.05 eV for Si) at room temperature, whereas 0.75 eV is required to break a covalent germanium bond and 1.12 eV for a covalent silicon band. In addition to this, when the temperature is increased, there will also be excitation of electrons from the valence band to conduction band (Tiwari, 2012).

The fifth electron which is free from the impurity atom moves randomly through the crystal in the same manner as do the electron present in an intrinsic semiconductor. When an electric field is applied, a steady drift towards the positive electrode represents the flow of current.

When the impurity atom loses an electron, it becomes a positively charged ion which cannot contribute to the flow of electricity. Impurity atoms like arsenic and antimony that contribute free electrons are called donors because they donate the electrons.

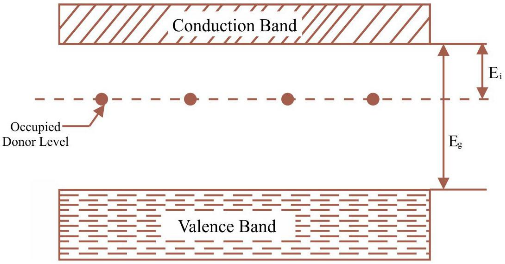


Fig. 10(a): *Energy diagram for donor impurity*

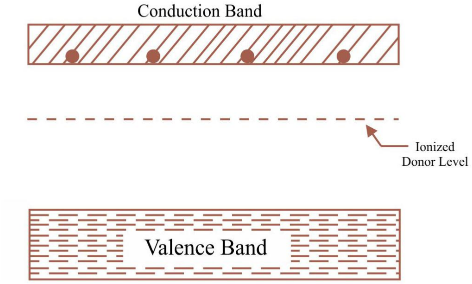


Fig. 10 (b): *Donor atoms are ionized by thermal excitation*

A semiconductor containing donor levels is referred to as n-type material, to indicate that the conduction below the intrinsic region is due to the negative charge carriers.

2. p-type semiconductor: If a pure silicon crystal is doped with atoms having three valence electrons (for example, boron, gallium or indium) a vacancy of one electron is created in the lattice, producing a hole with positive charge, which can freely move in the crystal silicon doped with such atom is known as p-type semiconductor.

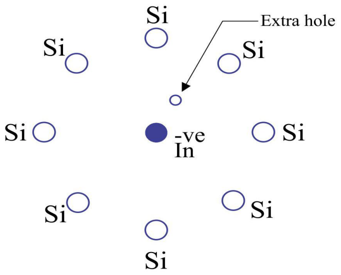
Fig. 11(a) shows silicon lattice in which indium (In) is doped. Three of the neighbouring silicon atoms form covalent bond with the three valence electrons of indium atom (trivalent impurity). Although, there is a natural tendency for each atom in the crystalline structure to form four covalent bonds, the trivalent indium atom is short of one electron. As a result, it tries to acquire a fourth electron and it does this by taking advantage of thermal motion that brings an electron from a neighbouring silicon atom into a favourable condition to be captured, (the energy required is 0.01 eV for Ge and 0.08 eV for Si). When this happens, the impurity atom of indium form a covalent bond to the four nearest silicon atoms. Then it becomes an immobile negative ion embedded in the crystalline structure.

The energy diagram is shown in Fig. 11(a). The activation energy (E_1) required to raise an electron from the valence band to the impurity level is very less than necessary to cross the forbidden gap ($E<<E$). Consequently, the holes are generated at a very high rate.

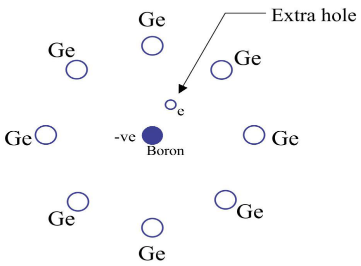
The act of stealing an electron from Si or Ge by impurity atom produces a hole that is similar to the holes arising from breaking the covalent bonds. This hole moves randomly due to thermal effect and when an electric field is applied, it tends to move towards the negative electrode and contributes to the flow of current.

Impurity atoms that contribute holes in this manner are termed as acceptors because they accept electrons from Si and Ge atoms.

Both n-type and p-type doped semiconductors (known as extrinsic semiconductors) possess higher electrical conductivity than the pure (intrinsic) materials.



(a_1) Silicon lattice with acceptor substituent



(b_2) Lattice with acceptor substituent

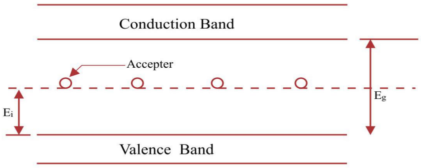


Fig. 10 (a) : *Energy diagram for donor impurity*

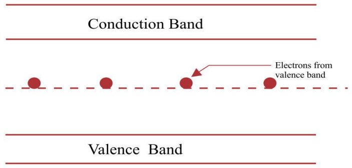


Fig. 10 (a) : *Acceptors have accepted electron from valence band at the expense of energy*

PHOTON ENERGY

As mentioned earlier, the behaviour of both types of semiconductors (n and p types) the electron motion from the lower orbit to higher orbit is possible if the external energy is supplied in the form of thermal or photon energy (solar rays carry the photon with some energy depending upon the wavelength). If the external supplied energy is higher than E_g (band gap energy), then the electrons start moving which is responsible for the flow of current.

Therefore, it is essential to know about photon energy and magnitude. This photon energy depends upon the temperature at which they are emitted and wavelength with which they travel.

Sunlight energy is composed of tiny energy particles called photons. The number of photons present in solar radiation depends on the intensity of solar radiation and its energy content depends on wavelength.

The solar spectrum constitutes three main regions of radiation as per wavelength:

(a) Ultraviolet (λ<0.4 μm)
(b) Visible region (0.4μm < λ < 0.8 (μm)
(c) Infrared region (λ > 0.8 (μm)

The solar energy in visible region is mostly used in solar cells. The solar intensity before entering the Earth's atmosphere is 1367 W/m^2 and it is known as solar constant. Amount of solar energy falling on the Earth surface is 1070 W/m^2 as the remaining is absorbed by the air surrounding the Earth.

When the photons (with energy 1.8 eV to 3 eV) falls on an atom of a semiconductor, they react with the electrons on the outer orbit and the electrons are driven off because of enhanced energy. In silicon, the band gap energy (Eg) is about 1.2 eV.

The energy in photon is given by:

$$\mathrm{Ep} = \frac{hc}{\lambda}(joules) \qquad (11)$$

where h (Planck's constant) = 6.63 × $^{10-24}$ J-sec, c (speed of light) = 2.988 x 10^8 m/sec and λ is the wavelength of photons in metres. Substituting these values in above equation, we get:

$$E_p = \frac{hc}{\pi}\ (eV) \qquad (12)$$

The photon energy at different wavelength is tabulated in Table 8.

It is essential that the photon energy (E_p) must exceed the semiconductor band gap energy (E_g) in order to get absorbed and generate an electron-hole pair. The absorption will not take place if $E_p < E_g$ and material appears transparent to these low energy photons.

Table 8: *Photon Energy and Solar Spectral Irradiance in Different Spectral Bands*

Wavelength Range (μm)	**Photon Energy (eV)**	**Solar Spectral Irradiation (W/m²)**
>1.15	0.00 - 1.08	317.7
1.15 – 1.00	1.09 – 1.24	95.1
1.00 – 0.90	1.25 – 1.38	82.9
0.90 – 0.80	1.39 – 1.55	99.3
0.80 – 0.70	1.56 – 1.78	123.7
0.70 – 0.60	1.79 – 2.08	1.51.5
0.60 – 0.50	2.80 – 2.49	177.7
0.50 – 0.40	2.50 – 3.11	187.7
0.40 – 0.30	3.12 – 414	101.7
0.30 – 0.20	4.15 – 6.22	16.3
0.20 – 0.10	>6.22	0.1

Source: (Tiwari, 2012)

If the photon energy, E_p is greater than E_g it still produces a single electron-hole pair and remaining energy (E_p - E_g) is lost to the material in form of heat. Therefore, it is desirable that the semiconductors used for this purpose must have band gap energy (E_g) such that the maximum % of solar energy is effectively absorbed. The maximum efficiency of a solar cell for converting solar energy to electrical energy is estimated as 31% for semiconductors having E_g = 1.51 eV with standard solar radiation. In case of silicon whose E_g = 1.1 eV/photons of λ = 1.1 pm or less are required to produce electron-hole pair.

In semiconductors, there are only two bands known as valence band (filled with electrons) and conduction band (which is empty). The energy difference between two bands is known as gap-energy (E_g).

The Fermi energy level (E_f) is the band energy position within the band gap (between valence and conduction band) from where a greater number of carriers (electrons in n-type and holes in p-type) get excited to become charge carrier. For an intrinsic semiconductor, the Fermi level exists at the middle of energy gap as shown in Fig. 12 (a), whereas it moves closer to E_c in n-type semiconductors and moves closer to E in p-type semi-conductor as shown in Fig. 12(b) and Fig. 12(c). In Fig. 12(b), E_d represents the energy level of electrons from donor-impurities while in Fig. 12 (c), E_d represents the energy level of excess holes provided by acceptor-impurities. The thermal energy kT (where k is Boltzmann constant = 1.38×10^{-23} J/K and T is absolute temperature) provides an energy difference (E_c - E_d) and ($E_d - E_v$) to excite the electrons.

When the thermal equilibrium is reached, the number of electrons n per unit volume of crystal in conduction band is given by:

$$n = N_c \exp\left(\frac{E_f - E_c}{kT}\right) \qquad (13)$$

where N is the original effective density in conduction band. Similarly, the density of holes p is given by:

$$p = N_v \exp\left(\frac{E_v - E_f}{kT}\right) \qquad (14)$$

where N is the original effective density in valence band.

The position of Fermi-level is determined as per the type of semiconductor (doped with donor or acceptor atoms). If N_d is the concentration of donor atoms and N_a is the concentration of acceptor atoms, then the above equation can be written as:

$$n = N_d = N_c \exp\left(\frac{E_v - E_f}{kT}\right) \qquad (15)$$

$$p = N_a = N_v \exp\left(\frac{E_v - E_f}{kT}\right) \qquad (16)$$

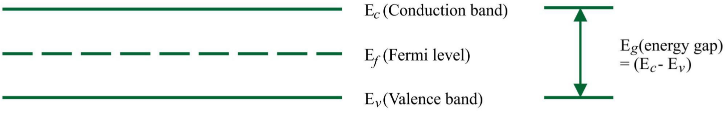
Solving the above equations for n-type semiconductor, the Fermi energy level is given by:

$$E_f = E_c = kT \exp\left(\frac{N_c}{N_d}\right) \qquad (17)$$

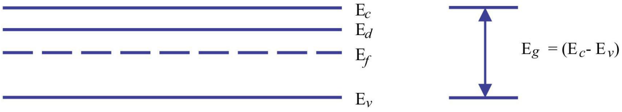
And for p-type material,

$$E_f = E_v = kT \exp\left(\frac{N_p}{N_d}\right) \qquad (18)$$

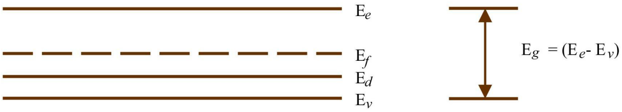
The importance of Fermi-level (from E_c as well as from E_v) lies in the fact that it decides the number of electrons excited and responsible for the current flow.



(a) Intrinsic semi-conductor



(b) Extrinsic n-type semi-conductor



(c) Extrinsic *p*-type semi-conductor

Fig. 12: *Energy Levels in Different Semiconductors*

WORKING OF SOLAR (PHOTOVOLTAIC) CELL

When two semiconductors, one of n-type where negative electrons are free to move about and conduct electricity and another one of p-type where electron holes or positive charges are free to move about and conduct electricity, are placed in contact with each other as shown in Fig. 13 they form a p-n junction. This sets up a potential difference across the junction when a photon of light strikes an atom of the cell, energy is imparted to the loosely bound valence electrons. If the energy exceeds the maximum level necessary to discharge the electron from the atom, a free electron of negative charge and electron hole of positive charge are produced. If the cell is connected to an external circuit, electric current will flow.

The energy balance equation for the cell can be written as:

$$\frac{h.c}{\pi} = W + \frac{1}{2} m_e V^2 \tag{19}$$

where *h* is Planck's constant, *c* is velocity of light, λ is light rays' wavelength, m_e is electron mass, *V* is electron velocity and *W* is the photoelectric work. The amount of work (*W*) that can be obtained depends upon the solar spectrum that is effective in providing the free electrons. The materials do not respond to the entire solar spectrum.

The main advantage of the system is a direct conversion of solar energy into required form of electrical energy and is not limited by the thermal Carnot efficiency.

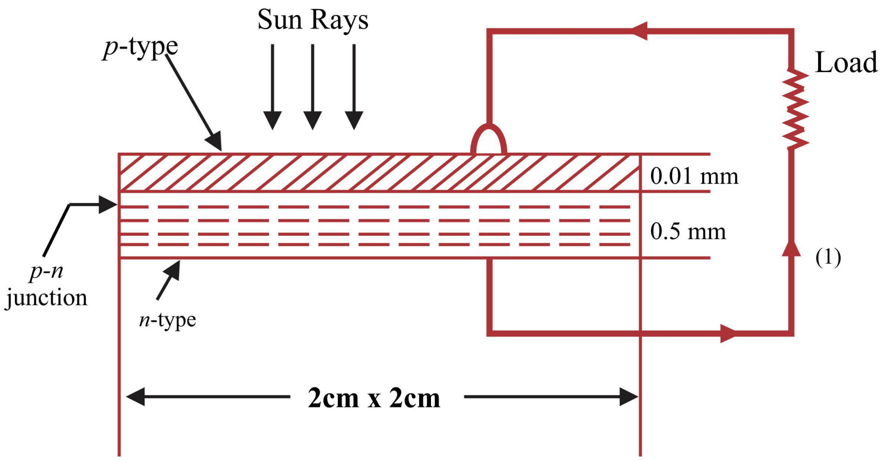


Fig. 13: *Connection of n-type and p-type semi-conductors*

In the arrangement of the cell, once an electron-hole pair is generated within the junction, both carriers will be acted upon by the built-in electric field. Since the field is directed from n to p side, it will cause the holes to swift quickly towards p-side. These carriers diffuse away from the junction as their concentration is increased near the junction. The excess charge carriers on each side of the junction result in a voltage across the external terminals of the junction. If load is connected across these terminals, the photon generated current will flow through the external circuit. This current flow will be proportional to the number of electron-hole pairs generated which in turn depends upon solar intensity.

ENERGY LOSSES AND SOLAR CELL EFFICIENCY

As per the conventional systems, the efficiency of the solar cell is the ratio of electrical power output to incident solar energy. The conversion efficiency of solar cell hardly lies between 12% to 15% because of many losses. Some losses are inherent in nature of physical processing and available input. These cannot be influenced by external means. The other losses can be reduced by selecting suitable cell material, the processing technology and working parameters.

The energy distribution in solar radiation (photon energy) depends on the temperature and wavelength which cannot be influenced by external parameters. A significant fraction of the photon energy cannot be used for generating electrical power as they have energy lower than the band gap energy (E_g = 1.1 eV), these photons have wavelengths more than maximum required (> 1.1 μm) which cannot generate photovoltaic effect. Such photons are between 15% to 25% of total portion which are not used for the purpose. On the other hand, the photons which have higher energy than E_g loses their energy in the form of heat. This loss lies between 5% to 20% of total photons energy. Therefore, nearly 20% to 45% of the total photon energy is not used at all for electrical generation because of spectral distribution.

Another significant loss arises due to inherent material properties and physical principle on which solar cell works. The separation of photon generated electron-hole pairs by the junction depends upon movement of the minority carriers to a region where they have minimum potential energy. This process is associated with loss of energy and its magnitude lies between 30% - 40% of the energy contained in the photo-generated carriers. Thus, the spectral distribution of solar radiation and inherent property of silicon p-n junction together result in total energy loss of 65% of the incident energy. Therefore, the photo generated carriers across the junction possess only 35% energy of the incident solar energy. But there are other losses which further reduce the cell efficiency to 10% to 15%.

During carrier collector process, some minority carriers are lost due to recombination in addition to this, there are losses due to reflection from the active surface of the cell and because of this, a fraction of incident photons will not enter into the bulk material. This loss can be reduced by providing anti-reflection coating on the active surface or by providing textured structure.

Silicon itself is a band gap material. The photons require adequate energy for travelling some distance in bulk material in order to get absorbed. If the thickness of the cell is not sufficient (100 microns), then some photons will pass through full thickness of the material without getting absorbed. To avoid this, a reflecting surface on the backside of the cell is used to enhance the photon absorption in the cell.

Table 9: *Loss Percentage in Silicon Solar Cell*

S/No.	Energy Loss	% Sun Energy Which is Not Converted into Electricity
1.	Excess energy photons	32
2.	Deficient energy photons	24
3.	Internal cell losses	21
4.	Reflection loss	3
5.	Shading	3
6.	Cell packing density loss	2
	Total loss	**85**

EFFICIENCY OF THE CELL

The electric-characteristics of the solar cell are expressed by current-voltage curves for the given solar radiation and temperature as shown in Fig. 14.

The significant parameters are short circuit current (I_{sc}) and open circuit voltage. The maximum useful power of the cell is represented by a rectangle with largest area as shown in the figure. I_m and V_m are the current and voltage, respectively, when the cell develops maximum power. The maximum efficiency of the cell is defined as ratio of maximum electrical power output to the incident solar radiation.

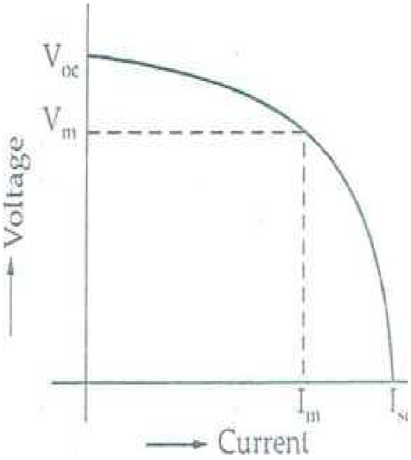


Fig. 14: *Current Voltage Characteristic of a Solar Cell*

$$(\eta_{cell})_{max} = \frac{I_m V_m}{I_{solar} \cdot A_c} \qquad (20)$$

where I_{solar} is incident solar flux and A_c is the solar surface area.

The solar cell has considerable low efficiency (15%) as mentioned earlier and the factors which are responsible for these are listed below.

1. When sunlight energy strikes the cell-surface, nearly 30% of that is reflected back but it can be reduced to 5% by providing anti-reflection coating to the back as mentioned earlier.
2. If the photon energy $h.c < E_{g,}$ then they do not take part in electron emission and this energy is converted to heats the cell and is lost to the atmosphere.
3. The excess energy of the photon ($h.c > E_g$) given to the electrons beyond the amount required to cross the band gap cannot be recovered as useful electric power is lost in the form of heat (35%).
4. With an increase in temperature of the solar radiation, the leakage of photons across the cell also increases. It reduces the power output relative to solar energy input. Output decreases by 1% with every increase of temperature by 2°C for silicon cell.
5. Generated current by the cell flows out from the top surface through a mesh of metal contacts to reduce series resistance losses. These contacts cover a definite area which reduces the active surface area to the incident solar radiation.

DIFFERENT SOLAR CELL MATERIALS

The solar cells made of different materials like silicon, cadmium and sulphide are commonly used as they provide high efficiency and manufacturing technology is very well developed.

Single Crystal Silicon Solar Cell

Most of the solar cells used for space applications are made of single crystal silicon type. These are made out of single crystal rod, cut into wafers then polished and p-n junctions are formed.

Silicon solar cell do not require high quality polysilicon (resistivity = 1000 O-cm.) used for transistors. Polysilicon with 1 Q-cm resistivity is considered quite suitable for solar cells and its cost will be 20% greater than high quality polysilicon. Dowcorning Co., USA, has developed a process for producing solar cells using reactive gas blowing and unidirectional freezing technique which has brought the cost of material from \$ 70 to \$ 10/kg. The present cost of material is Rs 1000 to Rs 2000 per watt generated (Domkundwar, 2010). Which is equivalent to =N=5042 to =N=10000 (2019) per watt in Nigerian currency.

The major problem in manufacturing solar silicon cell is its required thickness. One cannot handle less than 100 μ(4 mils) thick wafer where as effective thickness for absorbing solar energy is hardly few microns. Research and development work are going on to develop poly-silicon cells whose conversion η will be 50% of single crystal cell but cost will be $\left(\frac{1}{5}\right)$th of single crystal type, and material requirement will be $\left(\frac{1}{10}\right)$th of single crystal type. The overall cost will drastically come down.

Cadmium Sulphide Solar Cell

Extensive work has been done to develop these types of cells in USA, Germany and Japan. Baldon & Co. has developed a technology to produce the cells at low cost (Rs 2/W). Japanese have reported solar panel of CdS cell which gives 40% η.

The amount of semi-condenser material required and its cost is huge, even only lighting load in rural areas in India is provided with this method. In case of using polycrystalline silicon or CdS cells, the, film thickness is about 10μ and η = 5%, it requires 1 kg/kW power and if we have to cover 100 million rural homes with 1 kW-panel/home, then about 100 x 10^3 tons of semi-conductor material is required. But if we use single crystal silicon cell with 10% -q, then 5-times more material is required as its minimum thickness is 100μ (Domkundwar, 2010).

The effect of energy gap on cell efficiency for different cell materials and at different temperature is shown in Fig. 15.

It can be seen from the figure that the silicon is not only the efficient material for solar cell. Presently most efficient material known is GaAs as energy gap is 1.34 eV and the mobilities of the minority carrier are much larger than those in silicon. Another advantage associated with GaAs being a direct bond semi-conductor and all the usable hole-electron pairs are created in one or two micrometres of the material and it has a very sharp light absorption. Therefore, efforts are being made to develop thin film solar cells.

CdTe and CdS are other materials which have received special attention as photovoltaic materials. CdS appears more attractive photo-cells for high temperature range because of its high energy gap (2.4 eV at 0°C). The main advantage of CdS solar cell is that they can be made from micro crystalline thin films and do not require single crystals. These cells also can be produced by vacuum deposition of CdS on plastic. The major problem of this cell is its short life. The cells deteriorate rapidly in the presence of moisture and under ultra-violet radiation.

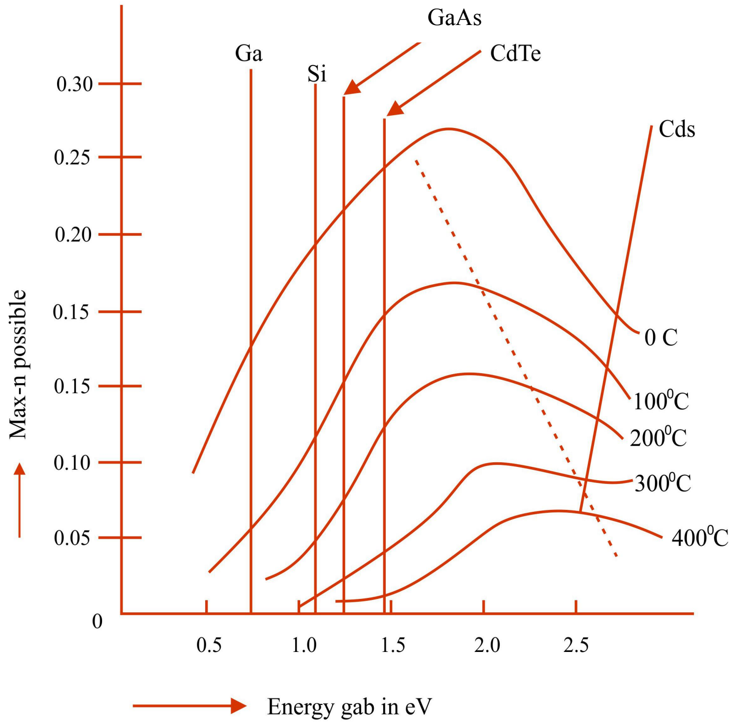


Fig. 15: *Of the max η with the energy gap temperature*

Some other photovoltaic cell materials under development are:

1. Multi-material photovoltaic cells
2. Graded energy gap photovoltaic cells
3. Multi-transition photovoltaic cells

It is claimed that the efficiencies of the cells lie between 50% to 60%.

SOLAR PHOTOVOLTAIC SYSTEMS (SPS)

Battery Storage with Inverter System: The solar photovoltaic system produces only D.C power. To use this power for household electrical equipment, inverters are used to convert DC to 220 V and 50 Hz AC power. Therefore, when power is generated with SPS, a battery with charge regulator is to be incorporated to provide backup power during period of low solar radiation and at night. Fig.16 shows the SPS with backup and inverter.

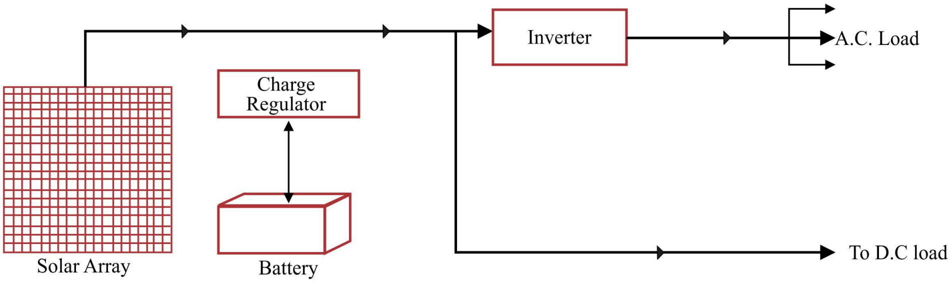


Fig. 16: *SPS with battery, charge regulator and inverter*

The capacity of the battery is expressed in amp-hrs (Ah) and each cell of lead-acid battery is of 2 volts. The batteries are installed with microprocessor-based charge regulator to control the voltage and temperature, and to regulate the input and output currents to avoid overcharging and discharging.

An inverter is provided for converting D.C power to A.C power. It is also protected against overloading and short-circuiting. The battery used with SPS must fulfill the following conditions:

1. It must be able to withstand several charging and discharging cycles.
2. Its self-discharge rate should be very small.

3. The maintenance should be as minimum as possible.

This is known as standalone SPS system. This type is generally used for street lighting and home lighting purposes.

Grid-connected (SPS) System: A grid connected SPS system is connected to the commercial electric grid. The capacity of SP system lies between 20 kW to 200 kW which can be used for schools and factories. In this system, the power is directly fed to the grid when solar generation exceeds load demand during daytime and taking power from the grid during night. Such system does not require storage battery but it requires additional component to regulate voltage and frequency to meet stringent requirements of feeding the power into the grid.

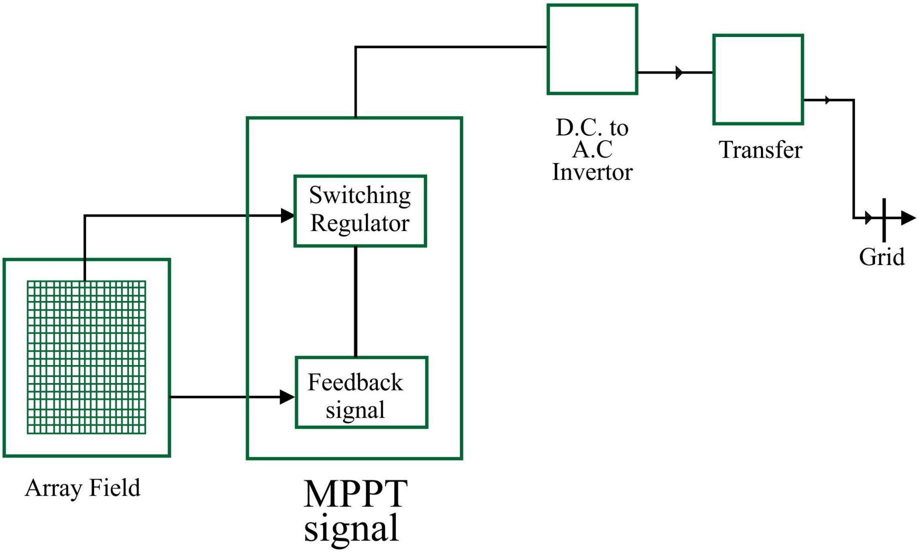


Fig.17: *Grid Connected SP System*

In this system, D.C. power is first converted into A.C. by inverter, harmonics are filtered and then the power is fed to the grid after adjusting the voltage level. Schematic diagram of such a system is shown in Fig. 17.

Hybrid SPS System

Sometimes, it is not practical and economical to supply all power from SPS system.

In such cases, part of the power is supplied by diesel generator or some other non-conventional source like wind. Such system is known as hybrid system. The best cost effectiveness is obtained from such system as the energy generated by SPS system is not wasted at all.

APPLICATION OF SPS

SP systems are more important in remote places (especially in villages and islands) where conventional power transmission system is not provided. Electric power is essential to improve health and education levels. SPS is best suited particularly for rural applications.

Solar Street Lighting

This is the most popular and very commonly used application of SPS. A pole mounted SPS system is shown in Fig. 18 (b). The lighting is required when the sun is not available, therefore, battery storage is essential. Energy efficient compact, fluorescent lamps are used at 25 - 35 kHz frequencies as SPS in an expensive power source. A conventional standard system consists of 11 W (900 lumens) CFL, 12 V storage battery with inverter and battery charger in addition to timer to switch on and off the light. The approximate cost of one pole-mounted street light is ₦240,000 (2019).

Another important application is solar powered telephones, Fig.18(a). The construction and arrangement are exactly the same as street lighting.

Fig.18(a): *Solar Powered Telephones*

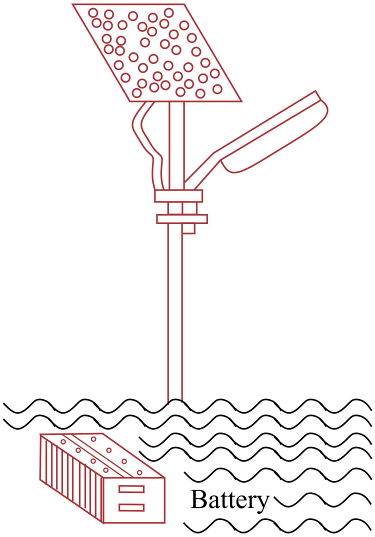


Fig.18(b): *An SPV Street Light Installation*

House Lighting System

It is similar to street light system but the array area required is considerably higher. It can provide the power to run 5-fans and 10 lights (each of 40 W capacity). It is also provided with battery charger and inverter. Generally house roof is commonly used for fitting the solar arrays.

Solar Farm

Solar farm is similar to roof-top array but larger in size generating power in large quantity (100 - 200MW) and therefore, such systems are directly connected to grid.

Satellite-Based System

SPS big array can be arranged in space as circling satellite in orbit (36,000km away from the earth). The solar energy will be re-generated by such power plant all 24 hours as earth rotation will not have any effect. In addition to this, the efficiency of the system will not be affected by the cloudy cover over the earth (Fig. 19).

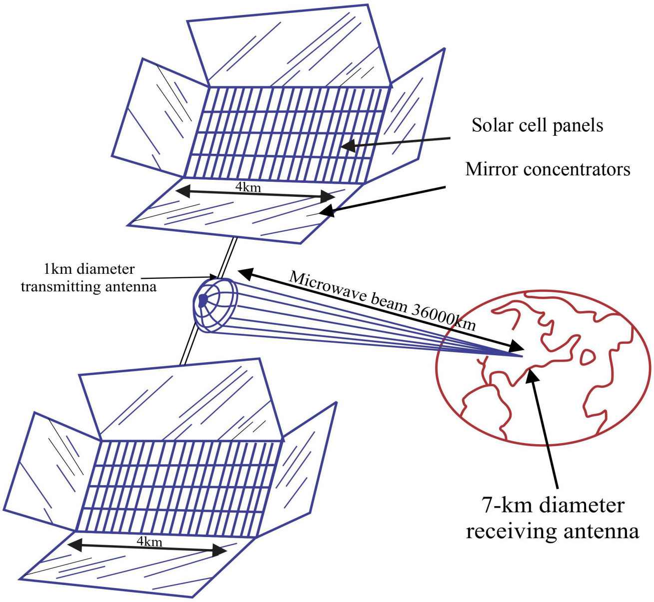


Fig. 19: *Solar Power Satellite Concept*

In addition to this, there are many more applications of photovoltaic system. These are listed below:

1. To operate remote radio and light beacons near the airport (used in seven mountain peaks near Medina airport in Saudi Arabia).
2. This is also used to power railway signals and earthquake alarm systems, for fire, flood, hazard warnings.
3. It is used for many defence equipment like mobile phones, remote radar and water purifier.
4. It can be easily used for pocket calculators, watches, clocks, torches, lanterns, garden lights, and portable fans in cars.
5. This is successfully used for generating and maintaining low temperature required for preserving life medicines particularly in rural areas.

ADVANTAGES AND DISADVANTAGES OF SPS

Advantages:

1. As solar energy is directly converted to electrical energy without any thermo-mechanical system, it has no moving parts.

2. It is reliable, durable and maintenance-free.
3. It responses instantaneously to solar radiation and is compatible with almost all types of environments.
4. They are noiseless and pollution free.
5. No transmission or distribution is required as it can be directly located at the place of use.
6. It can be located at any remote place.
7. Its lifespan is minimum of 20 to 25 years.

Disadvantages

The conversion efficiency is hardly 20% - 25%, therefore, very large array area is required.

1. The capital cost of the solar cell is very high compared with conventional system, making it uneconomical in MW-range.
2. Solar energy is intermittent, therefore solar cell produces energy when the Sun shines and is also in proportion to the solar intensity. Therefore, some kind of storage is required making the system more costly.

However, solar cells are used as a source of power for space vehicles and satellites for the last 50 years and remained unparalleled source for this purpose. These are universally adopted for the purpose because of their low weight, reliability and durability. Solar cells have survived the harsh physical conditions of space like high vacuum, high radiation and large temperature variations.

Their use for supplying electric power for terrestrial applications will become inevitable when the efficient materials with ample availability at considerably low cost will be made available. The challenges of producing reliable and competitively economic electric power by SPS for terrestrial applications have led to intense research work in all advanced countries during the last 40 years.

GREENHOUSE GASSES

America is the largest contributor of greenhouse gasses, followed by China and India. America alone contributes 25% of the carbon dioxide in the world. In 1997, 84 countries signed an agreement to limit CO_2 in the world and 38 developed countries signed to cut their CO_2 emitting level to 5%. USA, which emits 37%, refuse to sign (Domkundwar, 2010).

Methods of reducing greenhouse effects

1. Reducing population growths in the world as well as living standard (which depend upon the energy consumptions) per person.
2. Using the present available energy with uttermost care.
3. Not burning wastes.
4. Increasing forest area and planting new trees which will rapidly grow and absolve the carbon dioxide.
5. Finding out new methods to absolve or dump the emitted carbon dioxide.
6. Using non-conventional energy sources like Sun, wind and tides to generate power, as these do not emit carbon dioxide.

Carbon credit toward reducing green gas emission

1. Clean development mechanism
2. Joint implementation
3. International emission trading

CONCLUSION

Globally, the importance of diversifying energy sources cannot be overemphasised because of its effects on climate change. The demand for energy in the world has created a danger for human existence, as greenhouse effect is increasing with the increase in the use of conventional fuels (coal, oil and gas). This is as a result of increase in population of the world and the need for better standard of life. Renewable energy is the best option in reducing the effects of greenhouse gases on the environment; it also provides alternative energy sources to the world for present and future use. Among the renewable energy sources, solar energy is the most promising because of its abundance and and lifespan (it lasts for billions of yeas). At the 74th meeting of United Nations General Assembly (held on 24th September, 2019 in New York, USA), President Muhammadu Buhari of Nigeria in his speech to the assembly indicated his willingness to partner with United Nations on climate change by mentioning Nigeria's intention of having energy mix of 30 percent renewable energy by the year 2030. This will be a significant improvement in percentage contribution of renewable energy in the energy mix of the country. It will also go a long way in reducing the emission of carbon dioxide and other harmful gases to the environment which can affect climate change. Solar Photovoltaic System (SPS) will play a major role in this direction as its efficiency is being increased and its price of installation is falling daily due to breakthrough in researches going on in the world.

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