# UNIVERSITY OF LAGOS, NIGERIA

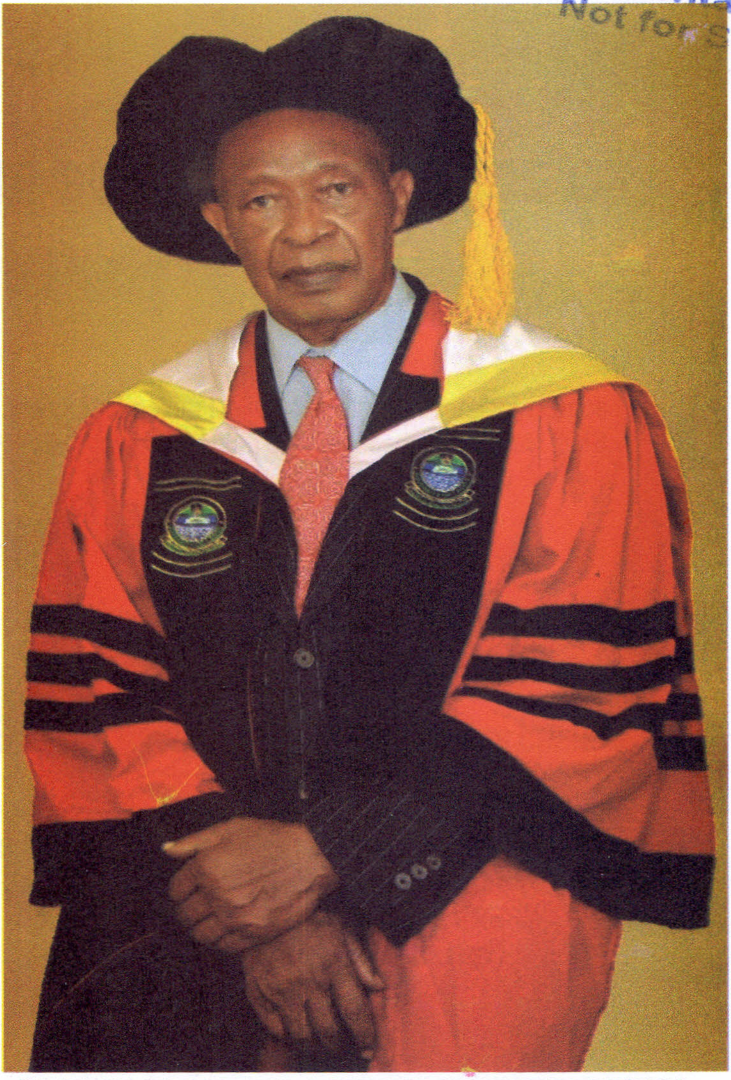
Inaugural Lecture Series 2018

TOPIC:

# THE SUN IN THE SERVICE OF HUMANITY


By

Professor Michael Anthony Chukwudi Chendo



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**Professor of Physics (Solar Energy)**

# THE SUN IN THE SERVICE OF HUMANITY

An Inaugural Lecture Delivered at the University of Lagos
J. F. Ade. Ajayi Auditorium on Wednesday l8th, July 2018.

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## DEDICATION

I am dedicating this lecture to all my teachers who nurtured and taught me throughout all my levels of education in Primary, Secondary, Advanced level and in the University in Akwa Ibom, Cross Rivers and Lagos States respectively.

I am also dedicating this lecture to all members of the Chendo-Okeke family, especially to my late parents, nuclear family and siblings (both dead and living).

**PROTOCOL**

The Vice –Chancellor,
Deputy Vice –Chancellor (Management Services),
Deputy Vice – Chancellor (Academics & Research),
Deputy Vice – Chancellor (Development Services),
Provost, College of Medicine,
The Registrar,
Other Principal Officers of the University,
Dean of Faculty of Science and other Deans here present,
Members of the University Senate,
Distinguished Academic and Professional Colleagues,
Distinguished Non-academic Colleagues (Administrative and Technical),
Your Lordship, Spiritual and Temporal,
Your Royal Majesties and Highnesses,
Invited Guests,
Dear Students (past & present),
Members of the Press (Print & Electronic Media),
Distinguished Guests, Ladies and Gentlemen.

**PREAMBLE**

To God be the Glory and I thank Him for keeping me alive to see this important and unique day in my academic career as a University of Lagos Lecturer.

It is with joy and deep sense of humility that I present myself this 18th day of July, 2018 to deliver this inaugural lecture in 2017/2018 Session, of this great, unique and University of First Choice in Nigeria.

I also feel humbled to deliver the first Inaugural Lecture as an alumnus of the Department of Physics in Solar Energy and the third Inaugural Lecture from the Department of Physics since its establishment. The preceding two lectures were delivered by my former Teachers, Prof. E. O. Olatunji and Prof. C. O. Oluwafemi.

Mr. Vice-Chancellor Sir, in 1976 the topic of my final year undergraduate project was "SURFACE TEMPERATURE OF THE SUN", little did I know that this project was going to be a game changer in my life. The first question that came to mind when this topic was given to me by my

Supervisor, Dr. E. F. Schmitter, was am supposed to travel to the sun which is about $150 \times 10^6$ km from the Earth with a thermometer to achieve this or what? At that time, it looked weird to me. But my Supervisor calmed my nerves by saying, "we shall use the photographic method of the solar spectrum". Anyway, after going through a course in Astrophysics, I took it up as a challenge, we had very reasonable results using the Wien's technique and the rest is history.

In August 1978, I was invited to participate in the 1st International Conference for young Astronomers hosted by the University of Nigeria, Nsukka. This Conference gave me more insight on the Sun and subsequently my interest in Solar Energy Studies was shapened. It was at this Conference that I met my bosom friend, Mr. Larry Amaeshi who came from the University of Ghana, Legon and also my project Supervisor, Dr. Schmitter who was one of the guest lecturers. At the end of the workshop, Mr. Amaeshi, Mr. Pius Okeke (now Prof. P.N. Okeke) who was pursuing his graduate studies under the supervision of the Workshop Coordinator, late Professor S. E. Okoye, and my humble self were given the opportunity to go to India for our postgraduate studies in Astronomy under one of the lecturers, Professor Swarup. Anyway, for reasons best known to GOD, Mr. Amaechi and I did not fancy travelling to India, we rather found ourselves securing employment with the University of Lagos.

I was admitted for M.Sc. Physics (Solar Energy) by research in 1978/79 session and shared a room in Amina Hall, B Block with my late friend, Dr. Emmanuel Chike Ezeani who was also pursuing his M.Sc. programme in Chemistry (May his gentle soul continue to rest in perfect peace in the bosom of our Saviour). Based on the exposure and experience I had from attending the International Conference for young Astronomers, Nsukka 1978/79 session, coupled with the guidance of my Supervisor, Dr. Edwardo Schmitter, my sojourn into the field of Solar Energy Physics began. In furtherance of this venture into the unknown, the Ag. Head of Department in 1979, Professor J.E.A. Osemeikhian (then Dr. Osemeikian) my academic father and mentor, launched me into the International World of Solar Energy studies. He obtained an application form for me to apply to the International Centre for Theoretical Physics (ICTP) Trieste, Italy. Luckily, my application was successful to participate in the 1st International

Workshop on Nonconventional Energy sources with all expenses paid by the ICTP.

In addition, one of my international contacts, Prof. T. Nejat Vezigrolu, the Director Clean Energy Research Institute in the University of Miami, Florida (USA), sent me an application form to participate in the International Conference on Solar Energy organised by the University of Izmir in Turkey and also Summer School for Young Scientists in Solar Energy in Istanbul, Turkey. To the glory of God, the two applications were successful with all expenses paid by the organisers. Being my maiden visit to Europe, I left the country without any foreign exchange since the organisers gave me full scholarship.

Thus, out of anxiety, excitement and naivety, I left the country in August 1979 having obtained the approval to travel and support from the University, I left the country while my Head of Department was not in Lagos. On his return, he quickly wrote me, expressing his shock on how I left the country without any Foreign Exchange. Mr. Vice-Chancellor Sir, when I got to Istanbul, Turkey, through God's intervention, I located my international mentor, Prof. Vezigrolu and explained my predicament to him as he was already in Turkey for the Workshop; he came to my rescue by offering a room at his family house in Istanbul. (Little did I know that he hailed from Turkey but was resident in the USA). Thus, with his kind gesture and God's help, my stay in Turkey (both in Izmir and Istanbul) was pleasant and rewarding.

At the end of my sojourn in Turkey I proceeded to Italy for the ICTP Workshop. When I landed at the airport in Rome, the Italian Immigration services said I was given only "one entry visa" which I used on my transit from Rome to Istanbul. At this point, I was confused and didn't really understand what they meant by 'single entry visa'. After some exchanges and pleadings with God's intervention, the immigration boss allowed me to re-enter Italy and the rest is history. There in ICTP, I met another of my mentors, Prof. Gussuppe Furlan whom I call my international academic father and mentor.

Mr. Vice-Chancellor Sir, my participation in both the Turkey conference and the Italian Workshop opened and initiated me into the International Solar

Energy Community that facilitated my ascendancy to the Chair of Physics (Solar Energy). Thus, it is a great honour on this day 18th July 2018 to present to you my significant research contributions within the general framework of my multidisciplinary training in Solar Energy Physics. Hence, the title of my Inaugural Lecture is **"THE SUN AND SERVICE TO HUMANITY".**

The Bible in Genesis started with a picture of a world without form and void but subsequently when light appeared on the scene (Gen. 1:14) things started to manifest. The Sun in this light is generally regarded as the power house of the world.

Mr. Vice-Chancellor Sir, permit me to say that the choice of this title is to wrap up my approximately 40 years of research in Solar Energy Utilisation, which was quite problematic, challenging and fulfilling.

## STRUCTURE OF THE LECTURE

Following the above preamble, this lecture is divided into the following sections:

(1) Introduction to Physics of the sun and its optics.
(2) Research and Contributions.
(3) Recommendations.

## 2.0. THE SUN

The sun is just an average star. Of the innumerable others, some are larger and others smaller, some are whiter and others show colours that are more inclined to red, some are believed to be older and others younger. Its absolute magnitude is 4.48, its spectral type G2, it is a dwarf and its surface temperature is about 6000 K. But it has something special and unique, the sun is 'our' star and the 'only' star whose shape and surface may be observed.

One of the most widely accepted schematics of the structure of the sun, Lof (1946), Selcuk (1977) cited by Garg (1982), is shown in *Fig 2.1*. The physical properties of the sun and the earth are listed in *Table 2.1*.

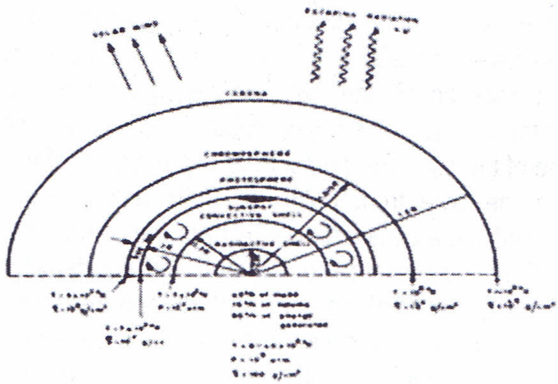


**Fig. 2.1: Interior structure and modes of outward energy flow of the Sun (Source: Garg, 1982)**

**Table 2.1: Physical Properties of the Sun and Earth (Source: Garg, 1982)**

| | |
|---|---|
| Sun Linear diameter of sun | $1.391\ 96 \times 10^6$ km |
| Angular diameter of sun at mean earth sun distance | 32' 2.4" |
| Surface area of sun | $6.093 \times 10^{12}$ km$^2$ |
| Mass of sun | $1.989 \times 10^{33}$ g |
| Volume of sun | $1.4122 \times 10^{33}$ cm$^3$ |
| Mean density of sun | $1.400$ g cm$^{-3}$ |
| Surface area of sun | $6.093 \times 10^{12}$ km$^2$ |
| Surface gravity of sun | $2.7398 \times 10^4$ cm sec$^{-2}$ |
| Absolute magnitude of sun | + 4.85 |
| Temperature of solar corona | > 1 000 000 K |
| Effective black-body temperature of photosphere of sun | 5762°K |
| Rate of sun's radiation | $6.5 \times 10^{16}$ erg s$^{-1}$ cm$^{-2}$ |
| Parabolic velocity at the surface of sun | 617.0 km/s |
| Period of rotation of sun at equator | 24.65 days |
| Net sidereal rotation of sun | 14°.197 daily |
| Diurnal rotation of sun at equator | 14°.37 daily |
| Parallax of sun | 8".80 |
| Approximate composition of sun (by weight) | |
| Hydrogen | 75% |
| Helium | 24.25% |
| Heavy elements | 0.75% |
| Moment of inertia | $6.0 \times 10^{46}$ kg m$^2$ |
| Value of solar constant | $1.95 \pm 0.02$ cal cm$^{-2}$ min$^{-1}$ |
| | 1370 W/m$^2$ |
| Rate of energy production | $3.90 \times 10^{26}$ W ? |
| Escape velocity at surface | 618 km/s |
| Earth | |
| Equatorial radius of earth | 6 378.17 km |
| Polar radius of earth | 6 356.79 km |
| Mass of earth | $5.977 \times 10^{27}$ g |
| Volume of earth | $1.083\ 22 \times 10^{27}$ cm$^3$ |
| Mean density of earth | 5.517 g cm$^{-3}$ |
| Surface gravity of earth | 980.665 cm s$^{-2}$ (Standard) |
| Normal gravity of earth | $(980.64 - 2.59 \cos 2L)$ cm/s$^2$ where $L$ is the geodetic latitude |
| Flattening | 0.003352 |
| Eccentricity of the earth's orbit | 0.01673 |
| Average pressure at sea level | 101.325 kPa |
| Mean earth–sun distance | $1.49\ 5985 \times 10^8$ km |
| Mean radius of the earth | 6371 km |
| Surface area of earth | $5.101 \times 10^{14}$ m$^2$ |
| Distance to sun at perihelion | $1.471 \times 10^{11}$ m |
| Distance to sun at aphelion | $1.521 \times 10^{11}$ m |
| Moment of inertia about axis of rotation | $8.04 \times 10^{37}$ kg m$^2$ |
| Escape velocity at surface | 11.2 km s$^{-1}$ |
| Rotational velocity at equator | 465 m s$^{-1}$ |
| Mean velocity in its orbit about the sun | 29.78 km s$^{-1}$ |

The mass of the sun is about 330,000 times bigger than the mass of the earth. It is estimated that 90% of the sun's energy is generated through a thermonuclear reaction, (Bethe, 1938) in the region from 0 to 0.23R (R is the radius of the sun) and this region contains 40% of the mass and 15% of the volume of the sun. The pressure at this region is of the order of $10^9$ atm. Outside the core from 0.23R to 0.7R is the region called the "radioactive shelf". At a distance of 0.7R from the centre, the temperature drops to $7x10^3$ K, the pressure to $10^{-2}$ atm and the density to $0.7g/cm^3$. Here, convection process of the energy starts and the zone from 0.7R to 1.0R is known as the 'Convective shell or Convective zone'. Beyond this zone, a 500 km thick region exists. The temperature of its inner layer is about $7x10^3$ K and its density is about $10^{-7}g/cm^3$. This zone is very important from the astrophysical point of view because it can be considered as the seat of solar activity: sunspots, flares, radio outburst, etc. Garg, (1982).

The convective zone generates shock waves which readily heat up the upper part of the atmosphere (chromosphere) and give rise to a very hot extended atmosphere (Solar Corona) which produces a continuous flow of particles moving out to very great distances (Solar Wind). The outer layer which is directly accessible for observation is called the 'photosphere' and consists of rarefied gases. The photosphere has a density of about $10^{-8}$ $g/cm^3$ and it is the main source of most of the solar radiations. The layer immediately above the photosphere is the 'reversing layer' which is at a comparatively lower temperature of about 5300 K than the photosphere and consequently gives rise to absorption lines in the spectrum. Beyond the photosphere, or surface of the sun is the solar atmosphere which is composed of the chromospheres and corona. Both regions of the solar atmosphere, offer very little resistance to radiation from the photosphere and in addition contribute very little to the sun's radiation output.

From the simplified structure of the sun, it appears that the sun cannot be assumed to be a black body emitting radiation at a fixed temperature. It may be concluded that it is impossible to determine the temperature of the sun and the energy distribution in the solar spectrum cannot be expected to correspond to that of a black body.

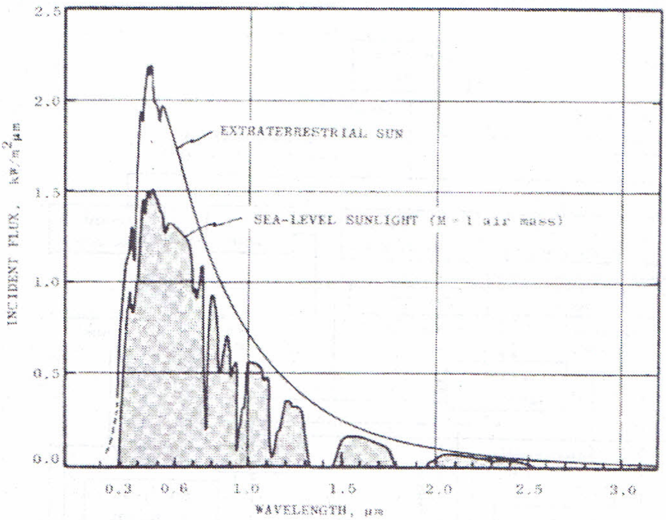



**Fig. 2.2: Spectral distribution of energy in sunlight above the atmosphere and after passage through one air mass (zenith) for an atmosphere containing 20mm precipitate water vapour (source: Meinel and Meinel, 1976)**

It can be seen from the solar radiation curve in *Fig* 2.2 that although it is close to a black body distribution for T = 6000 K, there are more important differences between them. Firstly, the maximum intensity is not 0.48µm but at 0.47µm. Secondly, the spectrum is cutoff on the ultraviolet side and is below the 6000 K curve on the infrared.

For all practical purposes, for thermal engineering processes, the sun may be assumed to be a black body radiator having a temperature of 5762 K. For other photovoltaic, photochemical, photo-thermals and other such applications where the spectral distribution is important, this average temperature may not be sufficient, thus more detailed information may be necessary.

Figure 2.3 shows the energy distribution and solar generation systems.

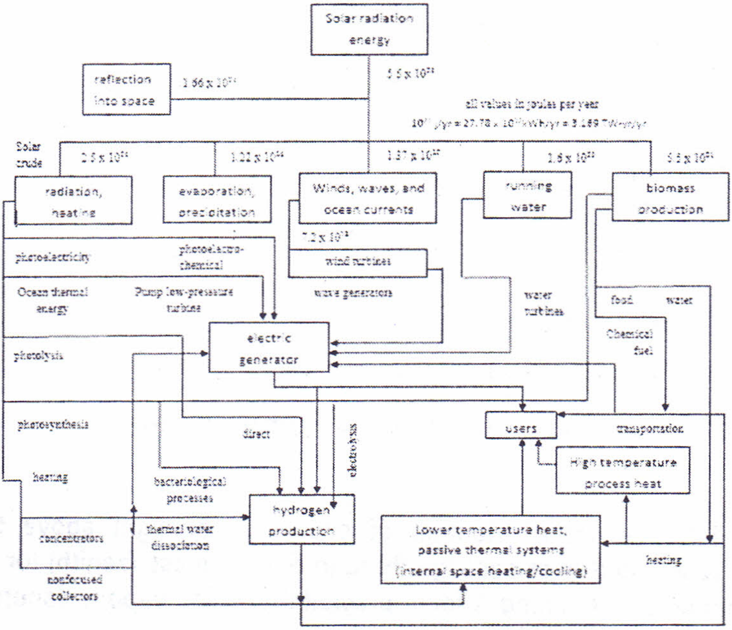



**Fig. 2.3: Energy distribution and solar power generation systems (Source: Energy Encyclopedia)**

## 3.0. BRIEF HISTORY OF APPLICATIONS

The history of solar energy application stretches into the dim recesses of prehistory perhaps as far back as the clay tablet era in Mesopotamia, when temple priestesses used polished golden vessels to ignite the altar fires (Meinel and Meinel, 1976).

The tales of similar solar devices that occurred in the Middle Ages agitated much discussions as related by Athanasius Kircher (1601-1680). Thus the great challenge to the science that was to emerge in the 17th century however, was the story of Archimedes (great inventive genius-282-212 BC) who with his inventious ingenuity, used solar rays to repel the invading Roman fleet of Marcellas in 212 BC as related by Galen (AD 130-220) though the feat was highly debated and finally relegated to myth when the Romans saw that an indefinite mischief overwhelmed them from no visible means, so began to think they were fighting with the "gods". The ambiguity posed a problem to Renaissance Science. The basic question was whether or not Archimedes knew enough about the science of optics to device a simple way to concentrate sunlight to a point where chips could be burned from a distance. After Archimedes, there was little progress in solar energy application until the Renaissance, the last word from the days of the Roman Empire concerning solar energy was recorded in the 12th century by Ioanne Zonaras, who told how Prochus repeated the feat of Archimedes using a large number of mirrors to burn the fleet of vitellius at the siege of Constantinople. The seeds of Science, however were slowly transplanted in Europe via the resumption of sea commerce stimulated by the crusades and emerged with vigour in the Renaissance. We finally see evidence of a rebirth of interest in solar energy in the 17th century (Meinel and Meinel, 1976).

Eighteen hundred years after Archimedes, Athanasius Kircher (1601-1680) performed some experiments to set fire on a woodpile at a distance to see whether the story of Archimedes had any scientific validity. Burning glasses had undoubtedly remained the chief means of using solar energy over the intervening centuries but once more, man's curiosity led him to seek answers to larger questions.

The next incident involving the sun was in Florence (Italy) where the experimenters, Averani and Targioni in 1695, attempted to melt diamond with a burning mirror.

More practical uses of solar energy were developed by Ehrenfried Von Tschirnhaus (1651-1700) who used lenses to melt ceramic materials.

The earliest attempts to convert solar energy into other forms of energy revolved around the generation of low pressure steam to operate steam engines. August Mouchet pioneered this field between 1864 and 1878 as shown in Fig. 3.1.

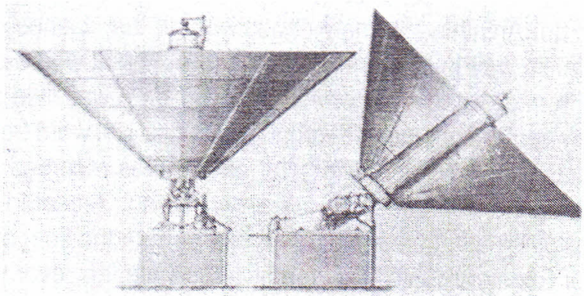


**Fig. 3.1: August Mouchet's multiple-tube sun-heat absorber of 1878 (Source: Meinel and Meinel, 1976)**

Abel Pifre, a contemporary of Mouchet also created solar engines made out of parabolic reflectors and of small mirrors which were used in operating a printing press as shown in Fig. 3.2 and 3.3.

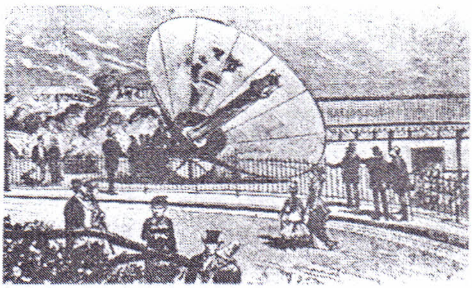


**Fig. 3.2: The first large solar collector of the axicon type was exhibited by August Mouchet's in 1878 (Source: Meinel and Meinel, 1976)**

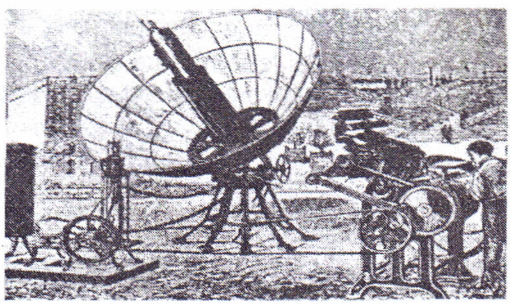


**Fig. 3.3: Pifre's sun-power plant of 1878 driving a printing press (Source: Meinel and Meinel, 1976)**

Solar engines of the 1880s worked only at the convenience of the sun. Night time and cloudy days imposed great limitations to their usefulness. In 1893, M.L. Severy obtained a patent for solar engines operating in conjunction with wet storage batteries to enable the users have access to 24-hours electrical power.

A lull in activity followed the advances made by Mouchet, Pifre Ericson etc. and it was not until after the 20th century that a new surge of activities began with significant developments especially with the works on solar energy by C.G. Abbot. He began studying the sun in 1905 and from time to time had personal contact with experimenters. In his early years, Abbot published little on solar energy but from 1926 to 1973, when he was 100 years old, he published very many scientific papers. Coincidentally, 1973 ushered in the big modern revolution into solar energy application as a fallout of the Arab-Israeli conflict that brought about the Arab World Oil embargo to the western world. This oil embargo challenged the Western powers who vowed to never again depend on foreign oil. Thus, intensive research into different facets of solar energy application began. (Mienel and Meinel, 1976).

## 4.0 THE CHARACTERISTICS OF THE SUN

The sun provides energy in many forms. For most of history sun was the energy for social and industrial life, first in the forms of food and firewood then as wind and water power. Visible spectrum drives photosynthesis and photochemical process and today photons can be converted directly to electric power in photovoltaic devices.

Kulijan (1954) states that: *"It is the sun that we owe the existence of all our coal, oil and gas, resources in the world. While these fossil fuels are still plentiful as far as present needs are concerned, at the accelerating rate at which we are converting them into power, they will be practically exhausted in a little over 100 years. There are many reasons we should take immediate steps to conserve these fossil fuels and learn to exploit renewable resources".*

The dramatic technological advances of the 21st century, allowed mankind to find better ways of producing and using both the conventional and nonconventional forms of energy. Energy is such an essential part of our daily lives that minor interruption in the supply chain causes many disruptions of our social and economic life. From studies conducted in the USA by Quraeshi (1984) and other parts of the globe, "the comparison of world population and growth of electric power indicated that fissionable fuels would be depleted by 2050AD. Despite the current supply of oil and the energy situation today, the long term availability of fossil and fissionable fuels is highly uncertain. So much attention is now being directed towards the sun as a potential source of future energy".

The abundance and continuous nature of this energy makes it most suitable for many applications. In the words of a British Physicist, J. D. Bernal (cited by Glaser, 1985), *"It may be that in the future man will have no use for energy and will be indifferent to the stars except as spectacles but if (as this seems probable) energy is still needed, the stars cannot be allowed to continue their old ways but will be turned to different heat engines"*. "It is estimated that every day the Earth receives approximately $8.8 \times 10^{12}$ GJ of energy from the sun, which is equivalent to the thermal energy in all the oil and gas available in the world. In just 10 days, we receive as much heat from the sun as there is in all the fossil fuels in the world and in 220 days we receive as much heat as there is in all fossil fuels and fissionable materials in the world" (Quraeshi, 1984).

Moreover, Atmospheric Physicists are concerned that more carbon (iv) dioxide build up from fossil fuel combustion, may lead to an increase in the world's temperature attributable to enhancement of the Green House effect. Such changes may lead to disastrous climatic changes as currently witnessed globally.

If this inexhaustible source of energy can be tapped, mankind will have solved its major energy problems of all times. Solar Energy is non-depletable, clean, easy to convert to conventional energy forms with existing technology and has no ongoing fuel cost. It is modular in nature, and eliminates the discontinuities of scale that typically affects the conventional power plants. Solar energy does not create environmental hazards on the scale of conventional fuels. *Figure 4.1* shows an organogram for non-conventional energy sources.

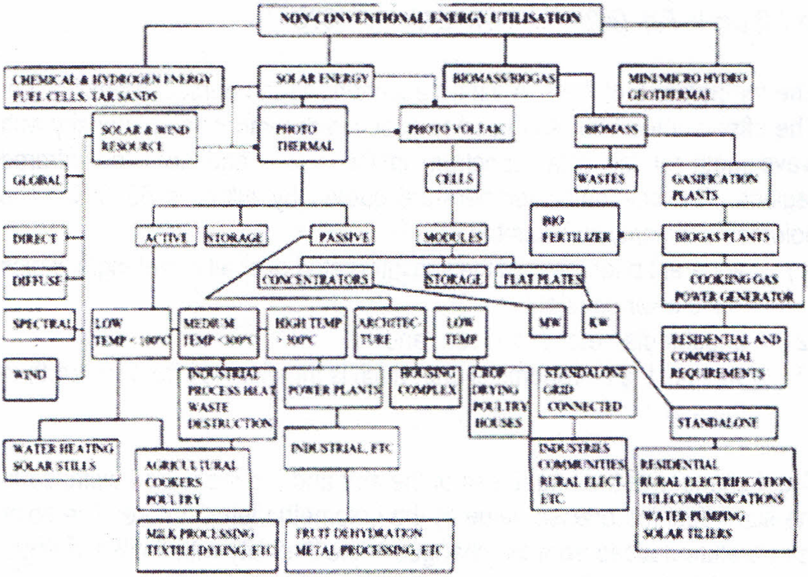



**Fig. 4.1 A schematic structure of non-conventional energy utilisation**

Although, a growing impatience to develop solar energy for widespread use is occurring and despite optimistic expectations, large-scale solar energy use may take longer time than it has been projected. Because of its low energy density and intermittence, solar energy cannot meet the total electrical energy requirements of the technically advanced countries. It would however be able to meet the demands of the developing countries and can therefore be considered one of the most promising renewable forms of energy for the developing countries. Fortunately, Nigeria lies near the equator (between latitudes 4° and 14°N) and is rich in solar energy resources. Ngoka (1982), estimated that Nigeria receives about $16.7 \times 10^{15}$ KJ of Solar Energy on each clear day.

## 5.0 SOLAR SPECTRUM

The distribution of solar energy as a function of wavelength is very important in the functioning of solar energy systems. The variation is basically that of a blackbody at 5800 K but it is modified by absorption in the solar atmosphere from the atomic lines by the negative hydrogen ion continuum, and by a few molecular bands. The resulting changes in the exoatmospheric spectrum are small and are shown by the regions from 0.3 to 0.6 μm in *Fig. (2.2)* (Meinel and Meinel 1976).

The temperature of the sun differs according to the particular application. The often quoted 5800K is used to describe the variation of intensity with wavelength for the solar spectrum in the visible and near the infrared regions. The bolometric temperature quoted by Allen, is 6350 K. The bolometric quantity involves the:

(1) apparent brightness of the sun integrated over all wavelength, which is the solar constant;
(2) angular diameter of the sun; and
(3) value of the astronomical unit which is the distance from the earth to the sun.

Slight changes in the brightness of the sun and the measured distance to the sun affect the precise value of the bolometric temperature. The solar temperature derived from the changes in the intensity with the wavelength is less subject to an error of measurement.

The spectrum temperature of 5800 K is used in evaluating the fraction of sunlight within a given wavelength interval as with solar cells or selective surfaces.

The bolometric temperature of the sun (6350 K) is used in evaluating the performance of a furnace. The atmosphere of the earth significantly modifies the exoatmospheric solar spectrum by the presence of absorption bands of water vapour and carbon (iv) dioxide and to a lesser extent by the presence of ozone in the terrestrial atmosphere. Ozone absorption effectively terminates the solar spectrum at 0.360 μm in the ultra violet region and water vapour effectively terminates it at about 200 μm in the infrared region. Between these two extremes, there are many other features of absorption that modify the spectrum as shown in *Fig. 2.2.* The molecular absorption bands in the region where there is significant solar flux are shown on a logarithmic intensity scale (*Fig 5.1*).

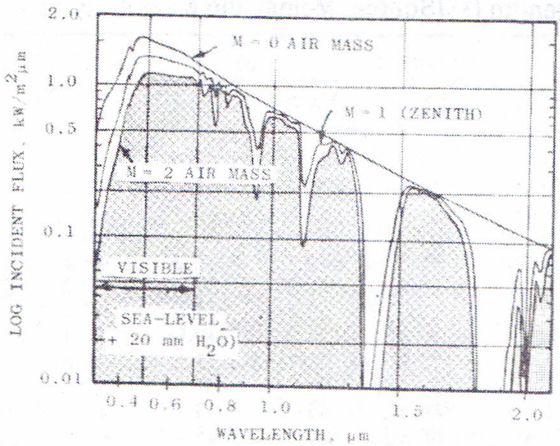



**Fig. 5.1 Spectral distribution of energy in sunlight on a logarithmic intensity scale to permit a more accurate evaluation of the effect of the molecular absorption bands in the near infrared. (Source: Meinel and Meinel, 1976).**

The standard sea level atmosphere adopted here is that defined by the Moon (1940) cited by Meinel and Meinel (1976), in which 200mm of precipitated water is assumed to exist. The increase in absorption which change from one to two air masses (30° elevation above the horizon) is shown in *Fig 5.1*. The percentage of the total energy in the spectrum of the sun long ward of a given wavelength is given for the three cases in *Table 5.1.*

**Table 5.1: Percentage of Solar Energy at Shorter Wavelengths than a given Wavelength (λ) (Source: Meinel and Meinel, 1976)**

| | 5800°K | *Sun* | | *Sea level* |
|---|---|---|---|---|
| (μm) | Σλ>0 | Σλ>0 | Σλ>0.3 | Σλ>0.3 |
| 0.30 | 3.6 | 1.27 | 0.0 | 0.0 |
| 0.40 | 13.6 | 9.15 | 8.0 | 2.3 |
| 0.50 | 25.5 | 23.5 | 22.5 | 14.4 |
| 0.60 | 38.0 | 37.4 | 36.5 | 30.0 |
| 0.70 | 51.3 | 49.1 | 48.3 | 45.1 |
| 0.80 | 60.7 | 58.3 | 57.7 | 57.3 |
| 0.90 | 67.6 | 65.1 | 64.6 | 67.4 |
| 1.00 | 73.4 | 71.3 | 70.9 | 73:4 |
| 1.10 | 77.8 | 76.1 | 75.8 | 80.8 |
| 1.20 | 81.7 | 80.1 | 79.8 | 83.6 |
| 1.30 | 84.5 | 83.3 | 83.1 | 88.6 |
| 1.40 | 86.9 | 85.9 | 85.7 | 89.7 |
| 1.50 | 88.7 | 88.0 | 87.8 | 90.1 |
| 1.60 | 90.1 | 89.8 | 89.7 | 92.8 |
| 1.70 | 91.5 | 91.2 | 91.1 | 95.1 |
| 1.80 | 92.6 | 92.4 | 92.3 | 98.6 |
| 1.90 | 93.5 | 93.3 | 93.2 | 96.1 |
| 2.00 | 94.3 | 94.1 | 94.0 | 96.3 |
| 3.00 | 98.1 | 98.0 | 98.0 | 99.0 |
| 4.00 | 99.2 | 99.1 | 99.1 | 99.5 |
| 5.00 | 99.5 | 99.5 | 99.5 | 99.6 |
| 10.00 | 99.0 | 99.9 | 99.9 | 99.9 |

These cases are:

(1) for a 5800 K blackbody;
(2) for exoatmospheric sun; and
(3) for sea level sunlight.

Note that the wavelengths in which 90% of the solar energy lies are at shorter wavelengths. When we measure the brightness of the sun at any particular time of the day and measure it later, there is usually a different apparent brightness. This is because of a change in the angular altitude of the sun and the corresponding change in air mass through which the sun travels. These changes must be taken into account in predicting the solar collector performance. The change varies from day to day as atmospheric condition changes.

The specification of the variability of the sunlight is complicated by the random nature of its variations. In view of this complexity, it is generally assumed that a "clear day" serves as a standard for evaluating the performance of a solar system. A steady state analysis based upon the input flux of a definite value, enables the specification of system performance under a wide range of flux values but these calculations are valid only when the actual flux remains at a specified value for a period of time that is longer than the system response time. A useful tool for analysing the performance of a solar thermal system under a fluctuating solar input is the Modulation Transfer Function (MTF). With this tool, the Fourier-Spectrum of the input solar fluctuations was utilised. This was achieved by taking the variation of the direct solar flux intensity and transforming it into the Fourier frequency domain. The advantage of going into the Fourier domain is that, each of the components of the system can be generally described by an MTF curve. The system output in terms of its modulation transfer function is simply the product of the individual MTF function from which the actual system output is obtained by the summation:

$$I_d(t) = \sum_{i}^{\infty} A_n \cos(\frac{n\pi t}{\tau}) + B_n \sin(\frac{n\pi t}{\tau}) + \frac{A_o}{2} \qquad (5.1)$$

Where: $A_n$ & $B_n$ represent the Fourier sine and cosine coefficients respectively. I is the period. The coefficients are determined from the input flux by using the Fourier time and cosine integrals:

$$A_n = \frac{I}{\tau} \int_{-\tau}^{\tau} I_d(t) \cos\left(\frac{n\pi t}{\tau}\right) d\tau \qquad (5.2)$$

$$B_n = \frac{I}{\tau} \int_{-\tau}^{\tau} I_d(t) \sin(\frac{n\pi t}{\tau})\, d\tau \qquad (5.3)$$

A preferred expansion in this case is:

$$I(t) = \frac{A_o}{2} + \sum C_n \cos(\frac{n\pi t}{\tau_n}) \qquad (5.4)$$

Where, $C_n = (A_n^2 + B_n^2)$ and $\tau_n = \tan^{-1}(\frac{A_n}{B_n})$

The coefficients $A_o$ and $C_n$ are identified as being the frequency spectrum of the input solar flux. The larger the value of one of the coefficients the more energy there is in the flux that can be characterised by the frequency.

## 5.1 DISTORTED WAVELENGTH GRAPHS

The evaluation of the efficiency of a spectral curve for selective surfaces is easier to visualise when a distorted wavelength scale is used for the abscissa of the plot. In this case the wavelength distance interval is proportional to the solar energy falling within that interval. This procedure widens the scale in the visible spectrum and greatly compresses it in the TIR as shown in *Fig 5.3*. It is necessary to use at least two distorted wavelength graphs for the presentation of the selective coating performance. *Fig 5.4* is for the solar spectrum, which is used to estimate the absorptance of the coating.

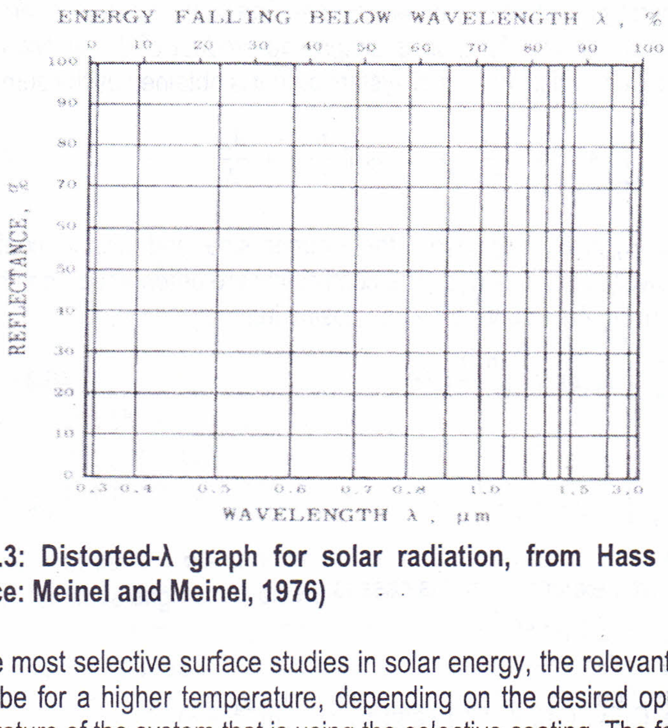



**Fig. 5.3: Distorted-λ graph for solar radiation, from Hass (1964) (Source: Meinel and Meinel, 1976)**

For the most selective surface studies in solar energy, the relevant graph would be for a higher temperature, depending on the desired operating temperature of the system that is using the selective coating. The fact that two graphs are needed for each selective surface, curves are not regularly used in daily research activities. They are most convenient when preparing diagrams for non-technical audience to emphasise the high value of absorptance and the low value of emittance that could be obtained through the use of selective surface coatings.

In most cases, we retain the logarithmic wavelength scale in all the wavelength diagrams since they can be translated into any distorted wavelength graphs as the occasion demands.

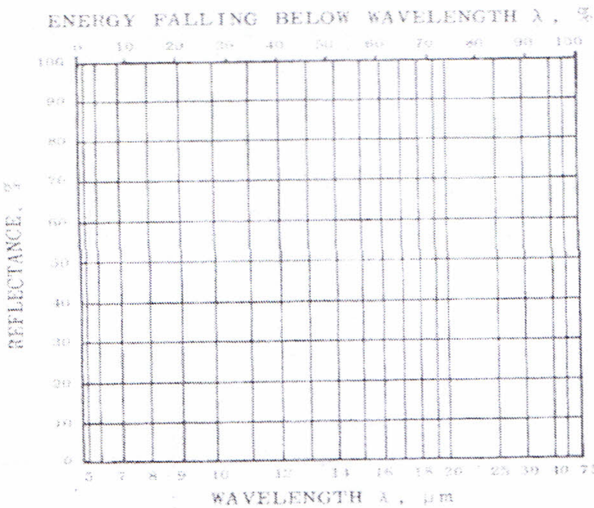



**Fig. 5.4: Distorted-λ graph for TIR radiation at 27 °C, from Hass (1964) (Source: Meinel and Meinel, 1976)**

## 6.0 THE SUN AS THE SOURCE OF RADIATION

The radiant energy of the sun is the only source of energy that directly or indirectly influence the atmospheric motions and many other processes in the atmosphere and surface layers of the earth's crust. The sun itself is a gaseous sphere whose temperature varies from about 6,000 K at the radiating surface to over $1 \times 10^6$ K at the tenuous outer atmosphere of the sun and over $1 \times 10^7$K in the deep interior. The theory of Bethe (1938), leads to a relationship between the temperature conditions of the sun, and the amount of liberated energy of the sun which is due to Thermonuclear reactions leading to the production of alpha particles (helium nuclei), hydrogen with carbon and nitrogen as catalysts. In this chain reaction, one alpha particle ($H_e{}^4{}_2$) is formed as a result of four protons ($H^1{}_1$) collisions but the amount of carbon and nitrogen remain unchanged. The duration of such a chain is 5.0 x $10^6$ years. Since the mass of one proton is 1.67x$10^{-27}$kg and the mass of one alpha particle is 6.644x$10^{-27}$ kg, therefore, the mass loss involved in the creation of one alpha particle from four protons is 0.044x$10^{-27}$ kg. According to Einstein's law ($E = mc^2$), where E is energy in Joules and C is the velocity of light in m/sec, one kilogram is equivalent to 9x$10^{10}$ Joules. Hence one kilogram proton liberates 6.3 x $10^8$ Joules when converted to alpha particles. The electromagnetic waves are transverse waves. The wavelengths of various electromagnetic waves cover a wave range as shown in the electromagnetic spectrum *(Fig. 6.1 and Table 6.1).*

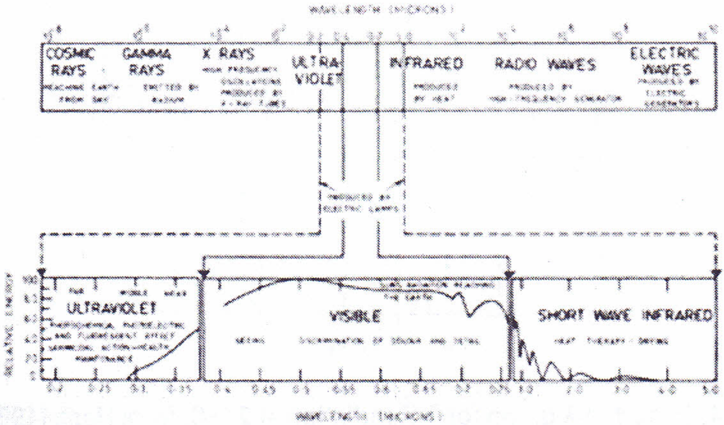



**Fig. 6.1: The electromagnetic spectrum (Source: Garg, 1982)**

**Table 6.1: Electromagnetic spectrum according to wavelength (1cm = $10^8$ AU = $10^4$ um) (Source: Garg, 1982)**

| Wavelength ($\mu$m) | Radiation |
|---|---|
| $< 10^{-6}$ | Cosmic rays |
| $10^{-6} - 10^{-3}$ | X-rays and $\gamma$-rays |
| $10^{-3} - 0.2$ | Far ultraviolet |
| 0.2 – 0.315 | Middle ultraviolet |
| 0.315 – 0.38 | Near ultraviolet |
| 0.38 – 0.72 | Visible |
| 0.72 – 1.5 | Near infrared |
| 1.5 – 5.6 | Middle infrared |
| 6.5 – 1000 | Far infrared |
| $> 1000$ | Micro and radio waves |

## 7.0 SOLAR GEOMETRY

The earth is shaped as an oblate spheroid – a sphere flattered at the poles and bulging in the plane normal to the poles. For most practical purposes we consider the earth as a sphere with a diameter of nearly 12,800 km. The earth makes one rotation about its axis every 24 hours and completes a revolution about the sun in a period of 365.25 days approximately. The earth describes an ellipse round the sun with the latter at one of the foci. The apparent path of the sun as seen from the earth is known as an 'ecliptic'. The eccentricity of the earth's orbit is very small (0.01673), so that the orbit is in fact very nearly circular. Thus, the shortest distance between the earth and the sun (when the earth is in perihelion) and the longest distance (when the earth is in aphelion) are respectively given as:

$$Rp = a\,(1 - e) = 147.10\text{x}10^6\ \text{km} \qquad (7.1)$$
$$Ra = a\,(1+e) = 152.10\text{x}10^6\ \text{km}$$

Where **a** is the semi measure axis of the earth's orbit. The so-called mean distance of the earth from the Sun is defined as half the sum of the perihelion and aphelion which is equal to **a**, with the numerical value 149.5985x $10^6$ km. By January 4th, the earth is closest to the sun while by July 4th, it is much remote being about 3.3% further away.

The earth's axis of rotation is titled 23.5° with respect to its orbit around the sun. In its orbital movement, the earth keeps its axis orientated in the same direction.

This tilted position of the earth along with the earth's daily rotation and yearly revolution accounts for the distribution of solar radiation over the earth surface, the changing length of hours of day light and darkness and the changing of the seasons. *Fig. 7.1* schematically shows the effect of the earth's tilted axis at various times of the season and *Fig. 7.2* shows the position of the earth relative to the sun's rays at the time of the winter solstice and summer solstice.

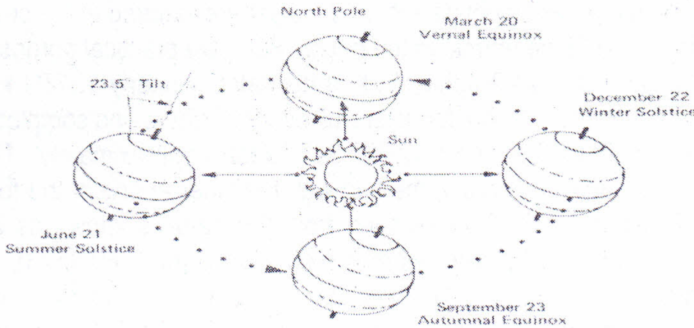



Fig. 7.1: Diagram of the Earth's orbit around the sun. From Solar Dwelling Design Concepts, HUD, Washington, D.C., 1976 (Source: Dickanson and Cheremisinoff, 1980)

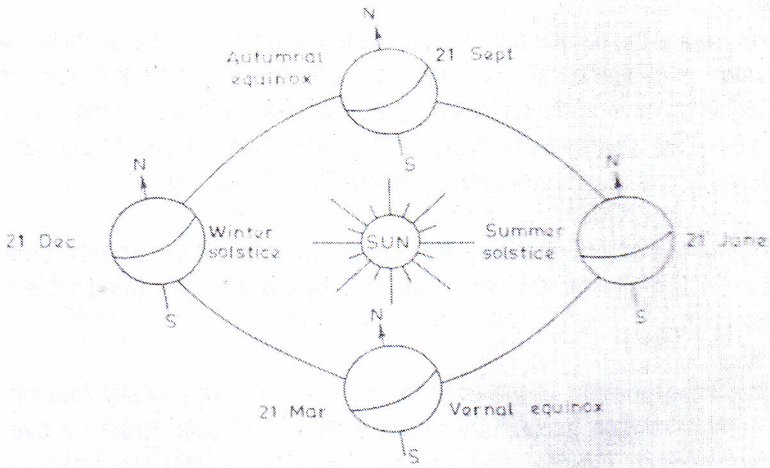



Fig.7.2: Positions of the earth with respect to the sun at solstices and equinoxes (Source: Dickanson and Cheremisinoff, 1980)

At the winter solstice (December 21), the North Pole is inclined 23.5° away from the sun. Thus, all points on the earth's surface north of 66.5° North latitude area in complete total darkness for 24 hours while all regions within 23.5° of the South Pole receive continuous sunlight.

At the time of the summer solstice (June 21), the situation is reversed. At the time of the two equinoxes (March 21 and Sept. 21) approximately, both poles are equidistant from the sun and all points on the earth's surface have 12 hours of daylight and 12 hours darkness.

The sun's motion in the sky due to the earth movement about the sun as seen by the observer at any given position is described in terms of two angles: solar zenith angle ($\theta$) measured from the vertical axis with the origin at the observers' position and (ii) solar Azimuth angle ($\alpha$) measured from a horizontal axis extending due south from the observer. The solar Azimuth angle is positive when measured east of south and negative when measured west of south.

## 7.1 SUN APPARENT MOTION

So far we have been discussing the actual motion of the earth with respect to the sun as the centre piece of the geometry. However, in order to design solar energy systems on earth, the earth must become the effective centre piece. Thus we will regard the Earth as stationary and speak of the "Sun's daily Path across the sky". For the Solar energy system design purpose, it is necessary to know the sun's position in the sky for any given day of the year and time of day. This knowledge is essential for designing either Active systems (for the location and orientation of the solar collector) or Passive systems, (orientation of the structure and placement of windows fixed glass and for estimating the shading effect of other buildings, trees, or nearby hills, etc.).

For an observer at a point along the equator will be able to note that: on June 21 (on the Northern hemisphere) the sun attains its most northerly track for its apparent passage around the earth.

The Sun rises earliest and sets latest on this day and the sun's path is higher on this day than any other day of the year. By September 21, a path moves back south again, and directed over the equator and both day and night are equal in length. By December 21, the sun's path is as far south as it will go and the sun is low in the sky all day and the sun rises late and sets early resulting in short days and long nights. Thus, if the Northern hemisphere of maximum solar radiations is desired on a fixed structure then the major axis should be given east–west orientation.

## 7.2 EFFECT OF THE EARTH'S ORBIT AROUND THE SUN

The earth revolves around the sun once a year in an elliptical orbit. The orbit is nearly circular, the earth sun distance varying by about 3% from a mean distance of 150 x $10^6$ km.

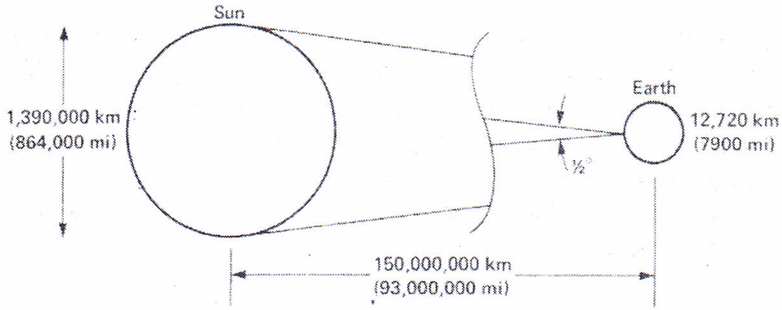



**Fig. 7.3: Distances and sizes of the sun and the Earth (Source: Garg, 1982)**

*Fig. 7.3* shows the relative dimension of the earth and sun. The earth is closest to the sun in the winter and farthest away in summer. This variation in distance produces a nearly sinusoidal variation in the intensity of the solar radiation (I) that reaches the earth as shown in *Fig. 7.4.*

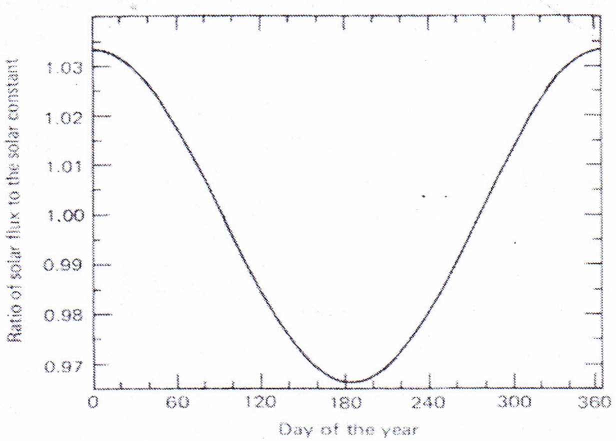



**Fig. 7.4: Yearly variation in the ration of solar flux above the earth to the solar constant This is caused by the variation of the distance between the earth and the sun (Source: Garg, 1982)**

This can be approximated by the equation (Dickanson and Cheremisinoff, 1980):

$$\frac{I}{I_{sc}} = 1 + 0.033\cos\frac{360(D-2)}{365} \quad (7.2)$$

Where $I_s$ is the solar constant, $D$ is the day of the year.

**Table 7.1: The conversion from day to day of the year**

| Day of Mo. | Month | | | | | | | | | | | | Day of Mo. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | |
| 1 | 1 | 32 | 60 | 91 | 121 | 152 | 182 | 213 | 244 | 274 | 305 | 335 | 1 |
| 2 | 2 | 33 | 61 | 92 | 122 | 153 | 183 | 214 | 245 | 275 | 306 | 336 | 2 |
| 3 | 3 | 34 | 62 | 93 | 123 | 154 | 184 | 215 | 246 | 276 | 307 | 337 | 3 |
| 4 | 4 | 35 | 63 | 94 | 124 | 155 | 185 | 216 | 247 | 277 | 308 | 338 | 4 |
| 5 | 5 | 36 | 64 | 95 | 125 | 156 | 186 | 217 | 248 | 278 | 309 | 339 | 5 |
| 6 | 6 | 37 | 65 | 96 | 126 | 157 | 187 | 218 | 249 | 279 | 310 | 340 | 6 |
| 7 | 7 | 38 | 66 | 97 | 127 | 158 | 188 | 219 | 250 | 280 | 311 | 341 | 7 |
| 8 | 8 | 39 | 67 | 98 | 128 | 159 | 189 | 220 | 251 | 281 | 312 | 342 | 8 |
| 9 | 9 | 40 | 68 | 99 | 129 | 160 | 190 | 221 | 252 | 282 | 313 | 343 | 9 |
| 10 | 10 | 41 | 69 | 100 | 130 | 161 | 191 | 222 | 253 | 283 | 314 | 344 | 10 |
| 11 | 11 | 42 | 70 | 101 | 131 | 162 | 192 | 223 | 254 | 284 | 315 | 345 | 11 |
| 12 | 12 | 43 | 71 | 102 | 132 | 163 | 193 | 224 | 255 | 285 | 316 | 346 | 12 |
| 13 | 13 | 44 | 72 | 103 | 133 | 164 | 194 | 225 | 256 | 286 | 317 | 347 | 13 |
| 14 | 14 | 45 | 73 | 104 | 134 | 165 | 195 | 226 | 257 | 287 | 318 | 248 | 14 |
| 15 | 15 | 46 | 74 | 105 | 135 | 166 | 196 | 227 | 258 | 288 | 319 | 349 | 15 |
| 16 | 16 | 47 | 75 | 106 | 136 | 167 | 197 | 228 | 259 | 289 | 320 | 350 | 16 |
| 17 | 17 | 48 | 76 | 107 | 137 | 168 | 198 | 229 | 260 | 290 | 321 | 351 | 17 |
| 18 | 18 | 49 | 77 | 108 | 138 | 169 | 199 | 230 | 261 | 291 | 322 | 352 | 18 |
| 19 | 19 | 50 | 78 | 109 | 139 | 170 | 200 | 231 | 262 | 292 | 323 | 353 | 19 |
| 20 | 20 | 51 | 79 | 110 | 140 | 171 | 201 | 232 | 263 | 293 | 324 | 354 | 20 |
| 21 | 21 | 52 | 80 | 111 | 141 | 172 | 202 | 233 | 264 | 294 | 325 | 355 | 21 |
| 22 | 22 | 53 | 81 | 112 | 142 | 173 | 203 | 234 | 265 | 295 | 326 | 356 | 22 |
| 23 | 23 | 54 | 82 | 113 | 143 | 174 | 204 | 235 | 266 | 296 | 327 | 357 | 23 |
| 24 | 24 | 55 | 83 | 114 | 144 | 175 | 205 | 236 | 267 | 297 | 328 | 358 | 24 |
| 25 | 25 | 56 | 84 | 115 | 145 | 176 | 206 | 237 | 268 | 298 | 329 | 359 | 25 |
| 26 | 26 | 57 | 85 | 116 | 146 | 177 | 207 | 238 | 269 | 299 | 330 | 360 | 26 |
| 27 | 27 | 58 | 86 | 117 | 147 | 178 | 208 | 239 | 270 | 300 | 331 | 361 | 27 |
| 28 | 28 | 59 | 87 | 118 | 148 | 179 | 209 | 240 | 271 | 301 | 332 | 362 | 28 |
| 29 | 29 | a | 88 | 119 | 149 | 180 | 210 | 241 | 272 | 302 | 333 | 363 | 29 |
| 30 | 30 | | 89 | 120 | 150 | 181 | 211 | 242 | 273 | 303 | 334 | 364 | 30 |
| 31 | 31 | | 90 | | 151 | | 212 | 243 | | 304 | | 365 | 31 |

[a] For dates after February 28 in leap years, add 1 to all numbers.

The rotational axis of the earth is inclined at 23.44° to the axis of the orbital plane as shown in *Fig. 7.1*.

The direction of the axis of daily rotation of the earth is essentially fixed in space. This causes a different tilt or declination δ of the axis relative to the sun and earth line for the different seasons of the year. In winter, the earth is tilted with the northern hemisphere away from the sun and a one-half year later in summer, the northern hemisphere is tilted towards the sun. The time of minimum and maximum declinations are known as the 'winter' and 'summer' solstices respectively. In between the winter and summer, the declination swings through zero and these times are known as the vernal and autumnal equinoxes.

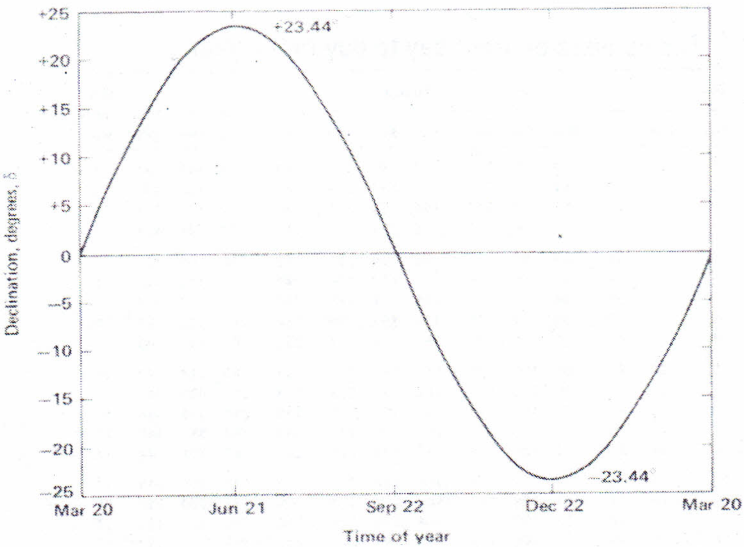



**Fig. 7.5: Yearly variation of the solar declination (Source: Dickanson and Cheremisinoff, 1980)**

Fig. 7.5 shows the declination with the time of year. Since the earth's orbit is nearly circular, this curve can be approximated by the sine function.

$$\delta = 23.45 sin \frac{360(D-81)}{365} \tag{7.3}$$

The point the sun is directly overhead at noon moves from one hemisphere to the other with the seasons. The sun is directly over the equator at the equinoxes over latitude 23.45°. For Lagos at latitude 6.5°N, the daylength varies from 11.6 to 13.35 (Chendo, 1980).

The variation in the length of the day is caused by the change in declination angle over the year and the latitude. The variation can be seen in *Fig. 7.6.*

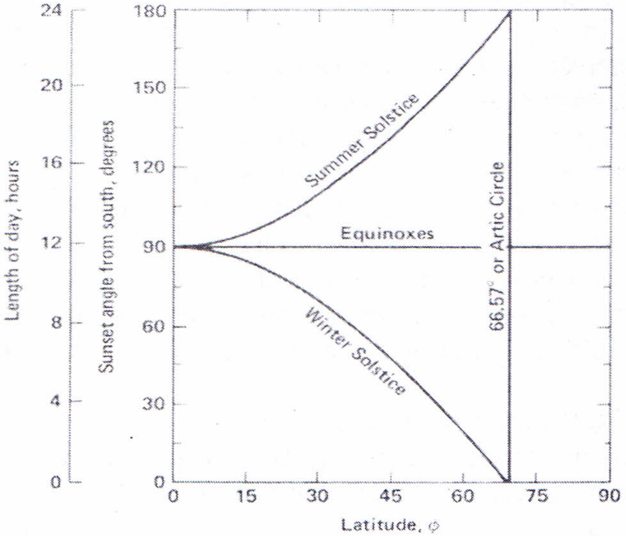



**Fig. 7.6: Variation of length of day with season and latitude in northern hemisphere. (Source: (Dickanson and Cheremisinoff, 1980)**

As the observer goes higher in latitude, the bulk of the earth blocks out more and more of the sun when it is low in the sky. At the winter solstice, the latitude where the sun just comes up to the horizon (is tangent to the surface) is 66.560 and is called the Arctic Circle. Similarly, the equivalent latitude in the southern hemisphere is called the Antarctic Circle. When the Artic is in constant darkness, the sun is shining continuously in the Antarctic and vice-versa.

## 7.3 SOLAR TIME AND CLOCK TIME

In Solar energy problems it is always desirable to convert clock time into solar time. Solar time is measured with respect to solar noon which is the time when the sun is crossing the observers' meridian. The difference between two of such consecutive solar noons, defines a solar day. Thus solar time is not the same as clock time for a variety of reasons. Clock time is the same for all locations in the same standard time zone.

Each time zone occupies 15° of longitude, the Meridian of longitude that runs through the middle of each standard time zone is called the "Standard Time Meridian". When the sun is directly overhead at a standard time meridian, local solar time and standard time are very nearly the same. At all other times and places across the zone, local time and standard time differ from local standard time by four minutes of time per degree of longitude east or west of the standard meridian time for that zone. In other words, solar noon occurs four minutes earlier than standard time noon. To overcome this difficulty, a fictitious sun so-called "mean sun" is defined which transmits the observers' meridian at a fixed interval of time every 24 hours. Two successive transits of this mean sun across the same meridian define one mean solar day. Time kept by our clock is the mean time differences between the mean time clock and the solar time called the equation of time. Thus equation of time = solar time - clock time.

Converting clock time to Local Solar time is the time specified in all of the sun angle relationships. It does not coincide with local clock time. It is therefore necessary to convert standard time to solar time by applying two corrections:

(i) Constant correction for the differences between the observers' Meridian location and the meridian on which local standard time is based.

(ii) The Equation of time which takes into account the perturbations in the earth's rate of rotation which affect the time the sun crosses the observers' meridian.

Thus solar time is related to standard local time by:

$$\text{Solar Time} = \text{STD LOCAL Time} + 4\,(L_{st} \pm L_{loc}) = E \qquad (7.4)$$

*Where:*

$L_{st}$ = *Standard Meridian for the local time zone.*

$L_{loc}$ = *longitude of the location in degrees west or east*

$E = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B$

= *Equation of time.*

$$B = \frac{360(n-81)}{364}$$

The factor 4 is the minutes of elapsed time for 1° of each rotation.

The approximate values of the equation of time and also of the solar declination may be obtained from a graph called the Analemma (*Fig. 7.7*).

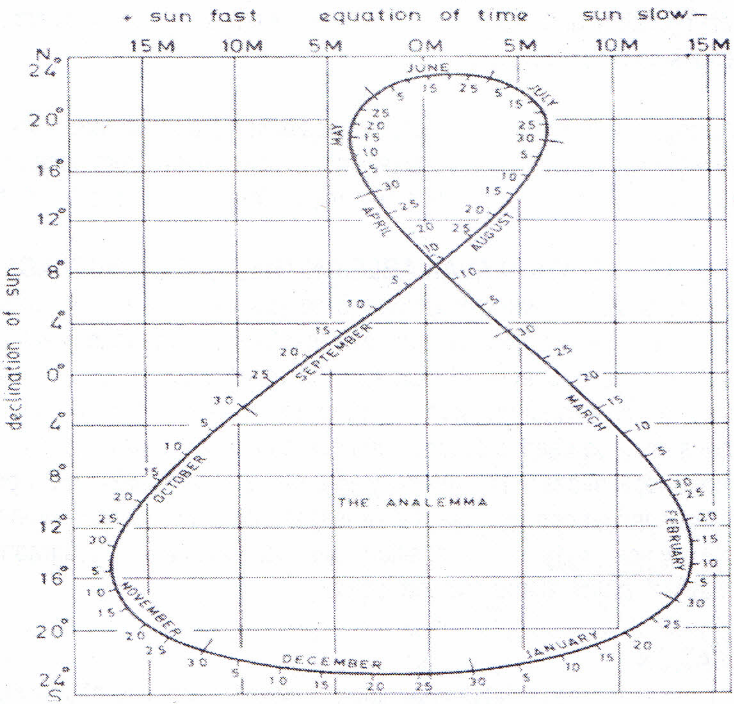



**Fig. 7.7: The Analemma (Source: Garg, 1982).**

## 8.0 DEPLETION OF SOLAR RADIATION BY THE ATMOSPHERE

The earth is surrounded by an atmosphere which contains various gaseous constituents, suspended dust and other minute solid and liquid particulate matter and clouds of various types. Therefore, the solar radiation is depleted during its passage through the atmosphere before reaching the earth's surface. If the atmosphere is very clear, the depletion in the solar radiation occurs simultaneously by three distinct physical processes: (i) selective absorption by water vapour, molecular oxygen, ozone and carbon (iv) dioxide in certain wavelengths; (ii) Raleigh scattering by molecules of different gases and dust particles that constitute the atmosphere; and (iii) Mie Scattering: Scattering of radiation by air molecules or gaseous particles where their sizes are very small compared to the theory of Rayleigh which indicates that the scattering coefficient would vary approximately as $x^{-4}$ where x is the wavelength of the radiation.

Roughly one half of the scattered radiation is lost to space and the remaining half is directed downwards to the earth's surface from different directions as diffuse radiation.

Scattering of radiation due to dust particles which are much larger than air molecules and which vary in size and concentration from location to location according to height and from time to time is difficult to compute.

## 8.1 SOLAR RADIATION AVAILABLE ON THE EARTH'S SURFACE

There are two basic ways in which the geographical distribution of solar radiation may be studied. One of this involves the measurement by a network of closely spaced station and the other is based on the use of physical formula and constants. In practice, a combination of both methods must be used in order to achieve an accuracy which is sufficient for most applications. The intensity of solar radiation falling on a plane receiver is influenced to a greater or lesser extent by a large number of effects which may be classified as: astronomical, geographical, geometrical, physical and meteorological.

### RADIATION

Direct and scattered radiation reaching the earth's surface is influenced by:

#### Astronomical

(i) The Solar spectrum between 0.3um and 0.54um and the magnitude of the solar constant.
(ii) Variation with the Earth–sun distance.
(iii) Variation with the solar declination.
(iv) Variation with the time angles.

#### Geographical

(i) Variation with Latitude of the location.
(ii) Variation with the Longitude of the location.
(iii) Dependence on the height above sea level (preferably expressed in terms of the mean pressure).

**Geometrical**

(i) Dependence on the altitude of the sun.
(ii) Dependence on the Azimuth of the sun.
(iii) The effect of the Tilt angle of the receiving surface relative to the Horizontal.
(iv) Variation of the Azimuth of the tilted plane.

**Physical**

(i) Extinction by pure atmosphere (Rayleigh scattering).
(ii) Water content of the atmosphere expressed in centimetres of perceptible water.
(iii) Turbidity coefficient.
(iv) The ozone layer of the atmosphere expressed in cm at NTP.

**Meteorological**

(i) Effect of the cloudiness of the sky.
(ii) Effect of the Albedo of the ground.

## 8.2 SOLAR ENERGY AVAILABILITY

The successful application of solar energy technology for utilisation at a particular location requires the knowledge of the availability of solar energy and climatic condition at the proposed site. Such information can be obtained from direct measurements of solar irradiance or by estimation using the appropriate solar radiation models. Solar radiation data are used in several forms and for a variety of purposes.

The most detailed information available are global or total beam and diffuse solar radiation on a horizontal surface by hours which is useful in the simulation of solar processes. Daily data are often available and hourly radiation can be estimated from daily data, monthly total solar radiation on a horizontal surface can be used in some process design methods. However, as process performance is generally not linear with solar radiation, the use of averages may lead to serious errors of nonlinearities which are not taken into account. It is also possible to reduce radiation data to more manageable forms by statistical methods (*Fig. 8.1*).

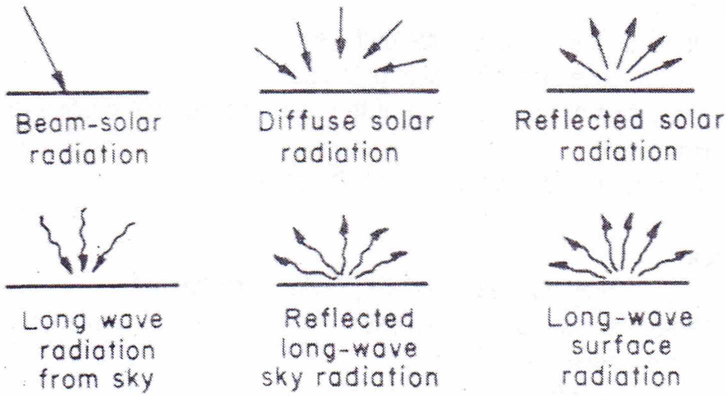



**Fig. 8.1: The radiant energy fluxes of importance in solar thermal processes. Shortwave solar radiation is shown by ↘. Longwave radiation is shown by ∿**
**(Source: Duffie and Beckman, 1991). [Shows the primary radiation fluxes on a surface at or near the ground that are important in connection with solar thermal process]**

The extraterrestrial solar radiation is entirely direct radiation. As it passes through the earth's atmosphere, it undergoes a complex interaction with the various components of the atmosphere. The major factors are scattering from the molecules and dust particles as well as absorption by the atmosphere and refraction. A significant fraction of the radiation which reaches the surface of the earth is reflected and encounters a similar set of interactions and the remainder is absorbed by the surface of the earth as shown schematically in *Fig. 8.2.*

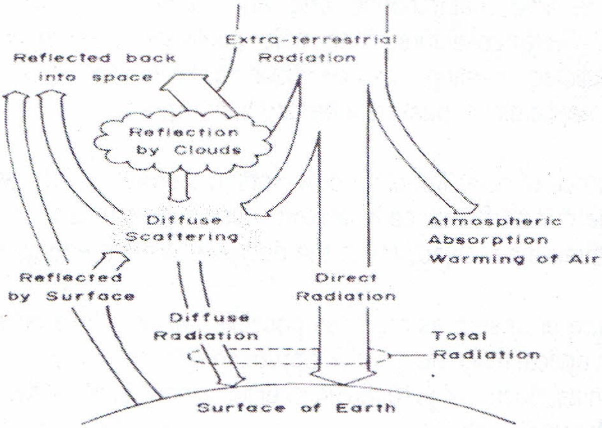



**Fig. 8.2: Direct, diffuse and total solar radiation (Source: Dickinson and Cheremisinoff, 1980)**

## 9.0 SOLAR ENERGY UTILISATION (SOLAR COLLECTORS)

A solar collector is a special kind of heat exchanger that transforms solar radiant energy into heat. A solar collector differs in several respects from the more conventional heat exchangers. The latter is usually accomplished as fluid-to-fluid exchange with high heat transfer rates and with radiation as an unimportant factor. In the solar collector, energy transfer is from a distant source of radiant energy to a fluid which in turn delivers the energy to a storage system or directly to the ultimate use (load).

In the evaluation of a solar thermal collector, the determination of the collector's thermal performance is the primary objective. However, a complete evaluation should include considerations of cost and durability or expected useful life (life cycle analysis). Thus, the analysis of solar collectors presents unique problems of low and variable energy fluxes and the relatively large importance of radiation. There are two main kinds of solar collectors namely Flat-plates and Concentrators. Flat-plate collectors can be designed for applications requiring energy delivery at moderate temperatures up to perhaps 100 °C above the ambient temperature. They use both beam and diffuse solar radiation, and do not require a solar tracker.

They require little maintenance and are mechanically simpler than concentrating solar collectors. Their major applications are in solar water heating, building heating, air conditioning, industrial process heat agricultural applications, passively heated building, etc.

The importance of solar flat-plate collectors in thermal processes is such that their thermal performance is treated in considerable detail.
There are three main objectives in the design of a solar energy collector, which are:

(i) capture or absorb as much as possible, the available solar energy (high optical efficiency) $(\tau\alpha)_{eff.}$ approaching unity;
(ii) retain as much of this received energy as possible (low thermal loss coefficients); and
(iii) transfer as much of this retained energy as possible into the coolant (high heat removal) factor $F_R$ close to unity.

## 9.1 DESCRIPTION OF SOLAR RFLAT-PLATE COLLECTION

The important parts of a typical fluid heating flat-plate collector are shown in *Fig. 9.1.*

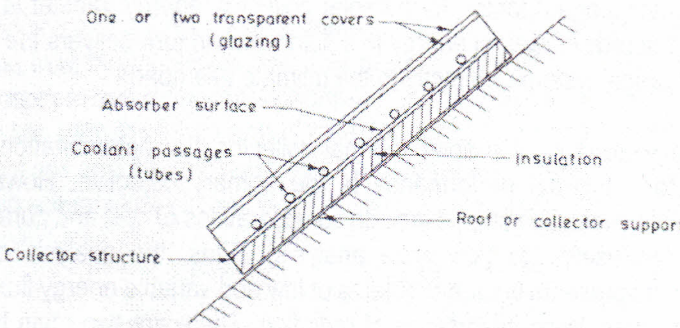



**Fig. 9.1: Schematic cross-section of a type of flat-plate solar collector illustrating the major functional parts**
**(Source: Garg, 1982)**

It consists of the 'black' solar energy absorbing surface with means for transferring the absorbed energy to a fluid, 'envelope' transparent to solar radiation over the solar absorber surface that reduce convection and radiation losses to the atmosphere and a back 'insulation' to reduce conduction losses. Flat-plate solar collectors are almost always mounted in a stationary position with an orientation optimised for the particular location in question for the time of the year in which solar device is intended to operate.

## 9.2 BASIC SOLAR FLATE-PLATE ENERGY BALANCE EQUATION

In steady state, the performance of a solar collector is described by an energy balance that indicates the distribution of incident solar energy into useful energy gain, thermal losses and optical losses.

The solar radiation absorbed by a collector per unit area of an absorber S is equal to the difference between the incident solar radiation and optical losses, which is given by:

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \frac{(1+\cos\beta)}{2} + \rho_g (I_b + I_d)(\tau\alpha)_g \frac{(1-\cos\beta)}{2} \qquad (9.1)$$

Where, $\frac{(1+\cos\beta)}{2}$ and $\frac{(1-\cos\beta)}{2}$ are the view factors from the collector to the sky and the collector to the ground respectively.

The subscripts b, d and g represent beam, diffuse and ground.

$\rho$ is the reflectance.

**β** is the slope of the surface.

$R_b$ is the ratio of average beam radiation on the titled surface to that on the horizontal surface for the month.

The thermal energy lost from the collector to the surroundings by conduction, convection and infrared radiation can be represented as the product of heat transfer coefficient $U_L$ times the difference between the mean absorber plate temperature $T_{pm}$ and the ambient temperature $T_a$.
In a steady state, the useful energy output of a collector of area Ac is the difference between the absorbed solar radiation and the thermal loss:

$$Q_u = A_c[S - U_L(T_{pm} - T_a)] \qquad (9.2)$$

The problem with the above equation is that the mean absorber plate temperature is difficult to calculate or measure since it's a function of the collector design, the incident solar radiation and the fluid condition at the inlet.

A measure of collector performance is the collection efficiency ($\zeta$) defined as the ratio of the useful gain over some specified time period for the incident solar energy over the same time period, i.e.,

$$\zeta = \frac{\int Q_u \, dt}{Ac \int G_T dt} \tag{9.3}$$

The design of a solar energy system is concerned with obtaining minimum cost energy. Thus, it may be desirable to design a collector with an efficiency lower than is technologically possible if the cost is significantly reduced. In any event, it is necessary to be able to predict the performance of a collector.

## 9.3 COLLECTOR HEAT REMOVAL FACTOR AND FLOW FACTOR

It is convenient to define a quantity that relates the actual useful energy gain of the collector to the useful gain if the whole collector surface were at the fluid inlet temperature. The quantity is called the collector heat removal factor ($F_R$).

The quantity $F_R$ is equivalent to the effectiveness of a conventional heat exchanger which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer. Thus, the maximum possible useful energy gain (heat transfer) in a solar collector occurs when the whole collector is at the inlet fluid temperature. Heat losses to the surroundings are then at the minimum. The product of collector heat removal factor and the maximum possible useful energy gain is equal to the actual useful energy gain $Q_u$.

$$Q_u = A_c F_R [S - U_L(T_i - T_a)] \tag{9.4}$$

Equation (9.4) is a convenient representation when analysing solar energy system since the inlet fluid temperature is usually known.

As the mass flow rate through the collector increases, the temperature rise through the collector decreases. This causes lower losses since the average collector temperature is lower and there is a corresponding increase in the useful energy gain. This increase is reflected by an increase in the collector heat removal factor $F_R$ as the mass flow rate increases.

## 9.4. CONCENTRATING COLLECTORS

For many applications, it is desirable to deliver energy at temperatures higher than those possible with the flat-plate collector. Energy delivery temperatures can be increased by decreasing the area from which heat losses occur. This is done by interposing an optical device between the source of radiation and the energy absorbing surface. The smaller absorber surface will have smaller heat losses compared to the flat-plate at the same absorber. They can be loosely classified in two ways- the geometry of the absorber (linear or point concentration) and the means of concentration (reflection and refraction).

Many designs have been set forth for concentrating collectors. The point focus systems require tracking of the sun during the day in two coordinates while the line focus systems require tracking only in one coordinate. The choice of tracking mode is an important element in the choice of optical design to yield maximum output for the greatest simplification over a fully tracking system. The principal point focus system for solar collector is the parabolic mirror whose schematic is shown in *Fig. 9.2,* while that for a linear focus is shown in *Fig. 9.3.*

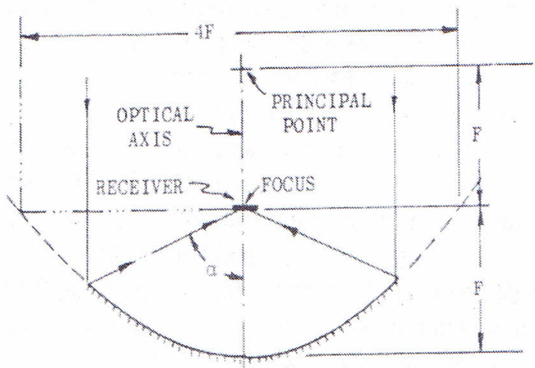



**Fig. 9.2: Basic geometry of a paraboloid. The rays marked α are for a rim ray angle of 70°. The maximum aperture of a paraboloid is 4F for a plane receiver normal to the optical axis at the focus**
**(Source: Meinel and Meinel, 1976)**

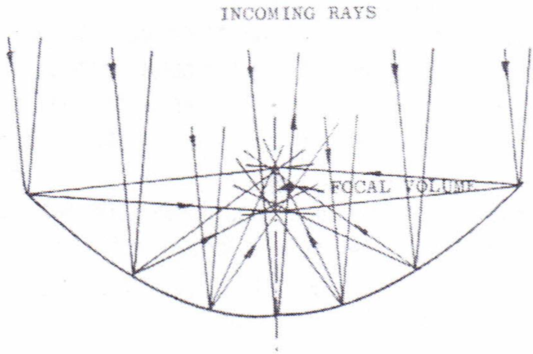



**Fig. 9.3: Diagram illustrating the formation of the focal ellipsoid for a source having a finite angular size**
**All solar optical configurations where the distance from the mirror to the absorber varies result in a similar focal volume.**
**(Source: Meinel and Meinel, 1976)**

## 9.5 THE CENTRAL RECEIVER

The concept of the central receiver is mainly to avoid heat loss when transporting a working fluid to a central location, we use sunlight itself as the transfer medium. This normally involves using a field of mirrors provided with the means of directing reflected sunlight to a central location or a location at one edge of the field of mirrors.

In the typical central receiver, the mirror is composed of many smaller mirrors each with its own heliostat to follow the sun. The heliostats are generally located in the horizontal plane. The basic difference between a single mirror concentrator and the heliostat system is that the heliostat system has a dilute mirror. This means that the entire surface of the system is not covered with the mirror surface. This diluteness is generally termed the 'fill factor'. A central receiver with a fill factor of 40% means that 40% of the land area is covered by mirrors. A schematic arrangement is shown in *Fig. 9.4*.

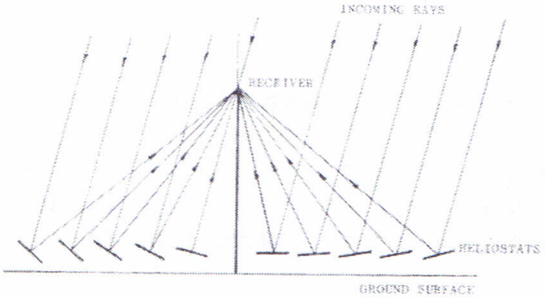



**Fig. 9.4: Schematic arrangement of a central receiver – heliostat array, producing the optical effect of a dilute paraboloidal mirror Note in this case that the fill factor is large and the heliostat mirrors obscure adjacent heliostats.**
**(Source: Sayigh, 1977)**

A central receiver optical system where many small mirrors are separately mounted to act together like a dilute paraboloid. They are mainly desired for solar power program.

## 10.0 PHOTOQUANTUM SOLAR ENERGY CONVERSION (PHOTOVOLTAIC SYSTEMS)

Photovoltaic (PV) is the direct conversion of sunlight to electricity with no moving parts. The development of Photoquantum solar energy can be traced to the year 1839 when Becquerel discovered that photovoltage resulted from the action of sunlight on an electrode in an electrolyte solution. Similar effects were also observed by Adams and Day in 1877 in the solid material, Selenium. Subsequent work on photovoltaic effects in Selenium and cuprous oxide, led to the development of the Selenium photovoltaic cell which has been widely used for many years in photographic exposure meters.

The modern era for photovoltaic began in 1954 when Chapin *et al.* (1954), reported a solar conversion efficiency of 6% for a silicon single crystal cell (Fahrenbruch and Bube, 1983).

The first application of photovoltaic was to supply the power requirements for the United States Satellite Vanguard 1 in 1958. During the 1960's, PV systems quickly established their dominance over all other space power systems for providing highly reliable and economic power systems for satellites.

In the 1970s, articles began appearing on evaluating PV for Terrestrial applications. In October 1973, propelled by the World energy crisis, a workshop was organised by the United States National Science Foundation to assess the potential of PV systems for terrestrial applications and to establish goals for both technology and costs (Backus, 1981).

The three most important factors inherent in solar cells that govern their widespread application in electricity production are: (i) cost; (ii) efficiency; and (iii) stability.

In the terrestrial application area, silicon solar cell panels have been deployed extensively and have shown stable, reliable and predictable performance. The only reason that they have not been extensively used terrestrially is because of their relatively high initial cost when compared with other conventional power sources.

## 10.1 PHOTOVOLTAIC (PV) ENERGY SYSTEM

Solar electricity performs no function until it is integrated into a system that matches the power supply with its load. Then, to size a PV generator to meet a particular electricity demand, we must first know the energy requirement and electrical characteristics of the load. There are a variety of electric power conditioning devices that usually must be added to a PV array to convert the solar energy to a form that can readily be used by a load.

Many energy applications require electricity during the nighttime or on cloudy days and a PV array is unable to provide this. Common principles often require that the electricity be alternating current (AC) while a PV cell only produces direct current (DC). Electric loads usually, can operate only with a relatively constant voltage power supply while a PV array voltage can fluctuate quite radically depending on the amount of sunlight and the size of the load. The PV array produces maximum power only when it is operating at its maximum power voltage. A load will often force the array to operate at a voltage that is less or more than its optimum. The application of a PV power source to meet a power demand may require using power conditioning equipment to address one or more of these three considerations: energy storage, voltage regulation and DC to AC conversion.

Solar electricity (PV) has the following inherent potentials compared to other sources of electricity supply:

(i) It is the best and least expensive power option today in the small power range up to a few kilowatts. It is suitable for all climates and have been installed in all regions of the world.

(ii) It is modular in nature, with low maintenance costs. Its long-term energy potential is enormous almost everywhere on earth. A typical house roof covered in solar cells captures enough solar energy to completely supply its electricity load provided that enough storage is installed.

(iii) Unlike the wind and solar thermal power, it does not necessarily require grid connection. The ground on which PV grows today, is the market of decentralised electricity.

(iv) The growing worldwide population and subsequent demand for electrical energy will be accompanied by a geographical shift since the envisaged largest growth rate will be in developing countries.

(v) PV makes use of semiconductors and from the view point of materials and processing technology, it is related to the microelectronics industry and vice-versa. By supporting PV research, one can invest in a fast growing microelectronic industry at the same time.

## 10.2 PV POWER SYSTEM TYPES

Terrestrial photovoltaic systems can be categorised into three basic application types as shown in *Fig.10.1* (Chendo 2000).

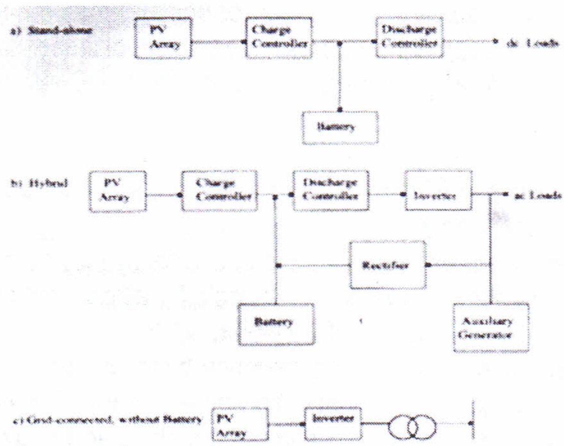


Fig. 10.1: Different types of PV systems (Chendo, 2000)

## 10.3 PHOTOVOLTAIC (PV) PLANT

The wide spectrum of semiconductor related technologies encompass the field of photovoltaic. All manufacturing processes are derived from and enjoyed the latest advances in microelectronics. From this point of view, PV converters belong to the so-called high technology field and any improvement in that field contributes to the progress in semiconductor technology as a whole.

The silicon solar cell manufacturing process involves basically three stages:

(i) Material preparation and shaping.
(ii) Cell processing.
(iii) Cell interconnection and encapsulation.

The conventional technological process, the flow chart which is shown in *Fig. 10.2* relies conventionally on the high purity semiconductor grade silicon available from the electronics industry wastes.

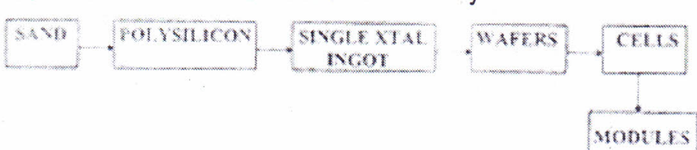



Fig.10.2: Flow chart of conventional technology (Chendo, 2000)

## 10.4 OPTIONS FOR ACQUISITION OF SOLAR PV TECHNOLOGY

Solar PV technology is undergoing continuous technological development mostly in the area of solar cell fabrication owing to efforts directed at reducing solar cell costs per peak watt and gaining greater economic competiveness as a decentralised energy source.

The condition for the acquisition of PV technology in the country depends largely on some important relevant criteria such as capital and human resources, availability of industry, infrastructure and educational environment (Chendo, 1992; 2000).

PV manufacture involves basically the following six components:

(i) Silicon material. Electronic grade or solar grade.
(ii) Other raw materials.
(iii) Solar PV cells.
(iv) PV modules.
(v) Balance of systems components and sub systems.
(vi) Design and integration of effective PV systems.

*Fig.10.3* shows the various components of PV manufacturing technology starting from the production of pure silicon material on any other suitable material to the finished PV models and balance of systems (Chendo, 2000).

The level of technical sophistication of the various stages of production is also indicated in *Fig. 10.3*. Thus, Nigeria can enter into PV manufacturing technology at any of the stages of production depending on the available industrial infrastructure and technical expertise available in the country.

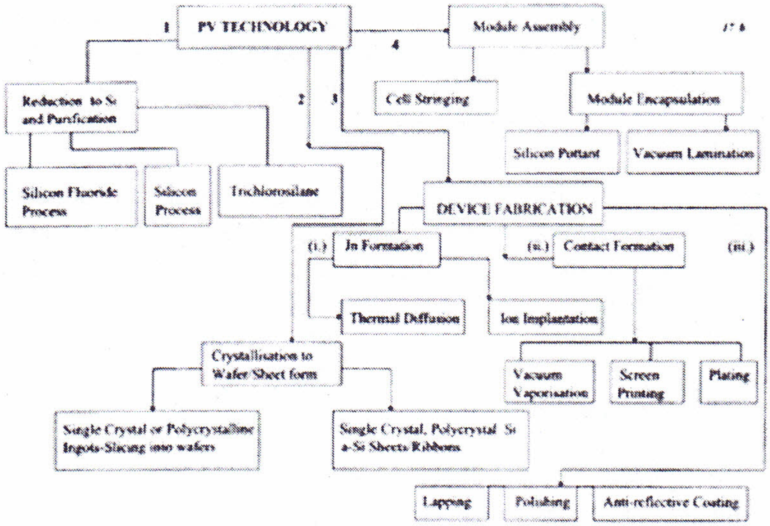



**Fig.10.3: Different stages of PV manufacturing technology (Chendo, 2000) adapted from Lashier and Ang, 1990)**

## 10.5 OTHER RAW MATERIALS

(i) Various chemicals such as acids, alkalis, organic solvent and diffusant.
(ii) Conductive parts made of silver and aluminum.
(iii) High transmission tempered "white" glass sheets.
(iv) Various laminating materials such as Eva and Teller.
(v) Various mechanical and electrical components such as junction boxes and interconnections.

Except for the laminating materials which are produced only by a few companies in the world, many of the third world countries like Nigeria have the necessary infrastructure and expertise to produce the above raw materials (Lashier and Ang, 1990).

## 11.0 RESEARCH CONTRIBUTIONS IN SOLAR ENERGY PHYSICS

Mr. Vice–Chancellor sir, having gone through some of the rudiments on how the power of the sun has impacted on the existence of humanity in our planet Earth, permit me to discuss some of my interactions with the sun for the past four decades. I will like to present my research contributions in seven segments:

(1) Solar Radiation.
(2) Solar Still and Transfer Functions.
(3) Photothermal/Photoquantum Solar Energy Conversion/Solar Beam Splitting Technique.
(4) Thin Film Solar Cell.
(5) Biomass/Biodiesel/Biogas.
(6) Environment and Climate Change.
(7) Biofuels and Algae.

**Solar Radiation Models**

Information on the development of solar energy technology in Nigeria dates back to 1960/61 when late Orji Okereke participated in the UN conference on new source of energy in Rome. In 1962 Okereke tried to draw a rough solar radiation map of the country by setting up solar radiation measuring instruments at the Federal Institute of Industrial Research (FIIRO), Oshodi. Thus, with no documented information on the available solar radiation intensity for Lagos, we began solar radiation monitoring in Lagos with a pyranometer loaned to us by the then Head of Department of Geography, late Prof. O.O. Ojo in 1978/79 which was later complimented with other state-of- the-art solar radiation measuring devices bought by the Department of Physics.

Thus by 1979, we began measuring hourly instantaneous global solar radiations for Lagos. Our results were published in the Nigeria Journal of Solar Energy (Chendo and Schmitter, 1982). In 1986, I worked on the Solar Spectrum splitting for solar energy application (Chendo, 1987). More detailed work on solar spectral profile and radiation model were embarked upon with my first Ph.D. student which resulted in the following publications (Chendo and Madueke, 1989; 1990; 1991; 1992; 1993a; 1993b; 1994a; 1994b; 1995; 1997; 1997a; 1997b), Obot and Chendo (2010); Erusiafe and Chendo, (2011); Erusiafe, et al. (2013), Erusiafe and Chendo, (2014).

Some of the models developed include:

i. $$Q/_{H_o} = a + b\left(H/_{H_o}\right) + c(n/_N) + d(n/_N)^2 \qquad 11.1$$

ii. $\frac{Q}{H} = a + b\left(H/H_o\right) + c\left(\frac{n}{N}\right) + d\left(\frac{n}{N}\right)^2$ 11.2

iii. $I_d/I = 1.526 - 1.448k_t - 0.1679\sinh + 0.06704\beta$ 11.3

iv. $I_d/I = 1.093 - 0.115k_t - 0.00134\sin(\alpha) - 0.001779Ta + 0.03714\Phi$ 11.4

**Solar Distillation/Desalination and Transfer Functions**

The conversion of saline or contaminated water to fresh water and distilled water through the use of solar radiation has been proven feasible especially where naturally available fresh water supplies are either inadequate or nonexistent. We constructed Solar Still which was operational for over two years. My supervisor and I developed a new technique, (modified) Optical Transfer function (OTF) and Modulated Transfer function (MTF) with which to predict its performance as shown in *Fig. 11.1.* (Schmitter and Chendo, 1980a ;1980b; Schmitter and Chendo 1983; Chendo and Egariewe, 1991; Chendo *et al.,* 1998; Salt recovery plant; Chendo and Okonkwo, 2008).

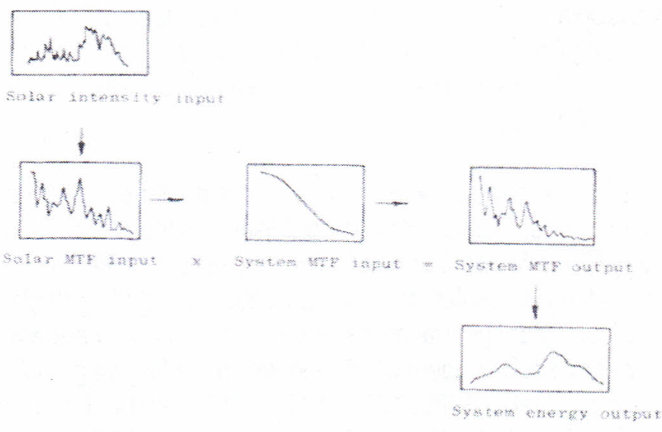



**Fig.11.1: Schematic diagram of the sequence of operations to go from the solar input to a given system output**

**Note that input and output change from the real amplitude/time domain to the Fourier amplitude/frequency domain for the application of the modulation transfer function operation (Schmitter and Chendo, 1982).**

The above flux can be represented by the equations:

$$I_d(t) = \left[\sum_i^{\infty} (A_n \cos\left(\frac{n\pi t}{\tau}\right) + B_n \sin(\frac{n\pi t}{\tau})\right] + \frac{A_o}{2}$$

Where:
$A_n$ and $B_n$ are the Fourier sine and cosine coefficient; and τ is the period.

The coefficients are determined from the input flux by using the Fourier sine and cosine integrals:

$$A_n = \frac{1}{\tau} \int_{-\tau}^{\tau} I_d(t) \cos(\frac{n\pi t}{\tau})\, d(t)$$

and

$$B_n = \frac{1}{\tau} \int_{-\tau}^{\tau} I_d(t) \sin(\frac{n\pi t}{\tau})\, d(t)$$

(Meinel and Meinel, 1976)

Solar disinfection of water and solar detoxification of hazardous organic waste using solar beam splitting technique are as shown in *figure 11.2.* (Chendo and Ugoji,1997; Chendo and Osborn,1988).

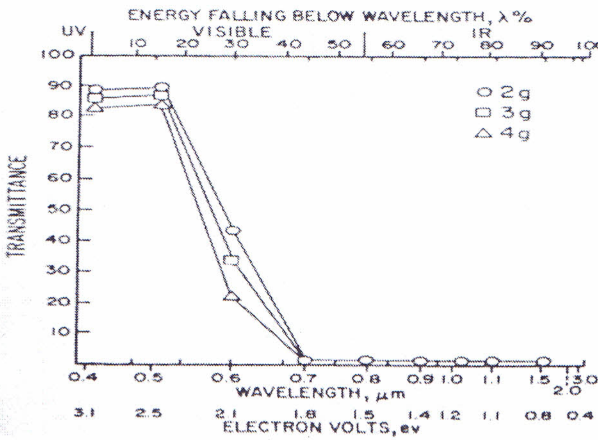



**Fig. 11.2: The effects of varied concentration on copper nitrate. Distorted-wavelength graph for solar irradiance at sea level (AMI). (Chendo, 1986)**

### Photothermal/Photoquantum

Solar cell efficiency decreases as the cell temperature rises due to phonon excitation in the cell (from excess energy photons) heating up the lattice. We developed ways to reduce this heating effect by either rejecting extraneous solar flux or removing heat rapidly from the cell. Thus, we came up with Solar Spectral Beam Splitting Technique (Chendo *et al.*, 1984; Chendo, 1984). In spectrum splitting, the solar spectrum is split into different energy components and the sunlight is directed to the cell that responds best to the light received. This concept was originally proposed by Meinel and Osborn in 1976. The SSBS filter directs by transmission or reflection section of the spectrum to different devices with the appropriate spectral response. An ideal response for a SSBS PV/PT system based on a silicon cell is shown in *Fig. 11.4,* where the vertical axis is either transmittance or absorptance. We developed one application technique of the SSBS concept by using absorption filters (Chendo *et al.*; 1985; Chendo *et al.*; 1986; 1987; Chendo, 1987a; 1987b; Chendo, 1988, Chendo and Salawu, 1988a; Chendo and Maduekwe, 1989; Chendo, 1992; Chendo and Ugoji 1994; Chendo, 1997; Erusiafe and Chendo, 2002; Chendo, 2002; Obot and Chendo, 2010; Chendo 1993; Chendo and Erusiafe, 2009). We also developed some potential heat transfer liquid for the photothermal/photovoltaic conversion. (Chendo, 1986; 1989; 1994) as shown in *Figure 11.3.*

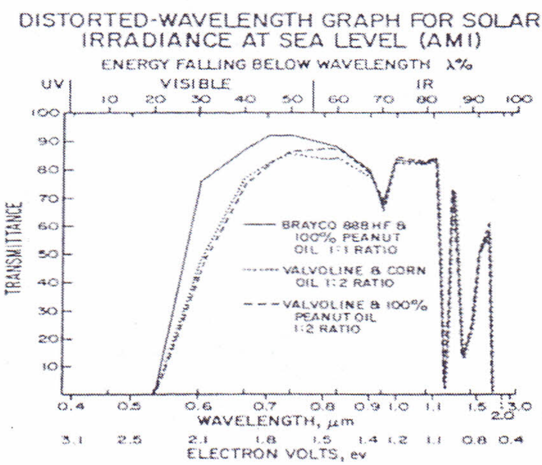
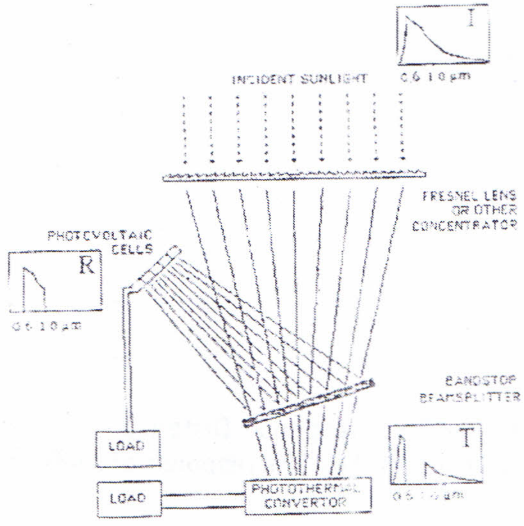



**Fig. 11.3: Transmission characteristics of Braycopea, Valvocorn, and Valvopea in 2-cm optical path. (Chendo, 1989)**




11.4 Basic design of hybrid solar energy conversion system with bandstop beamsplitter. Idealised case: R+T =I, A=O (Osborn and Chendo, 1985)

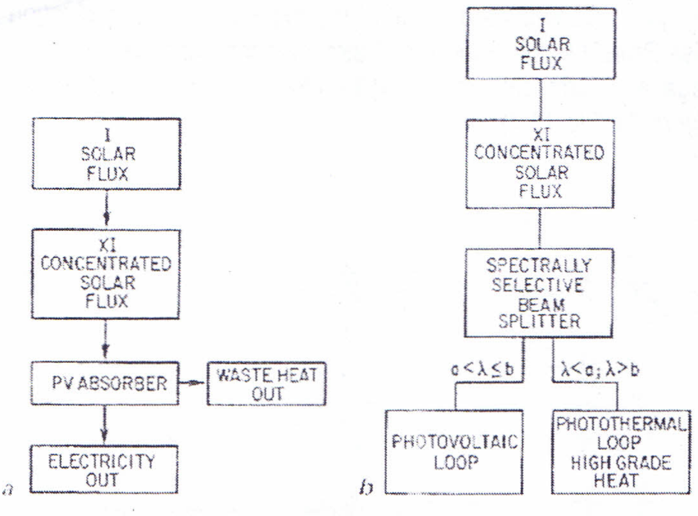



Fig 11: 5: (a)Conventional hybrid PV/PT system (b)SSBS solar hybrid concentrating system: a and b define the spectral windows of interest (Osborn and Chendo, 1985)

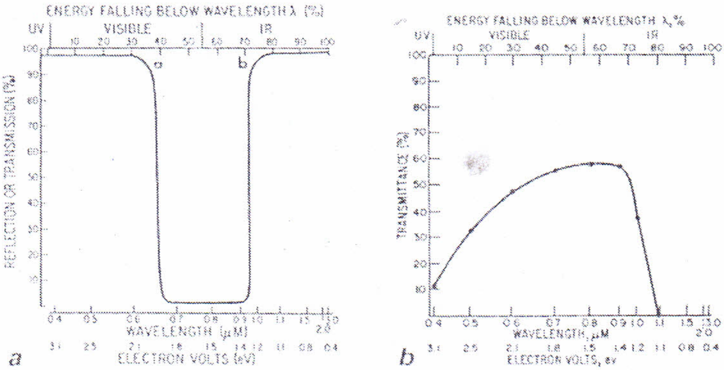



**Fig. 11.6: (a) Desired SSBS response. Distorted wavelength graph for solar irradiance at sea level (b) The response of a silicon cell**

## Biomass/Biodiesel/Biogas

In the pursuant of clean energy and sustainable environment, we worked on the conservation of our forest and the use of coal briquettes for more efficient burning and almost smokeless stoves for cooking. In addition, we also worked on Biogas production using human wastes for the production of cooking gas. This was as a result of my exposure and participation in the Besaisa Project in the Suburb of Cairo. Conceptual development of a solar village and farm settlements. (Chendo, 1987; Chendo and Ugoji, 1997) (*Figure 11.5 to 11.7*).

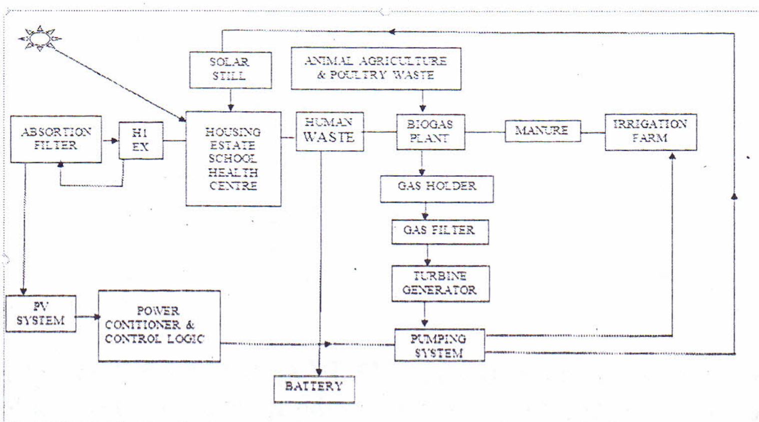



**Fig. 11.5: Schematic diagram for meeting the energy needs of a solar village (Chendo, 1987)**

working on Algae for Biofuel production using the Beam Splitting technique. I have produced two M.Sc. Students and currently one Ph.D. student who is awaiting Viva. We have developed an empirical model for algal growth optimisation etc. Alao and Chendo 2011; Humphrey, *et al.*, 2014a; 2014b; 2015, and Humphrey, *et al.*, 2017).

### THIN FILM SOLAR CELLS

The world's pursuit of greener environment, low cost, high conversion efficiency and long operating lifetime solar cells, as led to our working on thin film solar cells. The Nano thin film solar cells are the second generation solar cells that are made by depositing one or more thin layers of thin film of photovoltaics in the nanometer range on a substrate, such as glass, plastic or metal.

Currently, one of my Ph.D. students is exploring this research in the development of a third generation thin film solar cells. We have explored and developed new materials that are less toxic to the environment and their composition are from elements with high relative abundance. This area of research in the world of nanotechnology has led to results which have been presented and published in high impact journals (Adewoyin and Chendo, 2014; 2017; 2018).

### CLIMATE CHANGE & ENVIRONMENT

There are three major environmental problems arising from activities related to unabated conventional energy production, distribution and consumption. They include: Desertification/Deforestation, Pollution and Climate Changes. To ameliorate these effects, we worked on their mitigation by researching into various forms of Biofuel production using locally available products that will not impact negatively on food production such as palm tree, Jatropha, algae etc. I was also involved in the National Committee on the Environment and Climate change. (Chendo,1990; Chendo and Okoye, 2003; Chendo, 2006).

## 12.0 NATIONAL CONTRIBUTIONS

**I have been opportuned to serve nationally on various capacities as a:**

(1) Resource Person on New and Renewable Energy Source in the Federal Ministry of Science and Technology, United Nation

Committee Meeting on the Development and utilisation of Renewable Energy Source, New York, 28 March -8 April 1987.

(2) Guest Speaker, Federal Ministry of Science and Technology Monthly Technical Seminar, 30 June 1988, "Milestones in the development of Solar Energy in Nigeria and the hope it holds for National Development" Lagos.

(3) Ad hoc Committee Member, Establishment of National Advanced Laboratories (Energy) for Science and Technology Complex (SHESTCO) Abuja, Lagos. November 1988-January 1989.

(4) Renewable Energy Consultant. Directorate of Food, Roads and Rural Infrastructure (DFRRI). 1991 – 1994. (Chendo and Lodam, 1993).

(5) Council Member on the Implementation of Renewable and Alternative Energy Technologies in Nigeria, National Energy Centre, University of Nigeria, Nsukka, April 1992-2002.

(6) Photovoltaic Consultant to Sollatek Nig. Ltd. JAGAL, 1996-1998, where we installed the first solar street lights in Lagos State (1997).

(7) Member, Energy commission of Nigeria and National Youth Service Corps (NYSC) Rural Renewable Energy Project (Chendo, 1997).

(8) Member, Energy Commission of Nigeria on implementation of Photovoltaic project, 1999.

(9) Member, Federal Government of Nigeria to India on Science and Technology, 10-21 March 1999.

(10) Member, National Rural Development Committee, Federal Ministry of Agriculture and Rural Development, Abuja July 1999.

(11) Member, Federal Ministry of Science and Technology, Ministerial Committee on production of Photovoltaic solar cells, 2000.

(12) Member, National Committee on International Solar Energy Institute, representing Federal Ministry of Science and Technology, Abuja, 2000.

(13) Country Member group D8, Countries on Energy, 2014.

(14) Member, National Committee on Energy Policy. 2002-2005.

(15) Member, National Committee on Renewable Energy Master Plan, 2007-2008.

(16) Member, National Committee on Climate Change, 2007 -2009.

(17) Member, National Committee on SHEDA, Science and Technology complex (SHESTCO) Abuja, 2009-2010.

Committee Meeting on the Development and utilisation of Renewable Energy Source, New York, 28 March -8 April 1987.

(2) Guest Speaker, Federal Ministry of Science and Technology Monthly Technical Seminar, 30 June 1988, "Milestones in the development of Solar Energy in Nigeria and the hope it holds for National Development" Lagos.

(3) Ad hoc Committee Member, Establishment of National Advanced Laboratories (Energy) for Science and Technology Complex (SHESTCO) Abuja, Lagos. November 1988-January 1989.

(4) Renewable Energy Consultant. Directorate of Food, Roads and Rural Infrastructure (DFRRI). 1991 – 1994. (Chendo and Lodam, 1993).

(5) Council Member on the Implementation of Renewable and Alternative Energy Technologies in Nigeria, National Energy Centre, University of Nigeria, Nsukka, April 1992-2002.

(6) Photovoltaic Consultant to Sollatek Nig. Ltd. JAGAL, 1996-1998, where we installed the first solar street lights in Lagos State (1997).

(7) Member, Energy commission of Nigeria and National Youth Service Corps (NYSC) Rural Renewable Energy Project (Chendo, 1997).

(8) Member, Energy Commission of Nigeria on implementation of Photovoltaic project, 1999.

(9) Member, Federal Government of Nigeria to India on Science and Technology, 10-21 March 1999.

(10) Member, National Rural Development Committee, Federal Ministry of Agriculture and Rural Development, Abuja July 1999.

(11) Member, Federal Ministry of Science and Technology, Ministerial Committee on production of Photovoltaic solar cells, 2000.

(12) Member, National Committee on International Solar Energy Institute, representing Federal Ministry of Science and Technology, Abuja, 2000.

(13) Country Member group D8, Countries on Energy, 2014.

(14) Member, National Committee on Energy Policy. 2002-2005.

(15) Member, National Committee on Renewable Energy Master Plan, 2007-2008.

(16) Member, National Committee on Climate Change, 2007 -2009.

(17) Member, National Committee on SHEDA, Science and Technology complex (SHESTCO) Abuja, 2009-2010.

(18) Assigned by the Hon. Minister of Science and Technology to Survey and Study all the National Energy Centres in Nigeria to produce a blueprint for the commercialisation and utilisation of mass production of solar cooker and biogas plant.

(19) Solar detoxification of hazardous organic wastes (Chendo, 1988).

(20) Solar cathodic protection of buried petroleum pipe lines in areas where soil resistivity is of the order of 30,000.00 $\Omega$ $cm^4$ (Chendo, 1993; 2004).

## 13.0 CONCLUSION AND RECOMMENDATIONS

Mr. Vice-Chancellor sir, in this lecture I have tried to highlight some of my humble efforts towards how the adoption and embrace of the Sun's energy can through research development diffusion and implementation (RDDI), help sustain humanity and ensure a benign environment. The country has made strenuous and remarkable efforts in the past to adopt this into our energy mix but there is still a long way to go.

As it is traditionally done with Inaugural Lectures, I wish to conclude with a number of recommendations with regards to making this God's gift to nature accessible, available and affordable to the populace and improve our human development index (HDI). (Chendo,1997).

**(1) Educational:** The lack of awareness of the potential and importance of Renewable Energy Technology and the dearth of skilled manpower needs to be addressed (Chendo, 2002). Abdus Salam cited by Chendo (1994) states that, "*in developing countries, the total number of Scientists and Technologists is very small compared to the developed world, ten times as small as the North*". These numbers need to be multiplied so they can constitute a critical size, they have to be given proper recognition provided with scientific literature and comprehensive technological information as well as the requisite infrastructure for research development and implementation plus international contacts principally by those who run these countries. Mr. Vice-Chancellor sir, I am recommending that Energy (convectional and non-convectional) be included in our general studies/curriculum. The lack of qualified personnel in the field of Renewable energy demands an articulate and concerted plan of action by the appropriate authorities to provide specialised training in the technical and postgraduate education.

**(2) Institutional**: Energy planning should aim in particular at optimising supplies and reducing consumption in rural areas. A special group needs to be set up to study the impacts, socioeconomics, environmental or otherwise of such projects and formulate a comprehensive national plan for the development and diffusion of the sun's energy (Renewable Energy Technologies).

**(3) Finance:** Innovative finance is not only desirable but a requirement for facilitating technological advancement. Various avenues would need to be explored amongst which are the introduction of tax credits for RETs uses, low interest loans and loan guarantee, tax surcharges on fossil fuels with a proportion of the revenue gained used to fund research and development of Renewable energy sources and offset the cost of renewable energy tax-credits. (An airplane powered by solar energy has gone round the whole world).

**(4) Solar Thermal Collectors**: In my 1988, 1992 and 1994 papers, I advocated for the setting up of Nigeria Test methods and design guidelines for solar thermal collectors. Such a guideline will enhance research into a potentially attractive concept where modularity and simplicity of design would help to reduce capital costs through possible mass manufacturing of standardised design to avoid making Nigerian markets a dumping ground for substandard systems from different parts of the globe as is almost the case now!

In addition, indoor collector testing, making use of solar simulations must be vigorously pursued and possibly incorporated into the UNILAG National Energy Centre. For instance, in Europe any solar collector manufactured by any of the European countries must go through Diagnosis at the European Joint Research Center in Ispra, (Varese) Italy, for certification, etc. The UNILAG Centre should be equipped to also play that role.

**(5) PHOTOVOLTAICS (PV)**

PV business unlike similar electronics business requires a strong interaction between the customer and the PV expert to ensure proper design, sizing and installation. Currently there are many PV vendors in Nigeria and some of their installations have failed. Some of the reasons for the failure include: battery mismatch, as well as the service provider's lack of basic rudiments guiding PV design, sizing, orientation, installation and low quality solar cells with fluctuating efficiency. From a study by one of my past M.Sc. students (Uzundu, 2012), over 290 of such installations visited, failed within a short period of time which represents over 70% failure rates. This is not surprising to some of us because emergency solar PV experts are all over the place. In this regard, I am recommending that, like the thermal collector/system guidelines, a similar one for PV should be established. For now, Nigeria can import finished solar cells and assemble them locally into modules. A balance of systems (BOS) manufacturing industry will then exist alongside the module assembly plant industry. This option has the potential of reducing PV system cost without the need for high investment in an indigenous PV industry. This is suitable for countries with a sufficient local market for PV like Nigeria. A schematic representation of the options submitted to the Federal Ministry of Science and Technology, Abuja, is shown in *figure 10.3* (Chendo, 2000).

The following points should be noted:

- Visual inspection of some PV installation on UNILAG did not exhibit expert competency of installers.
- UNILAG energy research expert should be involved in future installation for standards to be maintained.
- UNILAG can drastically cut down its energy bill by adapting solar energy technologies as a compliment.
- The Energy Centre should be challenged to ensuring that most of the street lights on campus be powered by solar.
- The Advanced Energy Laboratory (SHESTCO) in Sheda, Abuja should be equipped to play the role envisaged for it when the concept was developed in 1988.

### (6) SOLAR COOKERS AND BIOGAS PLANT

In my report which I submitted to the Hon. Minister of Science and Technology June 2000, I recommended as follows:

(Ii) Setting up of working groups for both Biogas plant and solar cookers which will in turn chart out a National Programme for their actualisation.

(ii) The Nigeria Scientists and Engineers who visited China on training should be assembled to form the nucleus especially for the Biogas commercialisation. One of the militating factors for the commercialisation is its incompatibility with the conventional cooking gas used in various houses because of the status of the current burners and nuzzles in conjunction with Biogas plants for the commercialisation which are designed to operate on high pressure unlike biogas which currently operates on atmospheric pressure.

(iii) Training programme's outline: Three kinds of training programmes should be embarked upon and targeted towards: (a) Turn-key supervisors/Trainers; (b) Professional masons and (c) Professional Technicians/ Artisans.

Courses to be rendered can be classified as follows: (a) Training of Trainers; (b) Training of Master Mason and supervisors; and (c) Refresher/period training of Mason and supervisors (Chendo 2000). These should be practical oriented courses in the construction, installation as well as maintenance/repair of biogas plant and solar cookers.

**(7) CLIMATE CHANGE**

One of the identified ways of tackling global warming and climate change is through the promotion, production and use of renewable technologies (mitigation and adaptation). Thus, an aggressive education of the average Nigerian should be embarked upon by Economists, Sociologists and Scientists.

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