

# Solar Radiation, a Friendly Renewable Energy Source

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## 1. Introduction

'let there be light and there was light' , Genesis 1:1. This quotation from the Holy Bible refers to the coming into being, the "**Sun**"; thus "**Energy**", by the spoken words of God. The sun is a common feature in our sky; it is seen crossing the sky from one extreme horizon to the other every day, giving us light and heat. However, little did the world realize what a prodigious and free source of energy God has made available for mankind. Among the alternative renewable energy sources, solar power is a prime choice in developing affordable, decentralizable global power source that can be adopted for use in all climate zones around the world. This energy is free but the equipment to collect it and convert it to useable energy can be costly. Energy is radiated from the sun in all directions in space in the form of electromagnetic radiations (sun rays). The average amount of solar energy radiated to earth is about  $1\text{kW}/\text{m}^2$ , depending on the latitude and regional weather pattern of a location on the Earth's surface (Green, 2001).

### 1.1 The uncertainty of fossil fuel energy sources to meet world's energy demand

Before we go to the specifics of solar radiation and solar energy applications, we will discuss the inadequacy of the fossil fuels to meet the energy demands of the world now and in future and the potential dangers inherent in continue to use them.

The known conventional energy sources are: fossil fuels, which include coal, oil, natural gas and nuclear. Among the conventional energy sources, fossil fuels are the chief and the world's current main sources of energy .

The fossil fuels are unfortunately depleting fast to a point where it is unlikely to be able to sustain the great rate of the world energy consumption within the next 200 years. It is in fact understood that about 80% of the world's oil reserves have been consumed by 1980 at the rate of the world energy consumption in 1975 (Meinel and Meinel 1975) The remaining reserves of coal in the world is estimated to last for about 25 years, while the life expectancy of the oil and gas reserves in the world is not positively known.

As of now oil remains the chief source of energy of the world. According to Eden (1983) the projected world total energy demand, if oil were only the source, is  $130 \times 10^6$  barrels per day by the year 2000 whereas at that time the possible production of it is put at about  $53 \times 10^6$

barrels per day. This would represent about 38.5% of demand. This indicates the incapability of oil to continue to meet the energy demand of the world.

As the world population increases and the economic standard of third world countries improves, there is an expectation of an unprecedented rise in the global energy demands. To allow the traditional energy sources, that is, fossil, nuclear, or hydro fuel to meet these increasing energy demands now and for too long in the future will be unwise and suicidal. The reasons for this strong opinion being:

- There is a strong international consensus on the threat of dangerous climate change due to pollutants emitted from fossil fuels powered engines. This threat is heightened by the rapidly increasing demand for fossil fuels, which in recent years propelled the price of crude oil above US\$ 60 per barrel for the first time. This has demonstrated that production of “cheap” fossil fuels, which we may deplete by the middle of this century, can no longer cope with the demand. We therefore have to pay more to quickly bring about dangerous climate change and, if we survive that, wait for the highly probable energy crisis.
- The ecological impact of turning every river into a dam for hydroelectric power if possible, is scary and hard to imagine.

It has also been recognized that the heavy reliance on fossil fuel has had an adverse impact on the environment. For example, gasoline engines and steam-turbine power plants that burn coal or natural gas send substantial amount of sulphurdioxide ( $\text{SO}_2$ ) and nitrogen oxides ( $\text{NO}_2$ ) into the atmosphere. When these gases combine with atmospheric water vapor, they form sulphuric and nitric acids, giving rise to highly acidic precipitations which are very dangerous to plants and human beings. Further more, the combustion of fossil fuels also releases carbon dioxide into the atmosphere; the amount of this gas in the atmosphere has been observed to have steadily risen since the mid 1800, largely as a result of the growing consumption of coal, oil and natural gas. More and more scientists believe that the atmospheric built up of carbon dioxide (along with that of other industrial gases such as methane and chlorofluorocarbon) may induce a green house effect, causing the rising of the surface temperature of the earth by increasing the amount of heat trapped in the lower atmosphere. This condition could bring about climate changes with serious repercussions for natural and agricultural ecosystems.

Similarly, nuclear power generation as a source of alternative energy faces lots of social objections due to the possible radiation hazard that it may cause during production. Scientists cannot estimate the extent and gravity of destruction, both immediate and long term, that nuclear radiation hazard can cause when nuclear power reactor accident occurs such as the case of the Russian’s Chernobyl nuclear power plant accident in 1987, and the recent nuclear energy plants accident(tsunamis) in Japan, which gravity and extent of damage to life and properties cannot now be estimated and for how long the damaging radiation will be absolutely controlled. By this many countries are signing off nuclear energy utilization.

Moreover the nuclear power material if inappropriately stored could end up in wrong hands and get turned into weapon of mass destruction that will make terrorism assume a much more dangerous dimension.

However, nuclear energy is hoped to be potentially capable of at least deferring the world energy starvation for a long time. In fact it may be capable of taking over the bulk of energy supply as the fossil fuels become exhausted.

## 2. The sun, origin of solar energy

Here we will not bother ourselves with detailed specifications of the Sun, but give us just some relevant data of it.

The Sun is one of the many billion of stars in the Milky Way Galaxy, the galaxy of our solar system in the universe. It is the closest star to our planet earth; its effect and importance to us on the earth results from its closeness.

The sun is learnt to be formed about 5000 million years ago (Okeke and Soon 2004.). It is a great ball of hot gases with diameter of about  $1.4 \times 10^6$  km, which is about 109 times that of the earth, and it is about  $1.5 \times 10^8$  km distant from the earth. It is the most important celestial object to us because it is the source which supplies the energy that allows life to flourish on earth.

The energy of the Sun is derived from a process similar to that of nuclear fusion in which hydrogen nuclei are believed to combine to form helium nucleus. The excess mass in the process is converted to energy in accordance with Einstein's theory i.e.,  $E = mc^2$ .

Thus, the Sun produces a vast amount of energy but only a tiny part of it reaches the earth. The energy comes from the nuclear fusion occurring at the core of the sun. The sun is a stable star, it thus promises to remain at the same magnitude of its properties and surface temperature for a long time. It is interesting to note that the Sun is not one of the hot stars, but one of the cooler stars. Cooler stars are yellow in colour and the Sun is yellow in colour. Yet its heat from 93 million miles away is very effective in keeping us warm and sustains lives on our planet earth.

The Sun radiates about  $3.86 \times 10^{26}$  Joules of energy every second, a value which is more than the total energy man has ever used since creation. Although some of this energy is lost in the atmosphere, the amount reaching the earth's surface every second, if properly harnessed, is still probably enough energy to meet the world's energy demand (Maniel, 1974). Today it is a common knowledge that the Sun is the primary source of energy for all the processes taking place in the earth-atmosphere system. All lives on earth depend upon its radiant energy directly or indirectly to survive.

The Sun, therefore, is one of the popular emerging feasible sources of energy being looked into and sought by the world today for long-term, possible source of renewable and reliable energy. The Sun is available free for all land and mankind. It is free of politics. It only needs suitable devices to capture its rays and translate it into useful heat or work.

The amount of solar energy available for any land depends only on its location with respect to the Sun. If we examine the following expression for the solar energy available at the top of the atmosphere of any location from the sun,

$$H_0 = 24/\pi I_{sc} \cos\phi \cos\delta (\sin\omega_s - \pi/180) \omega_s \cos\omega_s \quad (1)$$

two angles in this expression are related to the location of a site on the earth's surface with respect to the sun:

$\Phi$ , the latitude, and  $\delta$ , the declination angle of the Sun.

The amount of solar energy received per unit area per second at the outer edge of the earth's atmosphere above a site is known as Extraterrestrial radiation, and is about  $3.0 \times 10^{26}$  Joules. The extraterrestrial radiation being received at the normal incidence (i.e. Sun - earth average distance) at the outer edge of the atmosphere of a site is known as the solar constant  $I_{sc}$  which is about  $4921 \text{ kJm}^{-2}\text{h}^{-1}$ .

If the Sun emits energy as said above, in form of electromagnetic radiation given by

$$E = mc^2 \quad (2)$$

where  $m$  is mass and  $c$  is velocity of light, the energy therefore, radiated by the sun, is equivalent to a mass loss by the sun every second and can be evaluated to be:

$$m = 3 \times 10^{26} / c^2 = 3.3 \times 10^9 \text{ kgs}^{-1}$$

If the Sun thus loses mass at this rate, it can be estimated that the Sun may extinct in about  $2 \times 10^4$  b years. Hence the energy of the Sun can be said to be in-exhaustible by the earth, i.e., the Sun is with us for some time to come.

However the amount of the energy reaching the earth's surface is about  $1.00 \times 10^3 \text{ Wm}^{-2}$  at noontime at the equator. The depletion of the Sun's energy as it passes through the atmosphere to the earth's surface, coupled with the seasonal, night and weather interruptions, constitutes the major impediment to the full realization of solar energy utilization. This notwithstanding, solar energy is proving by far the most attractive alternative source of energy for mankind.

Solar energy is pollution free, communitarian, conservational, decentralizable, adaptable, and the related devices to utilize it require very little or no maintenance, safe and cost effective. Solar energy utilization has come to stay as the possible future long-term energy resource. It can be argued that it is the only recurrent source, large enough to meet mankind demands of energy supply if properly harnessed. All other renewable energy sources depend directly or indirectly on the Sun for their existence.

### 3. Solar radiation fundamentals

#### 3.1 Electromagnetic spectrum of the sun

The sun emits energy in form of electromagnetic waves which are propagated in space without any need of a material medium and with a speed,  $c = 3 \times 10^8 \text{ ms}^{-1}$ . Electromagnetic radiation emitted by the Sun reaching out in waves extends from fractions of an Angstrom to hundreds of meters, from x - ray to radio waves.

An angstrom is a unit of length given by  $1\text{A} = 10^{-8} \text{ cm} = 10^{-4} \mu\text{m}$ .

Electromagnetic radiations are usually divided into groups of wavelengths. The wavelength regions of principal importance to the earth and its atmosphere are the;

Ultraviolet ( UV ) - ( 0.3 - 0.4  $\mu\text{m}$  ) representing 1.2%  
 Visible (VIS) - ( 0.4 - 0.74 $\mu\text{m}$  ) representing 49%  
 Infrared ( IR ) - ( 0.74 - 4.0  $\mu\text{m}$  ) representing 49%

It was discovered that 99% of the Sun's radiant energy to the earth is contained in these wavelength regions, that is, between 0.3 and 4 $\mu\text{m}$  and comes mostly from the photosphere part of the sun.

#### 4. Factors affecting the amount of solar radiation received on the earth surface

##### 4.1 Astronomical factor

As said above, only a tiny portion of the energy of the sun reaches the earth's surface. The sun-earth distance constitutes one of the factors affecting the amount of solar energy available to the earth. The earth is known to be orbiting round the sun once in a year and at the same time rotates about its own axis once in a day. The two motions determine the amount of solar radiation received on the earth's surface at any time at any place. The path or the trajectory of the earth round the Sun is an elliptical orbit with the Sun located at one of the foci of the ellipse. The implication of this is that the distance of the earth from the sun is variant; hence the amount of radiation received on the earth surface varies. For example, the shortest distance of the Sun from the earth is called the perihelion, and is 0.993AU. (Astronomical unit of distance(AU)=1.496  $\times 10^8$ km). It takes place on December 21st.

On 4th of April and 5th of October the earth is just at 1AU from the sun, while on 4th of July, the earth is at its longest distance, 1.017AU from the sun; this position is called Aphelion. The path of the sun's rays thus varies with time of the day, season of the year, and position of the site on the earth's surface. It becomes shorter towards the noon time, it decreases towards the perihelion position and increases towards aphelion. Thus the variation in the sun-earth distance causes variation in the amount of solar radiation reaching the earth surface. The path of the sun's ray through the atmosphere is perhaps the most important factor in solar radiation depletion. It determines the amount of radiation loss through **scattering** and **absorption** in the atmosphere.

The eccentricity ( $E_o$ ) of the elliptical orbit is expressed in terms of the sun-earth distance ( $r$ ) and the average,  $r_0$  of this distance over a year. It is given by

$$E_o = (r_0/r)^2 = 1+0.033 \cos(2\pi d_n/365) \quad (3)$$

where  $d_n$  is the Julian day number in the year. For example  $d_1=1$  on January 1 and  $d_{365}=365$  on December 31.

The elliptical motion of the earth round the sun gives rise to the seasons we experience on earth, and its rotation about its own axis determines the diurnal variation of the amount of radiation received. The amount of solar radiation received on a unit horizontal surface area per unit time at the top of the atmosphere is known as the **Extraterrestrial** radiation  $H_o$ , and is given by

$$H_o = 24/\pi I_{sc} E_o \cos \phi \cos \delta (\sin \omega_s - (\pi/180) \omega_s \cos \omega_s) \quad (4)$$

This equation gives the average daily value of extraterrestrial radiation,  $H_o$  on a horizontal surface at the top of the atmosphere, while

$$I_o = I_{sc} E_o \cos \phi \cos \delta (\cos \omega_i - \cos \omega_s) \quad (5)$$

gives the average hourly value of the extraterrestrial radiation.

where  $\phi$  is the latitude of the site,

$\delta$  is the declination angle of the sun

$\omega_i$  is the hour angle

$\omega_s$  is the sun set hour angle

The corresponding expressions for computing the extraterrestrial radiation on a tilted surface toward the equator at any latitude in the northern hemisphere are given by Igbal (1983). For the daily average, we have

$$H_{o\beta} = 24/\pi I_{sc} E_o [(\pi/180) \omega_s^1 \sin \delta \sin(\phi - \beta) + \cos \delta \cos(\phi - \beta) \sin \omega_s^1] \quad (6)$$

And for the hourly average, we have

$$I_{o\beta} = I_{sc} E_o [\sin \delta \sin(\phi - \beta) + \cos \delta \cos(\phi - \beta) \cos \omega_i] \quad (7)$$

where  $\beta$  is the angle of tilt toward equator

$$\omega_s^1 = \min\{\omega_s, \cos^{-1}[\tan \delta \tan(\phi - \beta)]\} \quad (8)$$

## 4.2 The atmospheric factor

The extraterrestrial radiation mentioned above is the maximum solar radiation available to us at the top of our atmosphere. The variable quantities affecting its amount at the ground surface are the astronomical factors mentioned above and the atmospheric factors.

Solar radiation however has to pass through the atmosphere to reach the ground surface, and since the atmosphere is not void, solar radiation in passing through it is subjected to various interactions leading to **absorption**, **scattering** and **reflection** of the radiation. These mechanisms result in depletion and extinction of the radiation, thus reducing the amount of solar radiation we receive at the ground surface of the earth. Several atmospheric radiation books describe and discuss these radiation depletion mechanisms.

## 5. Other radiation and atmospheric related parameters

The knowledge of radiation parameters, such as cloudiness index, clearness index, turbidity, albedo, transmittance, absorbance and reflectivity of the atmosphere through which the solar rays pass to the ground surface is very necessary for the utilization of solar energy. Also the knowledge of the meteorological parameters such as number of **sun shine hours** per day, **relative humidity**, **temperature**, **pressure**, **wind speed**, **rainfall** etc is desirable and important for accurate calculation of parameters of some solar energy devices. For example it is needed to know the average number of sun shine hours per day for accurate calculation of PV (photovoltaic) power needed in sizing solar power electrification for any location. In Nigeria, for example, we have an average of 4.5 hours of sunshine in a day. In detailed work, however, this value varies with geographical locations. Because of these, the

measurement of solar radiation amount and its spectral distribution under all atmospheric conditions is undertaken at many radiation networks around the world (Babatunde and Aro, 1990).

The knowledge of the spectral distribution of solar radiation available is also important for development of semiconductor devices such as photo detectors, light emitting diodes, power diodes, photo cells, etc; it is also essential in the design of some special solar energy devices for the direct conversion of solar energy to electricity.

## 6. Solar radiation measurement and analysis

It is inevitable to know the potential of solar energy available on daily and monthly bases at the site for solar energy application, not only in amount but in quality, particularly its spectral composition. For this, the measurement of solar radiation energy and its spectral distribution under all atmospheric conditions is undertaken also at many radiation networks around the world.

Solar radiation energy arriving at the edge of the earth's atmosphere is carried or conveyed in electromagnetic spectrum, of wavelengths ranging from about 0.2 $\mu$ m to 4 $\mu$ m, as said above. These groups of wavelengths of the solar radiation are of principal importance to the earth and its atmosphere, especially for the calculation of absorption by gases, clouds and aerosols in the atmosphere and to calculate the spectral variation of the earth - atmosphere albedo, and also essential for photosynthesis, photobiology and photochemistry in the atmosphere.

### 6.1 Basic radiation measurements

The basic radiation fluxes being actively measured and studied in many radiation network stations globally include the sw-total (global) solar irradiance, sw-direct solar irradiance, sw-diffuse or sky irradiance. Other radiation fluxes measured are global and diffuse photosynthetic active radiation( PAR), ultraviolet total optical depth and the sun photometric measurement, and commonly measured radiation parameter is the sun shine hours. However the brief analysis here on radiation measurements is on the global (total) solar irradiance,  $H$ , direct solar irradiance,  $H_b$ , and diffuse sky irradiance  $H_d$ .

#### 6.1.1 Global (total) solar irradiance

Global solar irradiance,  $H$ , which is the total sw-radiation flux, measured on a horizontal surface on the ground surface of the earth, comprising the direct sw- solar irradiance,  $H_b$  and diffuse sw- sky irradiance,  $H_d$ . In simple mathematics, the three fluxes are connected as in the following

$$H = H_b + H_d \quad (9)$$

If all measurements were accurate, wherever two of these fluxes are measured, the third can easily be obtained, but this is not always so.

Global (total) solar radiation flux is the most easily and commonly measured of all the radiation fluxes in almost all the radiation network throughout the world. Measurement is

done in the shortwave regions, 0.2 to 4.0 $\mu\text{m}$  wavelengths, which includes the photo synthetically Active Radiation (PAR).

The measurement is done to date, for example, at BSRN station, Physics Department University of Ilorin using Eppley Precision Spectral Pyranometer (PSP), serial number, SN17675F3 and 28866F3 with calibration constant of  $8.2 \times 10^{-6} \text{ V/Wm}^{-2}$  and well documented calibration history. Data quality is ensured by eliminating spurious errors that could arise from incidental and shading or partial un-shading of sensor by discarding all observations for which the insolation is less than  $20\text{Wm}^{-2}$ . The data assembled on minute - by - minute basis was used to generate the hourly, daily and monthly averages.

### 6.1.2 Direct solar irradiance, $H_b$

The direct solar irradiance or solar beam  $H_b$ , is the component of the total solar irradiance  $H$ , which comes directly from the top of the atmosphere, through the atmosphere, to the ground surface not deviated, nor scattered nor absorbed. The ratios of it to the total  $H$  i.e  $H_b/H$  and to the extraterrestrial radiation  $H_0$ , i.e  $H_b/H_0$ , are very important atmospheric radiation parameters in the radiative property of the atmosphere.  $H_b/H$  can be used to indicate the clearness of the atmosphere while  $H_b/H_0$  may be used to indicate the clearness of the atmosphere and to determine the transmittance property of the atmosphere.

The direct solar irradiance is similarly measured like the global solar irradiance. It is measured using the Eppley solar tracker(NIP) with calibration constant  $8.42 \times 10^{-6}\text{V/Wm}^{-2}$ . Unfortunately the incessant power outage prevented the continuous functioning of this radiation sensor in many developing nations. Therefore the data of direct solar irradiance is here, as in many other stations, obtained by computation.

### 6.1.3 Diffuse sky irradiance, $H_d$

This radiation flux is also known as the sky radiation. It is short wave radiation, coming from the sky covering angular directions of  $180^\circ$  to the sensor. It is incident on the ground surface as a result of scattering and reflection by particles in the atmosphere. Its ratio to the total flux  $H$ , i.e  $H_d/H$  measures the cloudiness and turbidity of the sky and its ratio to the extraterrestrial radiation  $H_0$ , i.e  $H_d/H_0$  is expected to measure the scattering co-efficient of the atmosphere.

This radiation flux is measured in same manner as those above. An Eppley Black and White Pyranometer model 8-48 with calibration constant  $9.18 \times 10^{-6} \text{ V/Wm}^{-2}$ , with a shadow ring across the sensor, is used for the measurement. Unfortunately and inevitably the shadow ring may cut off some diffuse radiation, thus making the measurement to be inaccurate. This is why eqn.6 may not be valid or suitable to obtain the correct direct solar irradiance  $H_b$ .

## 7. Radiation fluxes formulae

As part of measurements, formulas for generating the different radiation fluxes: global (total) solar irradiance,  $H$  and its components, direct solar irradiance  $H_b$ , diffuse solar irradiance  $H_d$ , are developed to generate the required data of these radiation fluxes where they are required and are not regularly measured. Some of the expressions were developed in terms of other easily measured radiation and meteorological parameters. Numerous of

these formulae exist, developed by many workers and published in relevant journals all over the world.

However many of them may not be applicable globally or valid at other geographical locations different from where they were generated (Page, 1964, Schulze, 1976), while some of them may be applicable at geographical locations similar in latitude to where they were originated (Chuah et.al, 1981). Some of them are the Angstrom type (Angstrom, 1924; Rietveld, 1978). Some are linear (Shears et.al, 1981 ; Glover and McCullouch 1958). Some are polynomials, some are parametric while some are indicial.

### 7.1 Total (global) solar radiation prediction formulae

Some prediction formulae for the radiation fluxes generated by the author include:

$$H/H_0 = 0.329 + 0.315(s/S_m) \quad (10)$$

where:

H is the global (total) sw - solar irradiance been predicted.

$H_0$  is the extraterrestrial at the top of the atmosphere of the site.

$s/S_m$  is the fraction of sun shine hours at the site.

Eqn.10 is of the Angstrom type obtained by the author in 1995 at the BSRN station University of Ilorin (Babatunde, 1995). Another is a multivariate one given by

$$H/H_0 = 0.0189 + 0.2599(s/S_m) + 0.0027V + 0.0101T \quad (11)$$

where:

$H_0$  and  $s/S_m$  are already defined in eqn 10.

V is the average visibility and T is the average ambient temperature at the location.

Eqns. 10 and 11 are formulae for estimating or generating global (total) solar radiation fluxes. Eqn.11 however is a multivariate expression. The magnitude of contributions by the meteorological variables in the expression to the amount of radiation obtainable at the location are indicated by their coefficients. The amount of global solar radiation predicted at the location depends, as can be observed from the equation, strongly on the variant,  $s/S_m$ , the number of sun shine hours, less on the ambient temperature T and much less on visibility V. The equation was developed by Babatunde and Aro (1996).

When tested, the value of global radiation flux predicted by eqn.10 was within 2.5% while that of eqn.11 was within 0.6%. Thus an equation developed in terms of multivariate meteorological variables, although cumbersome, gives a better value of the radiation flux than the one in terms of one single variable. However for estimating values of the flux, H, for engineering purposes, the two equations are found to be adequate and reliable.

### 7.2 The diffuse radiation prediction formulas

Some formulas for computing the diffuse sky radiation were developed at various times and also in terms of related radiation and meteorological parameters by Babatunde (1995 ; 1999). Three of them, two of which are Angstrom type, are presented.

$$H_d/H = 0.4949 - 0.1148S_h \quad (12)$$

$$H_d/H = 0.945 - 0.971K_c \quad (13)$$

$$H_d/H = 1 - K_c \quad (14)$$

where  $H_d/H$  is known as the cloudiness index.

$S_h$  is the fraction of sunshine hours.

$K_c$  is the clearness index  $H/H_0$ .

When they were tested on the year 2000 radiation data, the values predicted by eqn.12 were within 18% while that of eqn.13 was within 11% and that of eqn.14 was within 19%. Therefore it can be said of these equations that they will adequately produce diffuse sky radiation data with reasonable accuracy. Eqn.13 is however the best of the three. It is of the Angstrom type, obtained as a result of experimental analysis and not as a result of regression analysis like others.

### 7.3 Direct radiation prediction formulas

Direct radiation component data is the most difficult to acquire because of the nature of the equipment for measuring it. Estimation of its values has therefore been relied upon to provide the data when needed.

The following formulas by the author for computing it were developed at various times (Babatunde, 1999; 2000)

$$H_b = H^2/H_0 \quad (15)$$

$$H_b/H = 0.308 + 0.424 H/H_0 \quad (16)$$

The two equations were developed in terms of the total radiation  $H$  and extraterrestrial radiation  $H_0$ . The two radiation fluxes, the predictors, are easily measured and computed respectively with very reasonable accuracy. Eqn.15, in particular, is a unique equation, developed purely from experimental results, Eqn.15 and eqn.16 will produce dependable values of the direct radiation data in all atmospheric conditions.

Some other equations developed for predicting  $H_b$  for specific atmospheric conditions are:

$$H_b/H = 0.341 + 0.571 K_c \quad (17)$$

and

$$H_b/H = 0.247 + 0.415 K_c \quad (18)$$

They have been tested and proven to be much more suitable for clear - sky conditions and cloudy - sky conditions respectively. They are equally as good as eqns. 15 and 16 above but only at the atmospheric conditions specified.

## 8. Solar energy applications

The major areas of application of solar energy are in the provision of low and high grade heat, direct conversion to electricity through Photovoltaic cells and indirect conversion to electricity through turbines.

Thus solar energy is utilizable through the principle of energy conversion from one form of energy to another. In this case, the thermal and electrical conversions of sun's energy make realizable, the various applications of solar energy. The various applications feasible and in practice are enumerated as follow.

### 8.1 Solar energy thermal conversion application

- i. Production of hot water for domestic use.
- ii. Cooling and Refrigeration.
- iii. Solar passive drier in;
  - a. Agriculture drying.
  - b. Wood seasoning.
  - c. Mushroom culturing or growing
  - d. Production of pure water- distillation.

### 8.2 Solar electrical conversion application

- i. Thermal to electricity conversion.
- ii. Solar electric power systems (PV) Photovoltaic cell.
  - a. Solar water pumping.
  - b. Hydrogen Fuel.

There are some other types of solar electric power systems based on different technologies. Some of which are in practice and some are under development. Some of them are:

- a. Crystalline silicon
- b. Thin films
- c. Concentrators
- d. Thermo-photovoltaic
- e. Organic solar cells

The first four are the major ones while the fifth one, under development, is a latest technology in solar energy conversion. It is related to thin film, and will be discussed latter in the chapter.

### 8.3 Thin films

Thin films will be developed to become a reliable and more efficient source for solar energy application. The principle of its applicability in the solar energy application is discussed under spectral selectivity properties of a surface in solar energy application. An organic solar cell is an example of such thin films. Solar electric thin films are lighter, more resilient, and easier to manufacture than crystalline silicon modules. The best developed thin film technology uses amorphous silicon in which the atoms are not arranged in any particular order as they would be in a crystal. An amorphous silicon film, only one micron thick, absorbs 90% of the useable solar radiation falling on it. Other thin film materials include cadmium, telluride and copper indium diselenide. Substantial cost savings are possible with this technology because thin films require little semiconductor materials. Thin films are also produced as large complete modules. They are manufactured by applying extremely thin layers of semi conductor materials unto a low -

cost backing such as glass or plastics. Electrical contacts, anti-reflective coatings, and protective layers are also applied directly to the backing materials. The films conform to the shape of the backing, a feature that allows them to be used in such innovation product as flexible solar electric roofing shingles.

#### 8.4 Organic solar cells

This is a new solar energy electric conversion technology in which solar cell is currently being developed from various organic matters (dyes). They are sort of thin films discussed above. The crystallized silicon solar cells have being a standard technology in solar conversion devices for over fifty years. However they are still expensive, and relatively inefficient (they have achieved only 50% efficiency so far). Right now, various types of organic solar cells from dye materials are being studied and may soon replace the silicon solar cells, because they (organic solar cells) will be fabricated with greater efficiency, low cost processes, and they will be more versatile than silicon solar cells. Further still, they have added advantages of being thinner, lighter and more colourful than silicon solar cells.

### 9. Spectral selectivity surface applications

We now discuss a new specialized area of solar energy application, based on the spectral selectivity property of a surface. It is a new and special innovative concept in solar energy application.

It was discovered that optical properties of materials can be modified to select wavelengths of the solar spectrum to transmit, or absorb or reflect. On these principles the following applications are possible:

- Selective absorbers,
- Heat mirrors,
- Reflective materials,
- Anti-reflective,
- Fluorescent concentrator,
- Holographic films,
- Cold mirrors,
- Radiative cooling,
- Optical switching,
- Transparent insulating materials,
- Solar control window.

Spectral selectivity of a surface is achieved by applying special coatings on substrates, which may be transparent or opaque, with the intention of modifying the optical properties of the surface, such that the surface selects wavelengths of the solar spectrum to transmit or absorb or reflect. These properties are: transmittance, absorbance, reflectance, emittance, absorption coefficient ( $\alpha$ ) extinction coefficient ( $k$ ) refractive index ( $n$ ) to mention a few, and upon which relevant applications are based. Surfaces of different material coatings will produce different values of these optical properties at different wavelengths of the solar spectrum.

Solar radiation is transverse oscillating electric and magnetic fields. The electromagnetic fields interact with the electric charges of the material of the surface on which solar radiation is incident. The interaction results in the modifications of the solar radiation at different parts of its spectrum. As a result, some parts of the radiation are absorbed, some are transmitted, and some are reflected back to space (Granquist, 1985; Lovern, et al, 1976). Thus, by spectral selectivity of a surface, it is meant surfaces whose values of absorptance, emittance, transmittance and reflectance of radiation and other related optical properties vary with wavelengths over the spectral region,  $0.3 \leq \lambda \leq 3 \mu\text{m}$  (Loven, et al. 1976; Maniel and Maniel, 1976).

For example, a spectral selective surface having high absorptance in the wavelength range  $0.3 \mu\text{m} \leq \lambda \leq 3 \mu\text{m}$ , and high reflectance at  $3 \mu\text{m} \leq \lambda \leq 100 \mu\text{m}$  will appear black with regards to the short wavelengths range,  $0.3 \mu\text{m} \leq \lambda \leq 3 \mu\text{m}$  and at the same time appear an excellent mirror in the thermal region, i.e.  $3 \mu\text{m} \leq \lambda \leq 100 \mu\text{m}$ . A device with these properties is called a "heat mirror".

We shall discuss briefly, for example, the principle of the following spectral selectivity applications of solar energy.

- i. Heat mirror
- ii. Cold mirror
- iii. Solar control coatings.

### 9.1 Heat mirror

A solar collector with a highly selective absorber in the short wavelengths range of solar radiation, that is, at  $0.2 \leq \lambda \leq 3 \mu\text{m}$ , will reflect very highly the thermal radiation (IR) component of solar radiation. This implies that the device is black to this short wavelengths range because it absorbs them, and forms an excellent mirror in the thermal region because it reflects them. The device is called a "Heat mirror". Thus heat mirror is essentially a device that transmits or absorbs the short wavelengths radiation (UV - VIS) and reflects long thermal wavelengths (IR) of solar radiation. That is, it is a window to the short wavelengths and a mirror to the long wavelengths. Such a surface is therefore suitable for architectural windows in buildings, where low temperature or cooling effects is desired. This device therefore may be adaptable for passive cooling in a tropical climate region.

The heat mirror device is obtained by using a semiconductor-Metal Tandem. Thus, it can be called absorber-reflector Tandem. The semiconductor components are arranged to reflect the thermal radiation (IR), while the metal components absorb or transmit the UV - VIS radiation. A heat mirror device is also called a transmitting selective surface.

In the arrangement of the components, the reflective layer surface is arranged to cover the non-selective absorber base. In this way, the selective reflector reflects the thermal infrared radiation ( $\lambda > 3 \mu\text{m}$ ) and transmits the short wavelength range ( $\lambda < 3 \mu\text{m}$ ). The short wavelength radiation transmitted by the reflector is absorbed by the black absorber base. Some highly doped semi conductors such as  $\text{InO}_2$ ,  $\text{SnO}_2$  or the mixture of the two, Indium-Tin-Oxide (ITO), have been used successfully to produce the reflector component of the device (Seraphin, 1979). A heat mirror may therefore be used to separate heat radiation (IR) and light radiation (VIS) of the solar spectrum. The IR energy separated could be used for thermal purposes such as the thermo-photovoltaic.

## 9.2 Cold mirror coatings

Spectral splitting coatings can be used to divide solar spectrum into various broad band regions. By this, various regions of the solar spectrum can be separated for use for different purposes such as photovoltaic or photo thermal devices (Lambert, 1985).

A “cold mirror” device has opposite spectral response to that of the “heat mirror”. That is, cold mirror films reflect highly (low transmittance) in the VIS region of solar spectrum and reflect poorly, but transmits highly in the IR region, thus splitting the spectrum into short wavelengths and long wavelengths. The high energy waves i.e. the short wavelengths are used for photovoltaic generation while the low energy waves, the long wavelengths (IR) are used for photo thermal heating. This device can be used in “green house” with special arrangements of baffles on the roofs. The device will reflect the photosynthetic active radiation (PAR),  $0.35 \leq \lambda \leq 0.75 \mu\text{m}$  waves into the green house while transmitting the IR into the air channels which can be redeployed to maintain a suitable warm temperature in the green house. ZnS/ MgFs and  $\text{T}_1\text{O}_2/\text{S}_i\text{O}_2$  have been used to achieve these coatings.

## 9.3 Solar control coating

Solar control coating is a design intended to reduce the incoming heat radiation through windows of a building by reflecting off the heat radiation (IR). To achieve comfortable indoor temperatures, that is, to achieve cooling in a building, solar control coating surfaces that are transparent at  $0.4 \leq \lambda \leq 0.7 \mu\text{m}$  and reflecting at  $0.7 \leq \lambda \leq 3 \mu\text{m}$  may be used for the material of the windows in the building. By this, the infrared part of the solar radiation is reflected back, which is possible through the use of solar control windows. A 50% reduction in the internal heating of a building without noticeable reduction in the lighting of the interior of the building had been achieved. The use of such windows may achieve the same objective of a controversial air conditioner in a building. Solar control coating are particularly applicable in hot climate countries such as Nigeria.

In solar control and energy conserving windows, low transmittance windows are employed. If the medium is generally opaque to the passage of radiation but selectively transmits a particular small range of radiation, it is said to operate as a window in that range. A low thermal transmittance window reduces the heat radiation through the window. To achieve low thermal transmittance window therefore, surface coatings that transmits at  $0.3 \leq \lambda \leq 3 \mu\text{m}$  and reflects at  $3 \leq \lambda \leq 100 \mu\text{m}$  may be used. This means that maximum use is made of the solar energy in the short wavelengths range while the transmittance of thermal radiation is minimized.

## 9.4 Solar control and low thermal emittance materials

A thin homogeneous metal film is found capable of combining transmission in short wavelengths up to about 50% with high reflectance in long wavelengths (Okujagu, 1997; Wooten, 1972). The required thickness of such film, using copper, silver and gold is about 20mm. If the films are thinner, they will break up into discreet islands of strong absorptance of visible wavelengths.

Enhancement of luminous transmittance to more than 80% without significantly impairing the low thermal transmittance can be achieved by embedding the metal in anti-reflecting dielectric

with high refractive index layers, such as  $T_1$  and  $O_2$ . In the alternative to the metal base coatings, we may use doped Oxide semiconductor. However a wide band gap is needed in the semiconductor to permit high transmittance in the luminous and solar spectral range. To make the material metallic, electrically conducting and infrared reflecting for wavelengths exceeding a certain plasma wavelength, it requires doping to a significantly high level. Semiconductors suitable for this are: oxides based on zinc, cadmium, tin, lead and thallium and their alloys.

## 10. Conclusion

Energy is necessary for the growth of any nation, and for improving the standard of living of the nation. Therefore energy has to be made available and cheap by the nation for rapid and quality growth of the economy.

Fossil fuels energy, the main source of energy for the world for now, is unable to meet the world's demands of energy and it is, at the same time, rapidly depleting, hence the fever of the world's search for alternative sources of energy. Each country therefore faces the challenges of developing her energy resources.

The renewable energy sources, some of which are: **wind, marine, geothermal, biomass, bio-diesels, hydro-power, land fill and solar energy** have become object of research, because they could be the alternative dependable and feasible sources of energy that the world is looking for to meet her energy demands. They are truly possible alternative sources of energy if their technologies are developed and mastered. Out of them all, solar energy seems to be the most capable of meeting world energy demands if properly harnessed and made cheap. The amount of it received per second during the daylight on the earth's surface is 10,000 times more than the total energy requirement of the world today. The varieties of solar energy applications and advantages are enormous, only a few are mentioned and discussed very briefly in this chapter.

## 11. Summary of the chapter

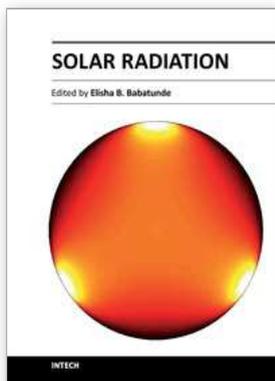
The inadequacy and inability and the inherent danger in the use of fossil fuels energy and other conventional sources of energy to meet the world's demands for energy both now and in the nearest future is highlighted and emphasized. The world eventually turning to the renewable energy sources, solar energy in particular, is inevitable, expected and wise. The inevitable impediment such as the earth's atmosphere and its effect on the passage of solar radiation, to the realization of full utilization of solar energy are identified.

The major possible uses that solar energy are put to are mentioned. A specialized and new area of utilizing solar energy, the area of spectral selectivity property of thin films of materials, are highlighted and discussed. Devices such as heat mirror "cold mirror" solar control windows, in buildings, which basic principle is spectral selectivity, to mention a few, are discussed.

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## **Solar Radiation**

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The book contains fundamentals of solar radiation, its ecological impacts, applications, especially in agriculture, architecture, thermal and electric energy. Chapters are written by numerous experienced scientists in the field from various parts of the world. Apart from chapter one which is the introductory chapter of the book, that gives a general topic insight of the book, there are 24 more chapters that cover various fields of solar radiation. These fields include: Measurements and Analysis of Solar Radiation, Agricultural Application / Bio-effect, Architectural Application, Electricity Generation Application and Thermal Energy Application. This book aims to provide a clear scientific insight on Solar Radiation to scientist and students.

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