



University of Venda

EVALUATION OF THE REGRESSION COEFFICIENTS FOR SOUTH  
AFRICA FROM SOLAR RADIATION DATA

A Thesis Submitted to the Department of Physics

for the Fulfilment of PhD in Physics

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## DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously, in its entirety or in part, submitted it at any university for a degree.

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## **ABSTRACT**

*The knowledge of solar radiation in this dispensation is crucial. The lack of grid lines in the remote rural areas of South Africa necessitates the use of solar energy as an alternative energy resource. Solar radiation data is one of the primary factors considered for the installation of renewable energy devices and they are very useful for solar technology designers and engineers. In some developing countries, estimation of solar radiation becomes a challenge due to the lack of weather data. This scenario is also applicable to South Africa (SA) wherein there are limited weather stations and hence there is a dire need of estimating the global solar radiation data for all climatic regions. Using a five year global solar radiation ( $H$ ) and bright sunshine ( $S$ ) data from the Agricultural Research Council (ARC) and South African Weather Service (SAWS) in SA, linear Angstrom – Prescott solar empirical model was used to determine regression coefficients. MATLAB interface was used whereby the linear regression plots were drawn. Annual empirical coefficients of 22 stations were determined and later the provincial values. The range of the regression coefficients,  $a$  and  $b$  were  $0.216 - 0.301$  and  $0.381 - 0.512$  respectively. The 2006 estimated global solar radiation per station in a province calculated from the modified models were compared with the observed and statistically tested. The root mean square errors were less than  $0.600 \text{ MJm}^{-2}\text{day}^{-1}$  while the correlation relation ranged from  $0.782 - 0.986 \text{ MJm}^{-2}\text{day}^{-1}$ . The results showed the regression coefficients performed well in terms of prediction accuracy.*

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## GREEK SYMBOLS

$\varphi$	Latitude of the location- Geographic coordinate in degrees ( $^{\circ}$ )
$\lambda$	Longitude of the location - Geographic coordinate in degrees ( $^{\circ}$ )
$\delta$	Solar declination angle in degrees ( $^{\circ}$ )
$\omega$	Hour angle in radians (rad)
$\omega_s$	sunrise/sunset hour angle in radians (rad)
$\varepsilon$	Eccentricity of orbit

## ACRONYMS

Z	Altitude or elevation in meters (m)
W	Watts
W/m <sup>2</sup>	Watts per square meter
$I_{sc}$	Solar constant (W/m <sup>2</sup> )
CPI	Consumer Price Index
IEA	International Energy Agency
CO <sub>2</sub>	Carbon dioxide
GtCO <sub>2</sub>	Gigatons carbon dioxide
MtCO <sub>2</sub>	Metric tons carbon dioxide
ARC	Agricultural Research Council
SAWS	South African Weather Service
SA	South Africa
WMO	World Meteorological Organization
WRC	World Radiation Centre
WRR	World Radiometric Reference
WSG	World Standard Group
AM	Air Mass
$H_D$	Daily radiation energy from sunrise to sunset (MJ/m <sup>2</sup> )
$H$	Average Daily Global Solar Radiation on the horizontal surface (MJ/m <sup>2</sup> day)
$H_o$	Extra-terrestrial Solar Radiation on the horizontal surface (MJ/m <sup>2</sup> day)
GHI	Global Horizontal Irradiation
CSP	Concentrated Solar Power

$S_a$	Average daily bright sunshine duration
$S_p$	Average daily maximum possible sunshine duration
$T_{max}$	Average daily maximum temperature in °C
$T_{min}$	Average daily minimum temperature in °C
$\Delta T$	Temperature difference
MBE	Mean Bias Error
RMSE	Root Mean Square Error
MPE	Mean Percentage Error
$a, b, c$	Empirical / solar regression coefficients
ppm	parts per million

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Papers attached as Annexure 1

# CHAPTER 1

## 1.1 Background of the research

All living organisms depend on different forms of energy. Accessibility to energy is critical to the human development. High percentages of people are migrating to urban areas where they will be closer to their working stations. Although people think that solar energy is for the rural area population, in the near future, this type of energy will play an important role. In these conditions, the natural light will be considered to reduce the negative impact of the use of fossil fuels on the environment so as to improve the energy balance of the buildings. The technology dependency of our industrialized world on fossil fuels and the ways in which these fuels are degrading the earth's environment is quite alarming. Fossil fuels such as coal received their solar energy input eons ago; they present their energy in a greatly concentrated form [1]. The CO<sub>2</sub> that coal releases when burnt, changes the environment whereby the ozone layer depletes and later affects the human activities since more of UV radiations reaches the surface of the Earth. The entire world is concerned about the depletion of energy resources coupled with an increase in population. The world's concern about the continuation of the use of fossil fuels drives its efforts to climate change. High levels of the living standards per country are contributing highly to the energy consumption. The cost of living is really increasing in all dimensions. Since 2008, the people of South Africa (SA) are living in fear of experiencing the power outages. ESKOM, the main supplier of electricity in SA, has been implementing load shedding for the last few years. The latest period of load-shedding started in November 2018. Energy crisis is a concern to the South African government so much so that it directed the Department of Energy to develop a strategic plan about the incorporation of alternative types of energy generation. High supply percentage of energy in SA is based on coal (fossil fuel) although there are varieties of energy supply such as biomass, hydroelectric, nuclear energy, etc. that can be implemented to reduce the constraints of energy.

Discussions are underway following the SA President's announcement on the plans to divide ESKOM into three entities for a more efficient administration and the involvement of the Independent Power Producers (IPP) in the power production .

Coal power plants operated by ESKOM account for 95 % of all electricity produced in South Africa. Electricity generated using coal is non-renewable and not environment friendly. Coal plants are the primary source of global warming and constitute the leading source of sulphur dioxide ( $\text{SO}_2$ ) which wreaks havoc on public health and causes acidic rain that damages crops, forests and soils. The amount of carbon dioxide ( $\text{CO}_2$ ) in parts per million (ppm) in the atmosphere is rapidly increasing due to these fossil power stations. In 2014 the level of carbon dioxide within the atmosphere had reached 400 ppm [1]. Even so, ESKOM has planned to build more power stations to rescue the country from the ongoing crisis of load shedding, but this will increase the emission of  $\text{CO}_2$ . It is suggested that if the emission of  $\text{CO}_2$  is less than 450 ppm, global warming can be held at safe levels [2].

Most of the solar radiation data received on a horizontal surface is considered as useful energy. Since only very few applications use this configuration, there is a genuine need for insolation estimations, that is, the solar radiation that reaches the Earth's surface to be carried out [3]. Solar radiation provides radiant and thermal energy to the Earth's surface and solar radiation powers soil as heat flux and soil temperature while the growth and evapotranspiration of plants and animals depend on the sensible heat flux. About 99.8 % of energy comes from the sun and it is up to us to tap it for good use on the Earth. All forms of conventional energy on the Earth are derived from the sun for example, fossil fuels have solar energy as input.

Solar radiation measured on the ground horizontal surface is one of the inputs for the performance calculations of solar energy systems and the renewable energy technologies typically depend on the availability of solar radiation, either directly or indirectly. The performance of the solar systems at a given location usually depends on the availability of the insolation and the climatological parameters. The design of solar systems requires a precise knowledge of availability of solar radiation falling at the site of study. For the locations where the measured data is not available, the solar empirical models play an important role.

SA is a high insolation country with an average of over 2,500 hours of sunshine in a year. SA as compared to some African countries has quite an extensive solar radiation output and is over twice that of Europe. The average annual global solar radiation of about 24 Gigawatt hours per square meter ( $\text{GWh/m}^2$ ) is received in SA [2]. This means that SA is among the countries that receives the highest amount of solar irradiance in the world and this makes it a perfect climate for solar energy. The above stated average sunshine hours show that SA is a fortunate

country located in a climate that is suitable for utilisation of solar energy. The agriculturists need the knowledge of solar radiation for their crops. The research study reported in this thesis is to be carried out with the main objective of deriving the solar regression coefficients in different regions of SA so that it can be easier to estimate some important parameters that determine the solar radiation patterns. The study will inform all stakeholders countrywide who want to use solar radiation data for the development of solar energy systems for specific locations.

This research is focused on the determination of the regression coefficients based on one of solar radiation models to enable us to perform the evaluation of the global solar radiation data on the horizontal Earth's surface whereby a five years data from the twenty-four different stations in SA were used. The meteorological data was requested from the Agricultural Research Council (ARC). Selection of the stations was determined by the variability of the climate conditions as well as the availability of the meteorological data to be used in the solar models selected. The linear Angstrom-Prescott model was employed. This model uses the climatological and meteorological data such as temperature, sunshine hours, extra-terrestrial solar irradiance and global solar irradiance, that are accessible either from National Aeronautics and Space Administration (NASA) of the USA, ARC and the South African Weather Service (SAWS).

There is an extensive literature on theoretical models for solar regression models. Some of the models that use the weather data to estimate the global solar irradiance are listed below:

1. Rensheng *et al* suggested the regression model that correlates maximum and minimum temperature, sunshine hours and the ratio of the extra-terrestrial and global solar radiation [4]

$$\frac{H}{H_0} = a * \ln(T_{max} - T_{min}) + b * \left(\frac{S_a}{S_0}\right)^c + d \quad 1$$

where  $a$ ,  $b$ ,  $c$  and  $d$  are the empirical coefficients,  $H$ ,  $H_0$ ,  $S_a$ ,  $S_0$ ,  $T_{max}$  and  $T_{min}$  are the daily global solar radiation, extra-terrestrial solar radiation, actual sunshine duration, the possible sunshine or daylength hours, maximum and minimum temperature respectively.

2. Jin *et al* based their model on the radiation data and the geographical information including altitude ( $Z$ ) and latitude ( $\varphi$ ) of the respective stations in China and is given by [5]:

$$\frac{H}{H_0} = 0.0855 + 0.0020 * \varphi + 0.030 * Z + 0.5654 * \frac{S}{S_p} \quad 2$$

3. Hay model incorporates the ground albedo  $\rho$ , cloudless sky albedo  $\rho_a$  and cloud albedo  $\rho_c$  and is given as [6]:

$$\frac{H}{H_0} = \frac{0.1572 + 0.5566 * \left(\frac{S}{S_p}\right)}{1 - \rho * \left[ \rho_a * \left(\frac{S}{S_p}\right) + \rho_c * \left(1 - \left(\frac{S}{S_p}\right)\right) \right]}$$

where  $S_p$  is the modified daylength whereby the fraction during which the solar zenith angle is greater than  $85^\circ$  is excluded and given by the equation,

$$S_p = \frac{1}{75} * \cos^{-1} \left( \frac{\cos 85^\circ - \sin \varphi * \sin \delta_c}{\cos \varphi * \cos \delta_c} \right)$$

where  $\delta_c$  is the characteristic declination.

In many areas, the temperature, wind direction and wind speed, rainfall, sunshine hours and other meteorological data are measured except the solar radiation data (that is global, beam (direct) and diffuse solar radiation data). Most of the solar technologies depend on the amount of solar radiation falling at the area, accordingly we found that there is a need for finding these empirical coefficients to estimate the global solar insolation in the areas where the observed data is not available.

## 1.2 Problem Statement

A thorough knowledge of solar radiation energy received on the planet Earth is required for the design and operation of any solar energy system in a location. In order to roll out solar energy technologies, solar radiation data should be available. Meteorological data measured at the locations where weather stations are installed is generally not sufficient to allow one to quantify all the phenomena which occur when a photovoltaic panel receives solar light. It is extremely costly to install equipment to measure meteorological data in various stations. Hence the need for empirical regression coefficients. Climatic conditions of locations vary and affect the amount of solar radiation that reaches the earth's surface. It is crucial to study and analyse solar radiation under local climatic conditions. Renewable energy developers always need to know whether the renewable energy projects they would like to provide to the communities are viable or not. This is possible if the historical solar radiation data is available. There is a need for characterising solar radiation in South Africa using different meteorological and climatological parameters such as air temperatures, mean sunrise hours, extra-terrestrial solar radiation. The challenge of developing a feasibility study of the sites ecological, forestry studies and solar plants at chosen specific areas are, is of a dire need. This leads to the evaluation of the solar regression coefficients to alleviate the shortage of solar radiation data. Any empirical solar model which is developed in each site using input data of classical weather parameters produced either by individual site installation or by a nearby meteorological station is only applicable to that site. For the prediction of the climate change in the future, it is necessary to model the ground global solar radiation in the horizontal surface.

### 1.3 Significance of the research

Just like the climate information that enables the agriculturists to determine the agricultural potential at a specific location, the modified regression models developed through the determination of the regression coefficients in this research study will enable the researchers to estimate the hourly, daily or monthly global solar irradiance data and inform the farmers so that they can identify suitable crops to grow during each season and predict the outcome in advance. When the architects design buildings, this data can also assist them to minimize energy consumption by selecting the correct building configurations, orientations, and air conditioning systems. The availability of the data enables designing and sizing solar energy systems through the knowledge of the variability of the data. This will greatly help in the growth of the economy of the country. Accurate solar radiation data benefits the technologists to identify the best geographic locations for the designed solar energy technologies. This research study will enable the climatologists to determine or interpolate global solar irradiance to compensate for the missing data. Furthermore, forestry and ecological studies require the knowledge of the variation of solar radiation over a location.

The renewable energy technologists and manufacturers will be able to develop solar resources that are suitable for specific areas. Monitoring of the adaption of plants and animals as well as plant growth phases by the farmers will be more easily predicted due to the availability of the estimated solar radiation data. Solar irradiance measurements require calibrated pyranometers and pyrheliometers. With the determined regression coefficients, we will be able to make forecast of the irradiation in a location. The solar irradiation data of the nearby sites will then be computed using the appropriate mathematical – statistical model that uses the empirical coefficients determined under this study.

## 1.4 Aim and Objectives

### 1.4.1 Aim

The general aim of doing this research work is to determine the regression coefficients for SA and hence evaluate them by comparing the estimated and observed global solar radiation.

### 1.4.2 Specific objectives

The specific objectives of the study are:

- To determine the regression coefficients at different stations in South Africa (SA)
- To use the determined coefficients and the meteorological data to modify Angstrom- Prescott model for various stations.
- To obtain the average annual regression coefficients for each province.
- To determine the daily global solar radiation for each province.
- To evaluate regression coefficients using statistical techniques in order to test performance of the models.

## CHAPTER 2: ABOUT SOUTH AFRICA

### 2.1 Introduction

South Africa lies between the latitudes 22°S and 35°S. There are three anticyclones that bring descending, dry, warming air resulting in clear skies and sunshine. The mid-latitude cyclones develop at the polar front between 40°S and 60°S latitudes. The cold front from this cyclone brings cold, wet and windy weather to the Western Cape, especially in winter. Most of the Southern Africa consists of a plateau with an average height of 1500 m. Daniel Ciolkosz indicated that South Africa is located at a latitude range and in a climate, that suits the utilization of solar energy [7]. There are some early assessments of solar energy availability according to Drummond & Vowinckel [8]; Schulze & McGee [74], who indicated that the insolation available in SA is as high as 29 MJ/(m<sup>2</sup>day). Assessments of solar radiation in SA by Eberhard and Schulze *et al* confirmed that general finding. Power and Mills indicated that those values are not static over time, with global and diffuse irradiance at South African locations changing as much as 1.7 % and 2.5% per decade [75].

The South African Department of Energy has indicated that most areas in South Africa average more than 2 500 hours of sunshine per year. Furthermore, SA is considered a “relatively dry country,” with an average annual rainfall of only 464 mm compared to the world average of 806 mm. Solar energy applications such as PV cells depend solely on solar radiation. The less the rainfall the more the chance of sunshine, resulting in more generated energy from solar PV. Most of South Africa’s large capacities for development exist in areas such as the Karoo. These locations are sun drenched, relatively flat, have sparse levels of vegetation and a low population density and so it is advantageous for PV solar cells and other applications of solar systems. In comparison, other countries such as Italy, Germany and the US often encounter overlaps of developed/commercialized areas and high irradiation areas, which inhibit the possibility to take full advantage of the solar irradiation exposed at these places. These factors contribute to the outstanding development opportunities for the South African solar industry.

The economic growth of a country is mostly driven by a good status of availability of energy. South Africa has already experienced energy crisis with the energy sector comprising of five main sub-sectors, i.e., electricity, biomass (fuelwood), petroleum products, coal, and other

renewable energy sources such as wind energy and nuclear energy. The country's energy needs are mainly derived from coal, which accounts for 88.5% of the total energy demand. Most of the rural households prefer to use wood for cooking even if electricity is connected to their houses because they cannot afford to buy enough electricity for both lightning and cooking.

## 2.2 SA's landform and its topography

The topography of an area plays an important role for solar energy. The country has considerable variation in climate and its topography which finally contribute in the reduction of the amount of solar radiation that reaches the Earth. Various distinct regions are categorized based on rainfall distribution.

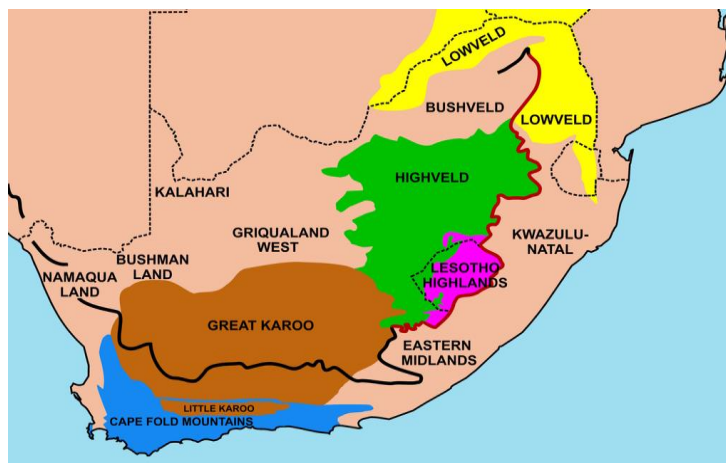


Figure 1: Geographical Regions of SA

In order to harness more solar energy, the knowledge of solar radiation in these topographical areas needs to be available. The following are the topographical divisions [9]

### 2.2.1 Great escarpment

This is a major topographical feature in Africa and it predominantly lies within the borders of SA. The thick line in Figure1 traces the course of the great escarpment. Its highest plateau is found in the east and its edge varies from 2 000 m to 3 300 m in altitude. This is known as Drakensberg Mountains with borders in Namibia, Angola, Zimbabwe and Mozambique. Drakensberg, Khomas Highland and Serra de Chela are different names given to the escarpment in SA, Namibia and Angola respectively.

### 2.2.2 Central Plateau

The plateau covers great Karoo, Griqualand East, Highveld, Bushveld, Bushman land and Kalahari.

### 2.2.3 Coastal plain

This is a flat and low-lying land which is close to the sea coast. The width of the South African coastal plain ranges from 60.0 km to over 250 km in the north-west to north-east. A solar energy project in the form of case study needs to be conducted in such areas.

### 2.2.4 Cape Fold Mountains

These mountains are separated from the great escarpment by approximately 100 to 150 km wide plain known as Lower Karoo at an altitude of 600 - 800 m above the sea level. The formation is due to the folded rocks in the Cape Town hinterland.

### 2.2.5 Coastline

The coastlines in South Africa are smooth and have few harbours for docking ships. The study of solar radiation in these topographical areas would be of utmost importance.

## 2.3 SA Climatic conditions

SA as compared to other countries in Africa has a variety of climatic zones due to being located near the two oceans, i.e. Indian and Atlantic. Our country is a viable area for variety of renewable energy systems such as photovoltaic (PV), wind energy in the coastal areas, bio-energy in the form of biogas digesters due to large percentage of farming, concentrated solar power, biomass, etc. The suitability of each of these systems in the area can be described and documented provided the amount of solar radiation falling in that specific location is well known.

The climatic types per region are shown in Figure 2 below, where the Northern Cape is considered a hot desert area. Recently, several renewable energy technologies, such, the biggest concentrated solar plant (CSP), solar parks as well as wind energy plant have been established in this province. These climatic zones give a good information that relates to the solar exposure that the country experiences. Limpopo Province is referred to as hot and semi-arid and our government has already taken some initiatives of installing solar plants for electricity generation in the region.

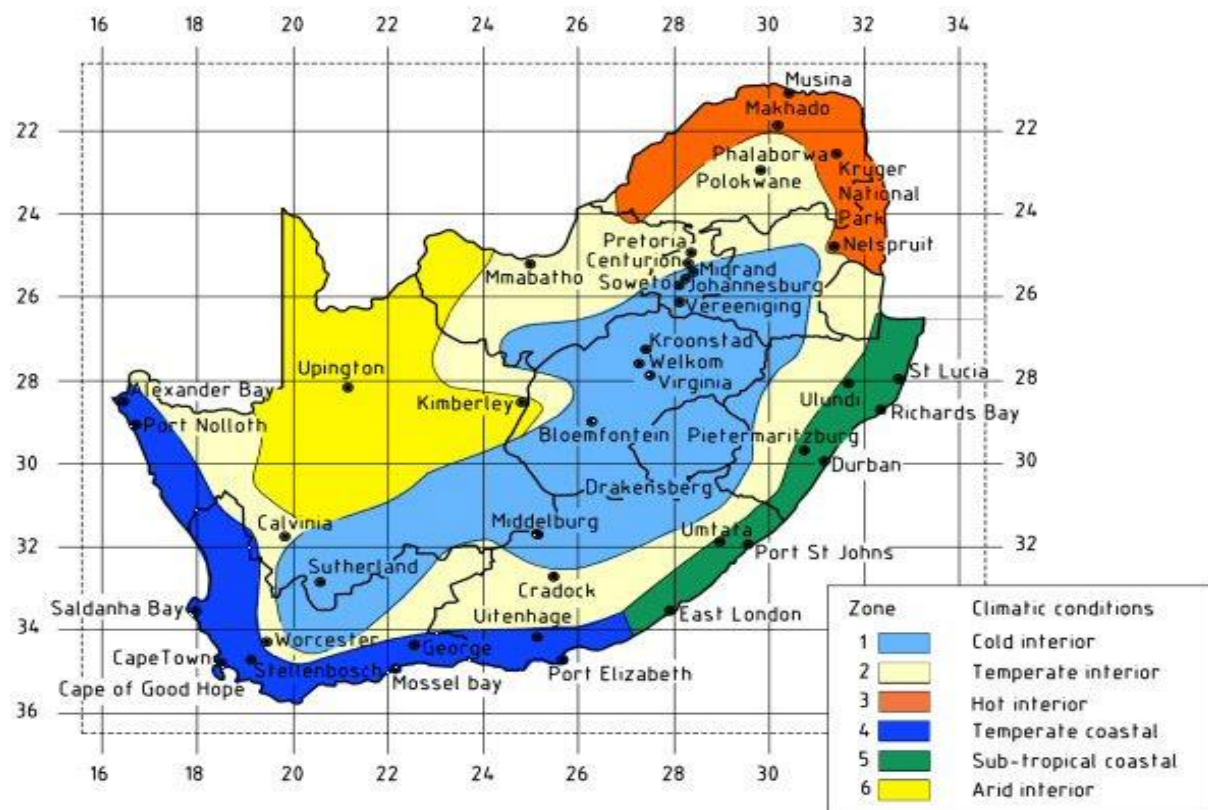


Figure 2: SA Climatic Zones

Cold and warm coastal currents are attributable to the difference of temperatures in the country. Most of the provinces of our country receive rain in summer except Western Cape that has Mediterranean climate with winter rainfall. The oceanic regions are suitable for wind energy systems. It may be seen that more than one climatic condition exists in each SA province. For instance, Western Cape is associated with temperate coastal, temperate interior and cold interior, Eastern Cape experiences the sub-tropical coastal, the temperate coastal, temperate interior and cold interior. In Northern Cape, most of its area is considered as an arid interior.

In most of the rural areas, the households do have herds of cattle, goats, chickens and /or farming, so they can use cow dung, goat or poultry manure to feed biogas digesters for the generation of electricity for cooking. Awareness among the communities of climatic zones is necessary for their livestock. Farming is impacted by the climate conditions which influence the types of domestic animal or crop farming the people should have.

Köppen, the Russian plant physiologist, classified the climatic zones in terms of the vegetation groups . It is of importance to investigate whether the regression coefficients vary according to these zonal demarcations, so the trend of the amount solar radiation falling on each zone can then be known.

Several solar models for the prediction of global solar radiation with temperature data are proposed in the literature. A temperature – based model by Hargreaves and Samani is commonly used and involves the maximum and minimum temperature as well as the temperature coefficient. Some of these models are explained in chapter 3. The average temperatures of some areas in SA in both summer and winter seasons are given in Table 1 below:

*Table 1: Annual average temperatures in SA*

Location	Summer		Winter	
	Maximum	Minimum	Maximum	Minimum
<b>Musina</b>	34	21	25	7
<b>Thohoyandou</b>	31	20	24	10
<b>Polokwane</b>	28	17	20	4
<b>Johannesburg</b>	26	15	20	4
<b>Pretoria</b>	29	18	24	5
<b>Durban</b>	28	21	23	11
<b>East London</b>	26	18	21	10
<b>Upington</b>	26	20	21	4
<b>Kimberly</b>	33	18	19	3
<b>George</b>	25	15	19	7

The range of temperatures in a location play an important role in the performance of the renewable energy systems. The performance of the systems depends on the amount of the temperature received at the specific location where the solar system is installed. Although the PV panels react differently to the ambient temperature, in all the cases the efficiency of a solar panel decreases when operating at high temperature [10]. At the locations where there are no

weather stations installed, the temperature data can be used as the predictors for the solar radiation data as well as for evaluation of the regression coefficients.

## 2.4 Solar radiation and the atmospheric effects

Solar radiation passes through the atmosphere which is full of variety of particles as indicated in Figure 3. Some of them are dust, aerosol, smoke, pollen, volcanic activity, bacteria and viruses. These particles reduce the amount of solar radiation that reaches the Earth.

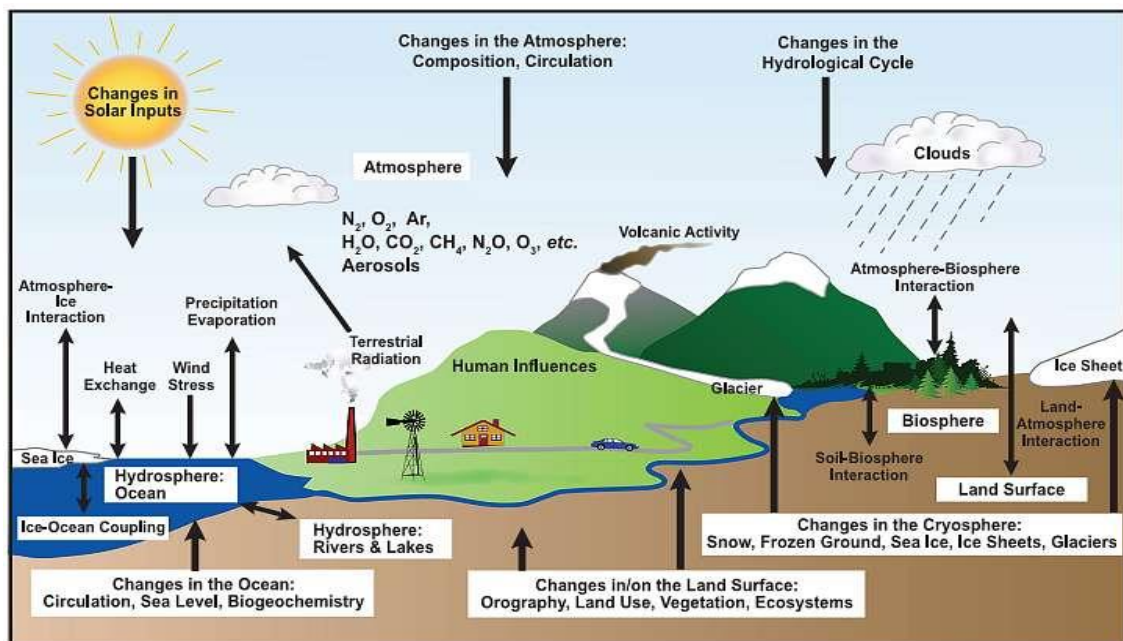


Figure 3: Causes of the variability of solar radiation

Aerosols contribute significantly to change climate and though they are naturally part of the atmosphere, burning fossil fuels such as oil, coal and gas increases their percentage in the atmosphere. A country like SA, depends mostly on coal for the generation of electricity, so we are polluting the atmosphere. The amount of solar energy can be changed by the aerosols in the atmosphere through reflection. When aerosols are struck by sunlight and or black carbon particles of wood or fossil fuels, they react differently. Burning of fossil fuels attributes to the formation of clouds which reflect the incoming solar radiation back to space. Scattering, absorption and reflection are the processes that alter the amount of solar radiation. Part of the incoming solar radiation scatters due to gas particles that are in the atmosphere.

High percentage of the scattered shortwave solar radiation is directed back to space. The same particles that reduce the incoming solar radiation have the ability to absorb it. The particles retain it and later convert it into heat energy. The absorption of solar radiation by the particles in the atmosphere causes the rise in temperatures. According to Wien's law, substances whose temperatures are less than 1 800 °C emit the radiation in the longwave band.

Atmospheric particles reflect the incoming solar radiation. The reflectivity of clouds is considered the highest.

## 2.5 Solar radiation map

Solar radiation maps that are developed in different countries do assist the energy developers in identifying the location where high amount of solar energy is found. We need to recall that these maps are generated from the in-situ or satellite data. In the locations where observed solar radiation data is not available, the estimated data can be used. Institutions such as SAWS, GeoSUN, ARC and ESKOM do perform ground solar radiation measurements. This enables them to generate solar maps that assist the solar developer to identify the potential areas for solar systems installations. One can observe from the map in Figure 4 below, that the whole country is suitable for one kind of renewable system or the other. The South African average global solar irradiance in kWh/m<sup>2</sup> for the period 1994 – 2013 is also depicted in the figure.

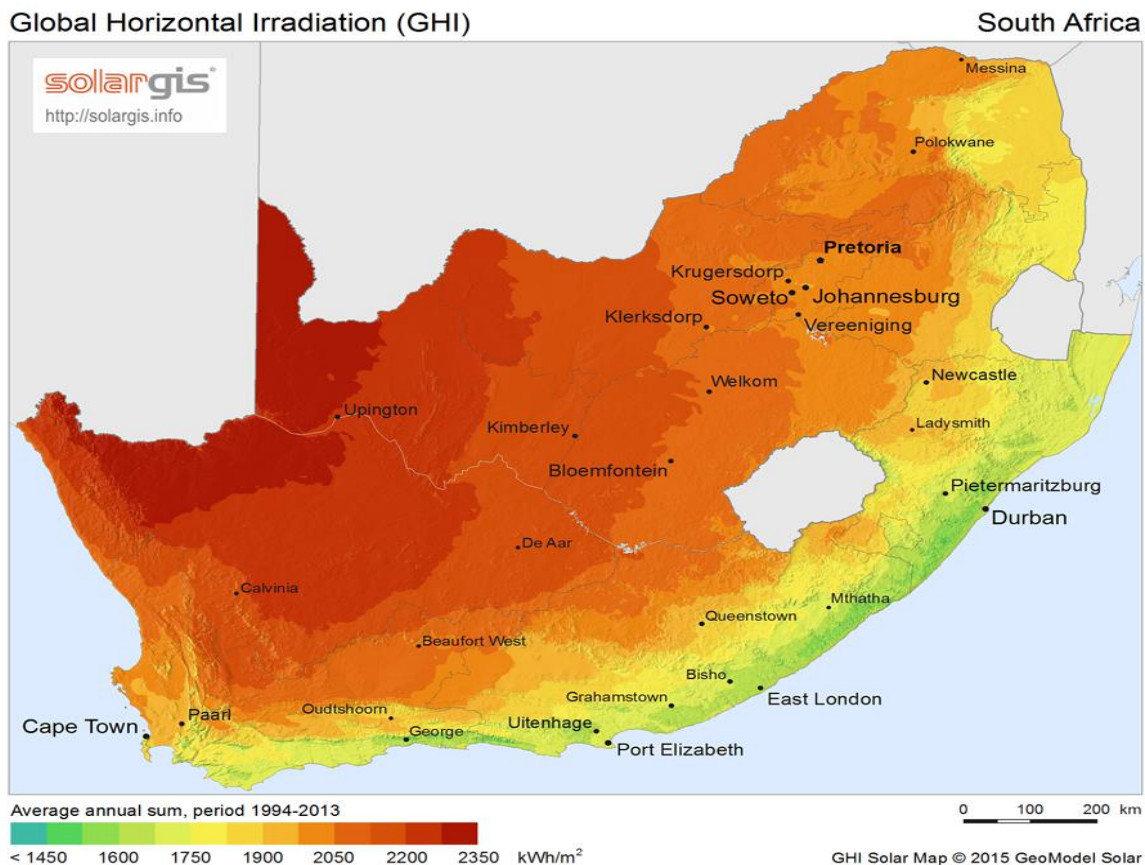


Figure 4: GHI South African Solar Map ( 2017 The World Bank, Solar resource data: Solargis.)

The highest solar irradiance is observed in the Northern Cape Province near Namibia with a maximum of 2350 kWh/m<sup>2</sup>. Generally, this solar map shows that there is a potential for developing solar plants, i.e. concentrated or PV solar plants depending on the amount of direct and/ or the global solar irradiance harnessed and the use of solar energy in a variety of solar systems throughout the country. Some of the solar plants that are installed in the Northern Cape Province are Kalkbult (75 MW), Kathu Solar Park, a concentrated solar plant (CSP) with the capacity of 100 MW which was planned to be in operation in 2018. It was planned to supply electricity to 179 000 homes during the peak demand period; the largest plant is the De Aar solar farm plant with capacity of 175 MW [11]. Many solar developers saw the opportunities of getting involved in the installation of PV solar plants in South Africa.

On the coastal region, as we analyse the wind speed data, the applicability of wind energy is more viable. It must be noted again that the meteorological data of interest can be modelled since not all sites do have the measured data.

## 2.6 Energy status

South Africa largely relies on fossil fuel resources to sustain economic growth and a present-day standard of living. However, it is by economically exploiting the conventional energy resources that have become increasingly limited because of natural limitations. The use of these resources is also questionable because of their adverse environmental impacts and the contribution to global climate change. Figure 5 shows how coal mining destroys the landscape and hence the environment.



*Figure 5: Coal Mining Areas in SA*

Source: [projectsiq.co.za/coal-mines-in-south-africa.html](http://projectsiq.co.za/coal-mines-in-south-africa.html)

Coal prices have increased by about 300 % for the past 20 years and the reserves show depletion. The quality of coal supply is also questionable for the generation of electricity[12]

At present, there are about nine power stations that are at very low coal stockpile levels as announced by the ESKOM on the 28<sup>th</sup> August 2018. Now the country is experiencing stage 1 of load shedding and so, economy is also affected.

The greenhouse gas emissions per country are proportional to the electricity demand. The world annual energy demand has been increasing by 2.3 % since 2008 as predicted by Bundschuh and Hoinkis. The human impact on climate during the last two centuries exceeds impacts caused by the known changes in natural processes, such as solar radiation changes and volcanic eruptions [13]. In order to overcome the natural limitations of conventional energy sources, the country has to use domestic renewable energy sources together with the implementation of energy efficient technologies that are of sustainable options.

Implementation of these options contribute to the reduction of greenhouse gas emissions and make the countries less dependent on energy imports and fossil fuel price fluctuations. We have observed the electricity tariffs increase enormously since 2008 in South Africa and this confirms high percentage dependence on fossil fuels for the generation of electricity. As for now, ESKOM submitted the request to increase these tariffs by 15 %.

Renewable energy resources are economically very attractive compared to conventional energy sources especially in off-grid areas. New residential areas are allocated to the South Africans without the grid line of electricity. The renewable energy is a solution to this problem. For solar developers, the knowledge of solar radiation falling on the horizontal surface of the Earth at each location is crucial. Unfortunately, instruments for the collection of this essential data (solar irradiance) are not installed in many locations due to the shortage of funds and maintenance needs. The present study will come in handy whereby suitable models with correct regression coefficients are then employed for the estimation of solar radiation.

## 2.7 Energy security in South Africa (SA)

Energy security can be explained well using the three A's, that is Accessibility, Availability and Acceptability. Accessibility relates to how the public sector can access energy financially, whether the electricity tariff is affordable sustainably at the cost of suppliers. Most of the South African rural communities are not able to buy enough prepaid electricity, so they resort to the use of biomass, wood, for cooking though cutting of trees is not environmentally user friendly. It is an obvious case that the use of wood increases emission of gases hence a factor to the depletion of ozone layer.

The availability of energy relates to the long - term continuity of supply as well as short term supply of service to the community. Shortage of energy disrupts the economic development since both domestic and export may be mal-functioning [14]. The type of the energy resource that South Africa uses (i.e. coal) is not environmentally friendly because it pollutes the Earth. Due to high costs of electricity, most of the rural community resort to the usage of biomass that causes deforestation, land degradation and local soil erosion. This shows that acceptability is not actually at high percentage; the introduction of alternative energy resources is important.

Now, a total of 3900 megawatts of renewable energy has also been sourced, with 32 projects having a capacity of just over 1500 megawatts completed and connected to the grid.

## 2.8 State of electricity in SA

The rise of economic output has increased the electricity generation by 3.1 % or 780 TWh worldwide in 2017 as electricity demand rose faster than the overall global energy demand growth. Roughly, 89% of South Africa's electricity is generated through coal-fired power stations whereas only 2.4 % is provided by renewable energy sector. ESKOM supplies 95 % of its electricity generation to the South Africans' businesses, organization and households. It has 77 % connection rate in rural areas and 90 % in urban areas. One can conclude that, we still have a gap especially in rural areas in which 27 % of their population is living without electricity. The load shedding (blackouts) that have occurred in 2014-2015 and 2018 have highlighted the acute shortage of skills and resources to drive SA's R420 billion infrastructure plan. These blackouts have affected the businesses and mines economically. Most of the investors are worried about the future shortage of electricity. It was realised that for the next twenty years the demand for power would double due to population increase. The growth of the economy in the country is controlled by the availability of the resources. Eskom fast tracked three of the biggest power plants, that is nuclear energy plant, Medupi coal power plant at Lephalale in Limpopo and Bravo coal-fired power station near Witbank in Mpumalanga [15 & 16].

The on-going plans about developing some new power plants, either nuclear or coal-fired plants suggest that the electricity consumers expect annual hikes of electricity tariffs of up to 20%. For large resource companies though, the impact has forced ESKOM to review their project schedules until they can guarantee supplies of competitively priced power. This is investment SA can ill afford to lose. For the reduction of these tariffs, some alternative energy resources like renewable energy (PV solar cells, hydro-power, wind energy, etc.) must play a vital role. To address this challenge of electricity cut-offs, some community members have started to install the PV panels and most of them were off-grid. It is very crucial to know the amount of solar radiation falling at the specific area. Whether one is installing the solar water heater or the PV panels, the amount of irradiance is necessary to be known. For the development of a PV solar plant, the developer must know the historic amount of solar radiation received at that specific site.

To diversify the country's energy mix and attract more Independent Power Producers (IPPs) to the sector, SA has developed a renewable energy independent power producer program over the past five years, namely the Renewable Energy Independent Power Producer Procurement Program (REIPPPP), that has proven very successful in bringing renewable energy projects to commercial operation. To date, REIPPPP has successfully procured 6.4 GW from 102 IPPs across six bid windows [15].

According to the then finance director at Eskom holdings, Bongani Nqwababa, building large projects would take about four to five years to start commissioning. During this stage, as a country, we should be able to have enough capacity. It was also stated that there were some projects that were planned already that fall under the twenty-five years of Eskom's supply deal. An example of the projects is Alcan Aluminium smelter at Coega. Anglo Platinum's R39 billion expansion programme required an extra 500MW of capacity from 2013 in addition to its current consumption of about 1000 MW. The company was confident that the power can be supplied [17].

South Africa is experiencing financial problems pertaining to service delivery. According to the SA constitution, people are entitled to be given land which must be accompanied by the provision of electricity. Due to lack of funds, it is difficult and expensive to distribute and put transmissions of energy generated from fossil fuels to the most rural areas as well as new stands with few houses, so producing renewable energy locally do offer a viable alternative.

## 2.9 Emission of CO<sub>2</sub>

The rising of population and energy consumption in South Africa has influenced the decision of building more coal power stations and so, increases the usage of fossil fuels which tends to raise the CO<sub>2</sub> in the atmosphere. The contributors of CO<sub>2</sub> to the atmosphere are many and include motor vehicle emissions, burning of fossil fuels, etc. The effects of excess CO<sub>2</sub> are listed in Figure 6, namely, increase in the GHG concentrations, incidence of respiratory and cardiovascular diseases, bad local air quality, etc. South Africa as a developing country needs more industries which results in the reliable and sufficient supply of energy sources.

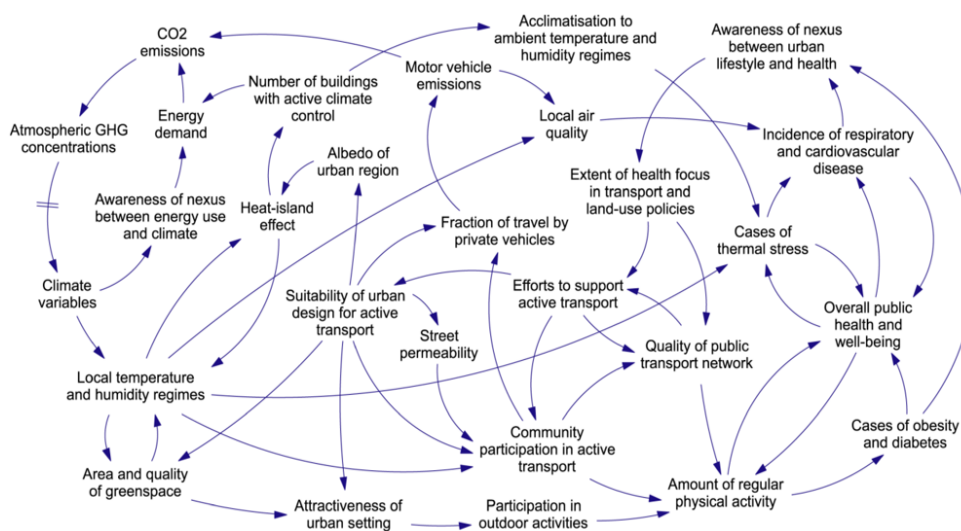


Figure 6: Generation and effects of CO<sub>2</sub>

The largest per capita percentage of CO<sub>2</sub> is due to fuel combustion. There is no doubt that the rise of the country's economic output is attributed to the energy production but if the production of energy is due to coal, the environment is badly affected. Bad local air quality contributes to the population's health problems such as cardiovascular diseases. The average local temperature and humidity increase lead to climate change. In 2017, the emission of CO<sub>2</sub> increased by approximately 1.5% globally as depicted in Figure 7 [16]. The increase in the emission of CO<sub>2</sub> has already shown some effects such as climate disruptions and local imbalances in food security as well as hydrology in South Africa. The Northern Cape province is one of the examples where drought had been experienced in 2017 when there is acute shortage of water supply. The socio-energy related problems can be alleviated provided our country introduce the use of renewable energy resources.

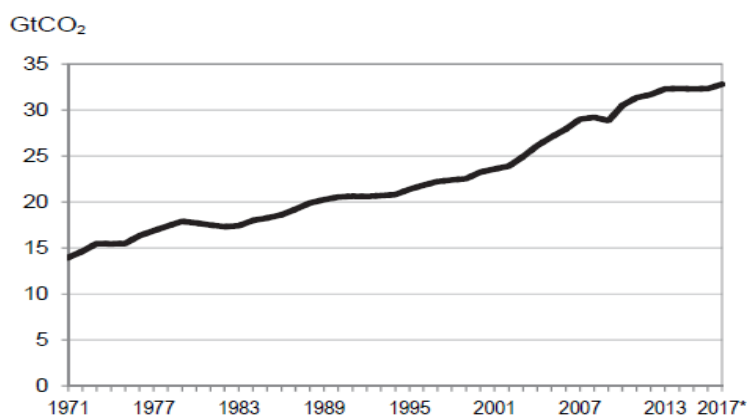


Figure 7: Global trend of the CO<sub>2</sub> emission from fuel combustion

Source: IEA (2018) - CO<sub>2</sub> emissions from fuel combustion.

There are a variety of non-renewable sources that produce CO<sub>2</sub>. As shown in Figure 8, there was a decrease in CO<sub>2</sub> due to coal. That was due to the implication of the strategies that the countries had made for themselves for the mitigation of climate change whereby they were to reduce the emission of CO<sub>2</sub>. One of the strategies was to use mixed resources of energy production, preferably the renewable energy resources. Waste in the figure below, refers to the industrial and municipality wastes. Due to the shortage of jobs and resources, people migrated to the urban areas, hence the increase in the municipal waste. The increase in the CO<sub>2</sub> emission by oil was attributed to transport. The more the people acquire their own cars and keep them on the road, the more the emission of CO<sub>2</sub>. South Africa once implemented the strategy of taking a friend to work to curb the emission of CO<sub>2</sub>, whereby people were expected to travel as a group to reduce the traffic on the road, but it was not sustained.

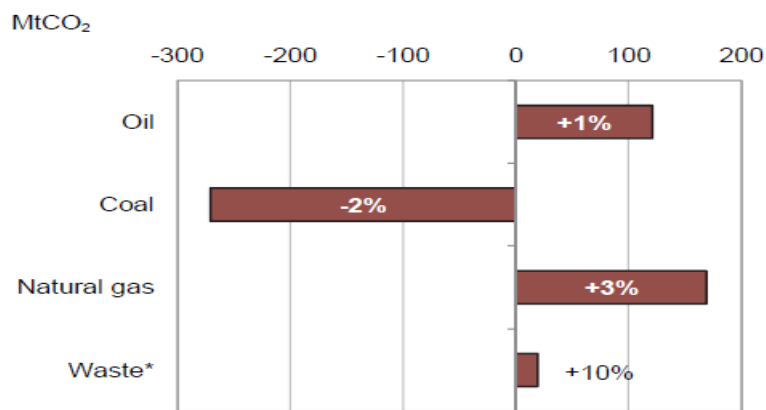


Figure 8: 2016 Global CO<sub>2</sub> emission by source

(Source: International Energy Agency (IEA) – 2018)

Global carbon dioxide emission attributed to coal has reduced by 2% while these other three sources, i.e., oil, natural gas and waste have led to increases of 1 %, 3 % and 10 % respectively. Waste has emitted more of the carbon dioxide due to the municipality garbage. The middle-class people are migrating from the rural areas to the urban areas due to lack of community services that the government is not supplying. Since the economic growth is linked to energy production, between the years 2000 – 2013, CO<sub>2</sub> emission was observed to have grown by 2.6 %. The implementation of the use of mixed or only renewable energy, reduces the emission of CO<sub>2</sub> which is harmful to the climate as well as human's health. [16]

Compared to fuel wood that most of the rural people use for heating and cooking purposes, coal fuel emits high percentage of CO<sub>2</sub>. Vegetation at different locations do contribute in parts

per million the CO<sub>2</sub> that the Earth's atmosphere receives though it is of very low percentage. To mitigate the depletion of ozone layer, the use of renewable energy for generation of electricity should be prioritized. Somehow, people should be warned against the cutting of trees that absorb most of the released CO<sub>2</sub>. The burning of fossil fuels produces about 21.3 Gigatons of carbon dioxide annually worldwide. The total CO<sub>2</sub> emission in SA was 367.6 million tons in 2011 and it was an increase of 20.76 million tons of CO<sub>2</sub> emissions as compared to the 2010 value of 346.837 million tons. Most of the South Africa's CO<sub>2</sub> emissions are from the use of coal and burning of other fossil fuels. The CO<sub>2</sub> emission in SA in the year 2013 is given in Table 2 below [17].

*Table 2: CO<sub>2</sub> emission in SA through fuel .*

Source of emission	Metric tons of CO <sub>2</sub>
Transport	13.15
Residential, commercial and public sources	5.63
Other sectors except residential buildings	2.52
Manufacturing industries and constructions	12.48
Electricity and heat production	66.22
Solid fuel consumption (the use of coal)	400.044

This seemingly proves that there is a net increase of some billion tons of atmospheric CO<sub>2</sub> annually since the natural processes can only absorb about fifty percent of that amount. Emission of CO<sub>2</sub> from the combustion of various fuels can be calculated using the following equation[18]:

$$e_{\text{CO}_2} = \left( c_f / E_f \right) \left( \text{MW}_{\text{CO}_2} / \text{MW}_c \right) \quad 3$$

where  $e_{\text{CO}_2}$  is the CO<sub>2</sub> emission in kg<sub>CO<sub>2</sub></sub>/kWh,  $c_f$  is the carbon content in the fuel in kg<sub>C</sub>/kg<sub>fuel</sub> and  $E_f$  is the energy content in the fuel in kWh/kg<sub>fuel</sub>.

$$\text{MW}_{\text{CO}_2} / \text{MW}_c = 44 / 12 = 3.7 \text{ tons of CO}_2 \quad 4$$

where  $\text{MW}_{\text{CO}_2}$  is the molar mass of CO<sub>2</sub> and  $\text{MW}_c$  is the molar mass of carbon (C).

South Africa like any other country emit CO<sub>2</sub> from the combustion of various fuels like coal (for electricity generation, warming houses, cooking), gasoline, oil, diesel, wood, etc. The emission of CO<sub>2</sub> into the atmosphere affects the ozone layer that acts like a blanket to the living organisms on the Earth. The depletion of ozone layer allows more of solar radiation especially ultraviolet (UV) radiation to fall on the Earth. Presently, the level of CO<sub>2</sub> has reached 380 ppm showing an increase of 36 % since 1850. The world is experiencing a temperature increase which causes a release of the CO<sub>2</sub> from the ground and seawater. Some possible consequences of these increases include ice melts in the Antarctica, sea level rises and severe storms because of the additional energy in the atmosphere. As the ice melts, the resulting darker water and ground absorb more sunlight, thus exacerbating the global warming. The melted water flows like a river, causing rapid heat transfer and erosion [17].

The use of renewable energy systems will reduce the emission of CO<sub>2</sub>. The South African government just like any other developing country has phased-in carbon tax for fuel and diesel. This tax is integrated to the producers as well as the purchase price of the consumer. In 2009, the electricity levy of 2c/kWh was implemented. Eskom's annual tariff adjustment for 2018/9 is 5.23%.

Table 3 below shows the annual adjustment for the period of 10 years:

*Table 3: Eskom tariff adjustment for the last 10 years.*

<b>Year</b>	<b>Average Price Adjustment %</b>	<b>CPI %</b>
<b>2009/10</b>	31.30	6.16
<b>2010/11</b>	24.8	5.40
<b>2011/12</b>	25.80	4.50
<b>2012/13</b>	16.00	5.20
<b>2013/14</b>	8.00	6.00
<b>2014/15</b>	8.00	6.00
<b>2015/16</b>	12.69	5.70
<b>2016/17</b>	9.40	6.59
<b>2017/18</b>	2.20	5.30
<b>2018/19</b>	5.23	4.6(forecast)

(Source: Eskom tariff & charges 2018/2019)

It clearly observed from Table 3 that the rates of electricity are increasing annually. Comparing the country's unemployment rate (especially in the rural areas) and continually rising cost of electricity is bought for the purpose of household use, a challenge is observed. Thus, most of the people would prefer to use electricity for lightning instead of heating and cooking. They opt for the use of LPG and /or wood in the rural area. For a prepaid electricity, currently, 312 units cost R400.0. For a period of the last 10 years, the average CPI was 5.54. [16]

## CHAPTER 3: THEORETICAL CONSIDERATIONS

### 3.1 Introduction

Meteorological data such as humidity, sunshine hours, air temperature, wind, rainfall and solar irradiance (global, diffuse and direct) play a vital role in the appropriate design of renewable technologies suitable for a given location. These parameters differ from one location to another due to several factors that are outlined in the next section. Due to the variability in atmospheric conditions (aerosol burden and water vapour, principally) the solar radiation varies in space and time such that when the atmosphere is dry and clean the attenuation (absorption and scattering) is expected to be low and vice versa.

Solar radiation data becomes very important due to the increasing number of solar energy applications in the country. The data can be expressed as average monthly, daily or hourly depending on the kind of the application. For the climatological studies or to conduct the feasibility study of solar energy, the monthly or daily data of solar parameters are used [20 & 21]. Measuring solar radiation data for a region is seldom feasible as it is highly variable from one region to another due to slope variation and surface orientation. In many countries, there is no adequate spatial actinometric stations due to the cost of such equipment that accurately measure meteorological data. Examples of actinometers include pyranometers, pyrheliometers and pyrgeometers. This shortage has prompted the development of techniques and procedures for estimating solar radiation data [22] .

In South Africa, many weather/meteorological stations that are available do not have the ground measured data of solar radiation; if it happens that they exist, it is not easy to access such data and hence there is a dire need for estimating the horizontal solar radiation data. Most of the theoretical models employed in the determination of solar radiation use the regression constants as inputs, so, it is of necessity to find these regression coefficients. Several solar models like the temperature-based equation, angstrom equations (linear, quadratic, exponential, etc.) can be used. Each of these equations has the need of some measured data like temperature data, sunshine hour data. The scope of records of available meteorological measurements varies from one station to another. However, the reliability of these data is also questionable. The reliability of the measured data is insufficient for use, so there is a need for the correlated data.

## 3.2 The importance of solar radiation data

Solar resource data plays an important role to all living organisms. For land reforms, the data helps in the understanding of the land atmosphere energy exchange [23].

As explain earlier, due to the shortage of finance and the cost of the solar radiation instruments, it is not possible to install enough apparatus in each region in South Africa, so the solar models play a crucial role in estimating solar radiation data. It becomes pertinent to have very good knowledge of the current and past records of solar radiation at a location so as to aid in the estimation of the performance of any solar energy system. We need to bear in mind that solar radiation is the driving force of both physical and biological cycles on the Earth [23].

Solar radiation data is of importance for the purpose of building solar energy devices, estimating crop productivity, designers and manufacturers of solar equipment. The knowledge of solar parameters such as temperature, possible sunshine hours, wind and its direction, altitude and latitude, plays an important role since these parameters are needed for the prediction of the efficiency of a possible solar system at a particular location [24].

For the purpose of worldwide marketing, a global study of the world distribution of global solar radiation requires the knowledge of solar radiation data in various countries [25]. The measured data is the best form of the knowledge needed but the coverage of the meteorological stations around the country is not enough, hence the common practice of estimating the global solar radiation.

## 3.3 The Sun and Quantification of Solar Radiation

The sun radiates electromagnetic energy. The annual total power that is incident on the Earth's surface is  $1.73 \times 10^{14}$  kW. The sun plays a vital role in all the living organisms on the Earth and it is the most important energy source available to us. As first established by Kepler, the Earth orbits elliptically as depicted in Figure 3.1 below [24]. This shows that the distance from the Earth to the sun varies throughout the year. The maximal intensity of sun rays hits the Earth  $23.4^\circ$  north of equator at the June Solstice (at the Tropic of Cancer), and  $23.4^\circ$  south of equator at the December Solstice (at the Tropic of Capricorn). The seasons vary due to this inclination.

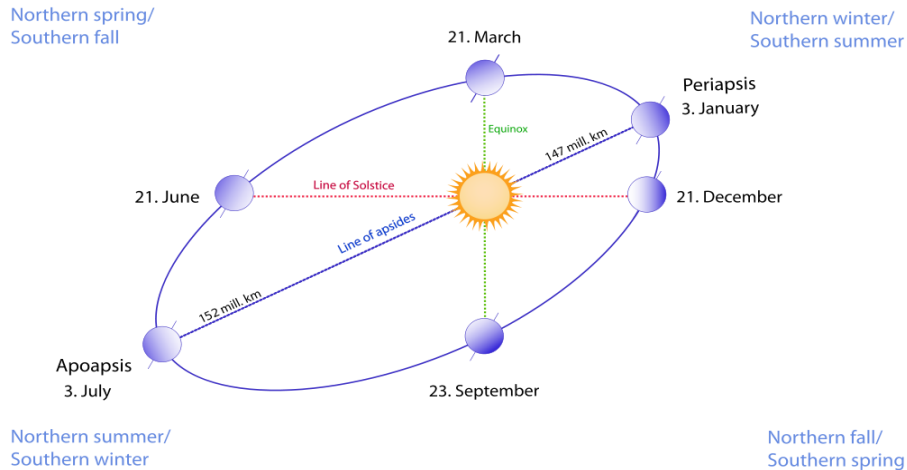


Figure 9: The schematic representation of the Earth's orbit around the sun

The average power of the solar radiation perpendicular to the main direction of the sun rays is  $1367 \text{ W/m}^2$ . Though this is called the solar constant, this quantity is not constant, but it varies inversely proportional to the square of the distance from the Earth to the sun. The fluctuation of average power of solar radiation is about 6.9 % annually. The sun and solar radiation have physical impact on the Earth such as, the currents and tides, the weather, and the biosphere. This tells us that, the sun is not only a direct renewable and practically inexhaustible source of energy but also the ultimate origin of most other renewable energy resources such as wind energy, ocean energy, as well as biomass. It is worth noting that biomass was the original energy material source for fossils fuels, coal, shale, oil, and gas, albeit a million years in the making. The intensity of solar radiation reaching the surface of the Earth is not geographically constant hence the need of measuring or predicting these components of solar radiation (i.e. global, direct and diffuse) in different locations [28 & 29].

There are different ways of quantifying solar radiation that reaches the surface of the Earth. Some of them are listed below:

1. Radiant energy (in Joules (J) or calorie (cal) which is defined as a measure of the capacity of an electromagnetic (EM) wave to do work by moving an object, heating, or changing its state from solid to liquid, liquid to gas or vice versa.
2. Radiant flux (W) which is the rate of energy flow passing through a certain location.
3. Radiant flux density ( $\text{W/m}^2$ ) is the flux intercepted by a planar surface of unit area.

- The flux density is also called irradiance which is the rate of incident energy and the SI units of irradiation are  $\text{kJm}^{-2}\text{h}^{-1}$  or  $\text{MJm}^{-2}\text{day}^{-1}$
  - Exitance or emittance is flux density leaving a surface.
4. Intensity which means irradiance from a certain direction and confined within a unit solid angle. In meteorology, intensity is used for radiative flux and the quantity of solar radiation arriving from the sky dome. This has an SI unit of  $\text{Wm}^{-2}\text{sr}^{-1}$  [30].
  5. Electrical energy is expressed in terms of kilowatt hours (kWh)

### 3.4 Spectral distribution of radiation flux.

Generally, solar radiation is defined as the radiant energy that is emitted by the sun, particularly electromagnetic energy. Energy from the sun is not evenly distributed over all the wavelengths as seen in Figure 10. This figure shows how solar radiation intensity is distributed at various wavelength intervals. The spectral integration of the extra-terrestrial solar spectrum over all possible wavelengths i.e. from zero to infinity is usually referred to as the “solar constant” or “air mass zero” (AM0) spectrum as depicted in Figure 10. A more proper name of the extra-terrestrial solar spectrum has been modified to the total solar irradiance due to the slight variation of the sun’s output from short (daily) to long (decadal) periods [28].

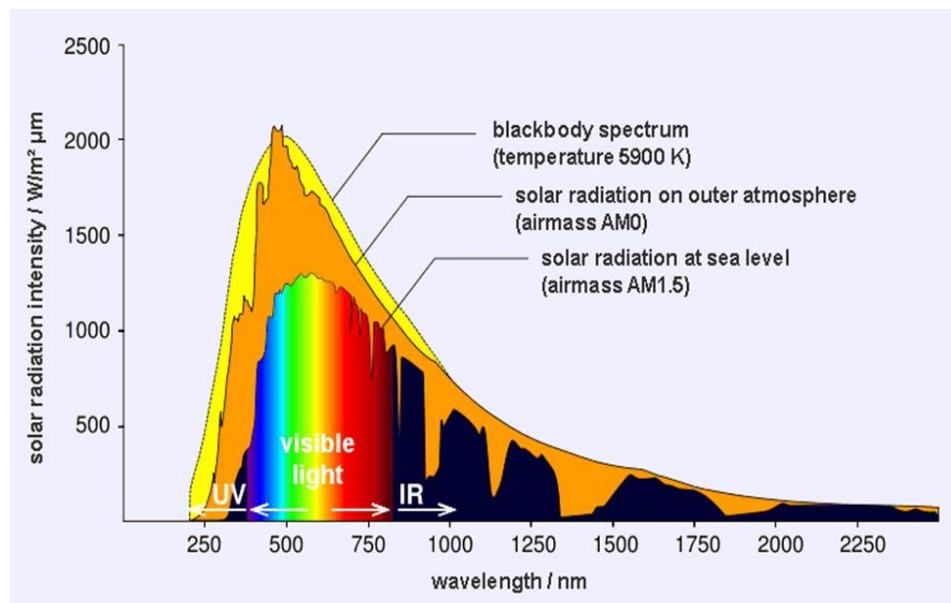


Figure 10: Spectral distribution of solar radiation

(Source: <https://images.search.yahoo.com/yhs/search?p=source+of+spectral+distribution+of+solar+radiation+chart>)

The radiation intensity from the sun is spread over a wide range of frequency. As observed from Figure 10, solar radiation contains electromagnetic wavelengths from as short as 250 nm (ultraviolet light - UV) to a maximum of 450 nm (visible light). The fraction of the total power emitted in a given wavelength band, say from  $\lambda_1$  to  $\lambda_2$  is expressed by the equation [30]:

$$I_{\lambda_1-\lambda_2} = \frac{1}{\sigma T^4} \int_{\lambda_1}^{\lambda_2} e_{b\lambda} d\lambda = \frac{1}{\sigma T^4} \left( \int_0^{\lambda_2} e_{b\lambda} d\lambda - \int_0^{\lambda_1} e_{b\lambda} d\lambda \right) \quad 5$$

where  $T$  is the temperature of the sun 5900 K,  $\sigma$  is the Stefan-Boltzmann constant whose value is  $5.6697 \times 10^{-8} \text{ W} \cdot \text{m}^{-2}\text{K}^{-4}$  and  $e_{b\lambda}$  is the total emissive power of a blackbody (in this case we consider a blackbody as the sun) at the wavelength  $\lambda$ .

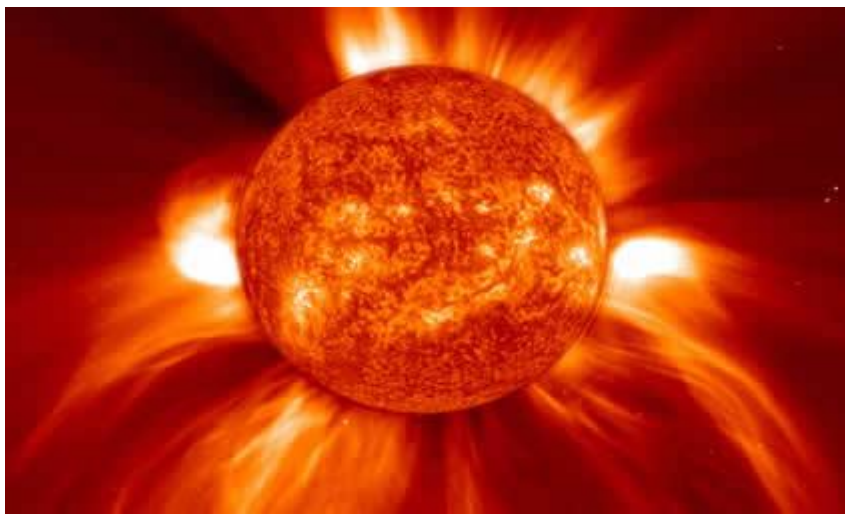
The emitted radiation by the sun is greatest in the visible region of the spectrum. Living organisms respond differently to different parts of solar spectrum. In the renewable energy utilization of solar radiation, we generally bank on the so called “optical radiation”, that is visible radiation with a spectral range of about 300 - 7000 nm.

A perfect radiator also called a blackbody obeys Planck’s equation for average energy radiated:

$$E_{av} = \frac{hf}{e^{\frac{hf}{kT}} - 1} = \frac{hc/\lambda}{e^{\frac{hc}{\lambda kT}} - 1} \quad 6$$

where  $T$  is the temperature of the sun 5900 K, Planck’s constant,  $h = 6.6261 \times 10^{-34} \text{ J} \cdot \text{s}$ . Solar radiation as measured on the outer surface of the atmosphere varied slightly annually and according to WMO the averaged value is  $1367 \text{ W/m}^2$ . This value is called solar constant which is defined as the quantity of solar energy at normal incidence outside the atmosphere at the mean sun-earth distance. It is of importance to have the knowledge of solar irradiance from the sun since this is the driving force of all living organisms. All other forms of energy are derived or generated from the sun. The intensity of solar radiation at the upper atmosphere is subject to both seasonal and diurnal variations. South Africa is surrounded by mountains and the topographic variation in the slopes of terrain do produce local differences in solar radiation falling at that specific area. It has been also noted that changes in elevation alter temperature, precipitation, and winds. [76].

The sun emits an amount of radiation that depends on the presence of solar flares and sunspots. Solar flares which are defined as the explosion of energy on the sun take place when the magnetic energy accumulated in the solar atmosphere is suddenly released. The observation of solar flares is rapid and intense in the variation of bright light as shown in the Figure 11. The radiation released by solar flares interferes with the radio communications on Earth. Solar flares are sometimes accompanied by a coronal mass ejection (CME) which are huge bubbles of radiation and particles from the sun. These CMEs can also interrupt the power utility grids which can cause electricity shortages and power outages. [31]



*Figure 11 : Solar Flares*

Sunspots: These are regions that appear to be dark on the solar system (as shown in Figure 11). The temperature of the sunspot is about 6500 degrees Fahrenheit. Sunspots are formed at the strongest regions of the magnetic fields. Variation of solar radiation reaching the Earth surface is also due to these magnetic fields that keep some of the heat within the sun hence keeping the sunspots cool. The large number of sunspots that passes across the point of observation reduces the radiative intensity measured at that point.

### 3.5 Factors that affect solar radiation reaching the Earth

The amount of solar radiation that reaches the Earth varies due to several factors. The amount depends on the solar flux known as solar constant. This is described by the following relation:

$$I_0 = I_{sc} \left( 1 + 0.0344 * \cos \left( \frac{n}{365} * 360^\circ \right) \right) \quad 7$$

where  $I_0$  represents the hourly extra-terrestrial irradiance on the horizontal surfaces,  $I_{sc}$  is the solar constant whose value is  $1367 \text{ W/m}^2 \sim 4921 \text{ kJ m}^{-2} \text{ h}^{-1}$  as adopted by the World Radiation Centre (WRC) considering the results of over 25 000 ground measurements of the absolute radiometers of different type and design of the so-called world standard group (WSG) maintained at WRC. In equation 7,  $n$  is number of days (from 1 January to 31 December) of the year [32].

The recently adopted value of  $1367 \text{ W/m}^2$  has a standard deviation that ranges between  $\pm 1.6 \text{ W/m}^2$  to  $\pm 7 \text{ W/m}^2$ . The hourly extra-terrestrial irradiance varies throughout the year due to elliptical orbit of the Earth as it revolves around the sun. In 1971, NASA adopted an  $I_{sc}$  value of  $1353 \text{ W/m}^2 \sim 4871 \text{ kJ m}^{-2} \text{ h}^{-1}$  whose estimated errors were  $\pm 1.5 \%$ . Some of the factors that influence the amount of solar radiation received on the earth are briefly discussed in the following subsections 3.5.1 – 3.5.2:

#### 3.5.1 Atmospheric effects

The atmospheric effects reduce the power of solar radiation due to the absorption, scattering and reflection in the atmosphere. It is known from optics that when a ray of light strikes matter, part of it is reflected, another part is absorbed and yet the remaining part is transmitted, so it is for solar radiation as it is passing through the atmosphere. This impacts negatively on the photovoltaic applications. These effects also change the spectral content of solar radiation as observed from Figure 10. The impacts of the atmospheric effects on the amount of solar radiation falling on Earth is summarised in Figure 12 below:

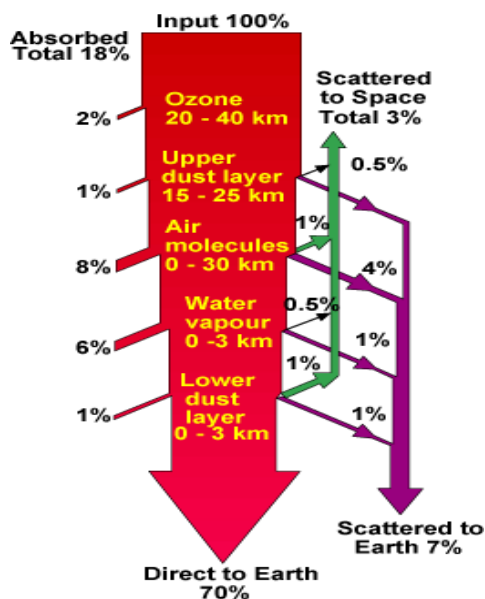


Figure 12: Solar irradiance falling on the Earth

Ozone, dust, air molecules and water vapour reduce the amount of solar radiation reaching the Earth as per absorption percentages indicated. The absorption of solar radiation by atmospheric molecules (i.e., water, oxygen, ozone and carbon dioxide) is a selective process that converts incoming energy to heat. As altitude increases, the concentration of  $O_2$  decreases while the concentration of  $O_3$  increases. Ultimately, the amount of ozone increases with altitude [29]. Robinson, 1966 found that there is a seasonal variation of the atmospheric ozone at different latitudes. South Africa's latitude of  $30^\circ S$  has the following monthly amount of ozone in (cm (NTP)) [15]:

Table 4: Seasonal variation of ozone content at  $30^\circ S$  latitude

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.27	0.28	0.26	0.27	0.28	0.28	0.29	0.31	0.32	0.32	0.29	0.29

It is observed from the tabulated data that high levels of the atmospheric ozone were measured between August – October which is a windy season confirming that dust does play a critical role. The concentration of gases is not homogeneously distributed in the atmosphere. These variations are caused by industrial and agricultural activities at the area of observation as well as its surroundings. In some places, like rural areas, the roads are dusty, hence we expect the scattering of solar radiation to be more compared to the urban areas. All these air molecules

deplete solar energy of all wavelengths by scattering though it is known that they absorb solar radiation at selective wavelengths.

Aerosol particles are also derived from factors such as forest fires, industrial smoke, volcano eruptions and dust. A hazy or turbid atmosphere shows that it has aerosol. About 7% of solar irradiance is scattered to the Earth. The absorbed solar radiation heats up the atmosphere of the Earth.

### 3.5.2 Local variations

The nature of the actual surface absorbing solar radiation varies from one place to another. These variations of the insolation are due to percentage of ice or snow that reflect solar radiation; dust causes Mie scattering— depending on the particles that constitute that dust and air pollution. The emission of carbon dioxide ( $\text{CO}_2$ ) reduces solar resource by scattering and absorption of solar radiation. Recent recorded evidence shows that human beings contribute to the budget of  $\text{CO}_2$  whereas the combustion of fossil fuel has steadily increased the rate at which  $\text{CO}_2$  is introduced to the atmosphere [19]. We cannot deny the fact that emission of  $\text{CO}_2$  differs from one area to another.

Aerosol particles scatter solar radiation (Rayleigh scattering) in the visible spectral range and absorb infrared radiation emitted by the Earth's surface and atmosphere. These particles are anthropogenically created through combustion and industrial processes such as mining, biomass burning, biomass burning and burning of forest resulting in smoke.

Seasonal variations also affect the amount of solar radiation we receive on the Earth. Noting that the sun orbits around the Earth elliptically, so it closer to the Earth during summer (i.e. in Southern Hemisphere, this occurs from November to February) and far away in winter. Forests do play an important role in the amount of solar radiation that the area receives.

### 3.6 Solar Energy

Energy demand is the primary driving force for almost all industrial capabilities as well as the economic development of a country. Just like in any other country, SA is also experiencing limited sources of energy while on the other hand the population is growing and exerting pressure on additional energy demands. There were times when power generators were popular and used by the middle-class people (those who had money), the poorest of the poor used wood (biomass) and paraffin where possible in South Africa . Since then the continuous growth of the energy economy across the world has focused on various sources of energy, such as solar, nuclear, wind, water, oil, and gas. Nuclear energy has the problems of potential radiation hazards and nuclear waste [20].

The electrical energy sources derived from coal, wood, gas, and oil generate large amounts of pollution in the form of carbon dioxide emissions, thereby posing health risks and depletion of ozone layer. The above-mentioned electrical energy power sources require large capital investments and scheduled maintenance. For instance, in case of coal-fired power plants, high capital investment, coal transportation cost, and delivery delay under adverse climatic conditions could pose serious problems, so these lead to load shedding as we, the South Africans have been experiencing since 2014. It is high time that alternative energy supply such as renewable energy sources were taken into consideration to provide pollution-free, self-contained, reliable, quiet, long-term, maintenance-free, and year-round continuous and unlimited operation at moderate costs.

The knowledge of the local solar radiation is essential for the proper design of different solar energy systems and evaluation of thermal environment within buildings [26]. Electricity tariff is increasing tremendously, so we recommend that the solar energy contributing about 5000 times the total energy input from all other sources be harvested and used.

### 3.6.1 The origin of solar energy

The sun's radiant power comes from the nuclear fusion reactions at its core. This power is generated by the proton-proton reaction whereby four hydrogens are converted to one helium. That is, [26 - 28]



The developed and underdeveloped countries are trying to tap the enormous amount of power generated by the sun, so we need to know the origin of this power. The sun's temperature calculated from Stefan – Boltzmann law is found to be 5 800 K. Solar radiation power density at the average position of the Earth outside the atmosphere is  $1366 \pm 3 \text{ W/m}^2$  and according to WMO  $1367 \text{ W/m}^2$  is the solar constant. This does not mean that the yearly solar radiation data do not vary.

The total radiation power from the sun is computed from the relation

$$S_{\text{total}} = 4\pi D^2 I_{sc} \sim 3.84 \times 10^{26} \text{ W} \quad 9$$

where  $D$  is  $1.5 \times 10^{11} \text{ m}$ . Since the entire world's energy consumption is approximately  $1.6 \times 10^{13} \text{ W}$ , the total power of solar radiation that the Earth receives from the sun is about two hundred trillion times.

### 3.6.2 Applications of solar energy

It is of vital importance to have the knowledge of the amount of solar irradiance falling on the surface of the Earth at specific areas. The production of electricity in the remote areas through photovoltaic panels, water heating using solar water heater, lighting as well as heating buildings through solar energy technologies depend on solar radiation falling at the specific site. Grain drying in agriculture is an oldest application of solar energy by the elderly people who were not at all scientists. Crops do rely on the amount of solar radiation, so for high production of solar fuel from crops that are grown and converted to fuel, more solar radiation is expected. Due to the prohibitive cost of the radiometers that should be installed throughout the country, the use of empirical solar models to estimate the insolation plays an important role.

The amount of insolation should be known for the proper functioning of the following applications of solar energy systems: the landing obstruction lights for airports, water pumping for irrigation, power sources for homes and commercial buildings (grid or off-grid lines), perimeter alarm transmitters, electronic border fences, intrusion alarms for security, highway signs, portable backpack radios, remotely located unmanned electronic surveillance systems, educational TV broadcasting, railroads, radio relay stations, navigation aid sensors, ocean - based earthquake warning systems, emergency alarm transmitters, communication satellites, and space-based missile surveillance and reconnaissance systems.

To determine the performance and economics of solar conversion technologies, designers and engineers use solar radiation data to estimate how much solar energy is available for a site. Common solar collectors are as follows: a photovoltaic array, a concentrating parabolic trough, a domestic hot-water collector, a window, a skylight or a canopy of foliage. For the designers and technologists to determine the size of the photovoltaic array to be installed at a specific site where solar radiation data is not available, they need to use hand calculation or computer simulation for solar radiation data.

Most of the South African regions depend on agriculture for livelihoods. Solar energy that power agricultural water pump systems relieves the farmers in respect of livestock and irrigation since water requirements are increasing due to climate change. The flow-rate of water by a solar-powered system in a particular time interval depends on the total amount of solar energy available during that time period. Long-term variability is related to the 22-year magnetic field cycle of the sun

### 3.6.3 Scientific way of measuring solar radiation data

As stated above, solar radiation data is used in different solar energy technologies. Some of these technologies require the so called global solar radiation which is referred to as the total solar radiation, the direct or beam solar radiation and / or diffuse solar radiation. Meteorological solar stations that are fully equipped are expected to have measuring instruments such as pyranometer for global solar radiation data, a pyranometer with a shadow band to measure the diffuse solar radiation as well as pyrheliometer for measuring the direct solar radiation on the

horizontal surface. Global, direct and diffuse solar radiation are measured in watts per square meter ( $\text{W}/\text{m}^2$ ).



*Figure 13: Solar Radiometers at CSIR Energy Centre*

(Source: <http://www.sauran.net>)

Figure 13 shows a Solly's tracker with two Kipp & Zonen CMP11 pyranometers for global and diffuse solar radiation measurements at the CSIR, Energy Centre, Pretoria. A pyranometer without a ball measures the global solar radiation while the other one with a ball (acting as a shadow band) measures the diffuse solar radiation. On the sides of the solar tracker, two CHP1 pyrhemometers are mounted to take direct normal irradiance measurements. The station does have instruments that measure the humidity, wind speed and wind direction.

Solar insolation is normally expressed in  $\text{kJ}/\text{m}^2$  per minute although it may also be given in megajoules per day. Some stations do measure the wind speeds, humidity, air temperatures, sunshine, rainfall and evapotranspiration per minute averaged hourly/daily/monthly or yearly.

### 3.7 Depletion of ozone layer

A good understanding of the meaning of ozone layer starts with the knowledge of different layers of the atmosphere. Ozone layer plays a vital role since it absorbs the sun's harmful rays and it is defined as a deep layer in Earth's atmosphere that contains ozone which is a naturally occurring molecule containing three oxygen atoms. These ozone molecules form a gaseous layer in the Earth's upper atmosphere called stratosphere. The lower region of stratosphere containing relatively higher concentration of ozone is called ozonosphere. The ozonosphere is found 15-35 km above the surface of the Earth, as shown in Figure 14 below.

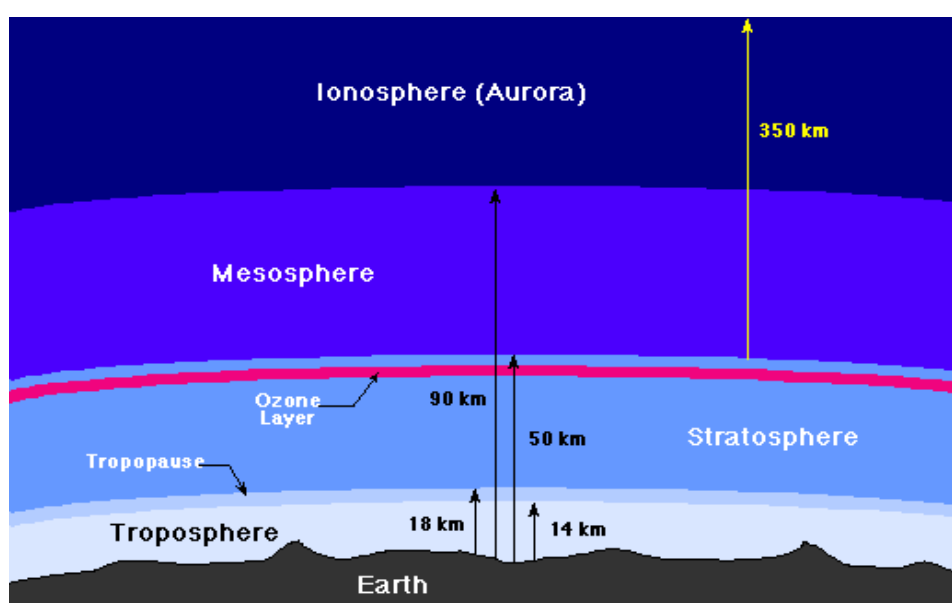


Figure 14: Layers of the Atmosphere

The reduction of ozone enhances the UV penetration to the Earth, and this leads to the increase in tropospheric reactivity. Any location or region whose  $NO_x$  is low enhances the reduction of ozone. The ozone layer protects life on Earth from strong ultraviolet radiation that comes from the sun. Ultraviolet rays can drive up the risk of deadly disorders like skin cancer, cataracts and damage the immune system. Ultraviolet rays are also capable of destroying single cell organism, terrestrial plant life and aquatic ecosystems [30].

The main cause for the depletion of ozone has been determined as the excessive release of chlorine and bromine from man-made compounds such as chlorofluorocarbons (CFCs). CFCs, halogens,  $CH_3CCl_3$  (Methyl chloroform),  $CCl_4$  (Carbon tetrachloride), HCFCs (hydro-

chlorofluorocarbons), hydro-bromo-fluorocarbons (HBFCs) and methyl bromide have the direct impact on the depletion of the ozone layer.

### 3.8 Weather stations capacity in SA

There are institutions that observe ground meteorological and climatological data such as rainfall, wind speed, temperature, humidity, sunshine hours, direct solar radiation, diffuse and global solar radiation. Some of these institutions are:

#### 3.8.1 SAWS

This is one of the public entities which is mandated by the South African government to provide weather services to the marine, aviation industry and other clients. Their observation network includes the following: 231 Automatic Weather Stations (AWS), 12 climate stations, national UVB, 1180 rainfall stations, etc. SAWS has 13 solar radiation stations. Taking into consideration the size of SA, more stations are still needed to forecast the atmosphere.



*Figure 15: An example of an automated station*

Figure 15 above shows the automated station measures the global solar radiation, wind speed, wind direction, humidity and rainfall [31]. One can also observe that the sky is dusty, that is, it has the atmospheric particles that affect the amount of solar radiation. The use of this type of instruments limits the human involvement and potential error but increases the efficiency of the monitoring process. Some parameters that are measured in this station are, wind direction,

humidity, global solar radiation, maximum and minimum temperatures, wind speed and rain gauge. The sensors of these instruments relay their data to a data logger or laptops.

### 3.8.2 ARC

One of the ARC's mandate is to foster innovation to support and develop the agricultural sectors. Their stations mainly measure the parameters such as temperature (maximum and minimum), rainfall as well as global solar radiation that assist the agriculturists [32].

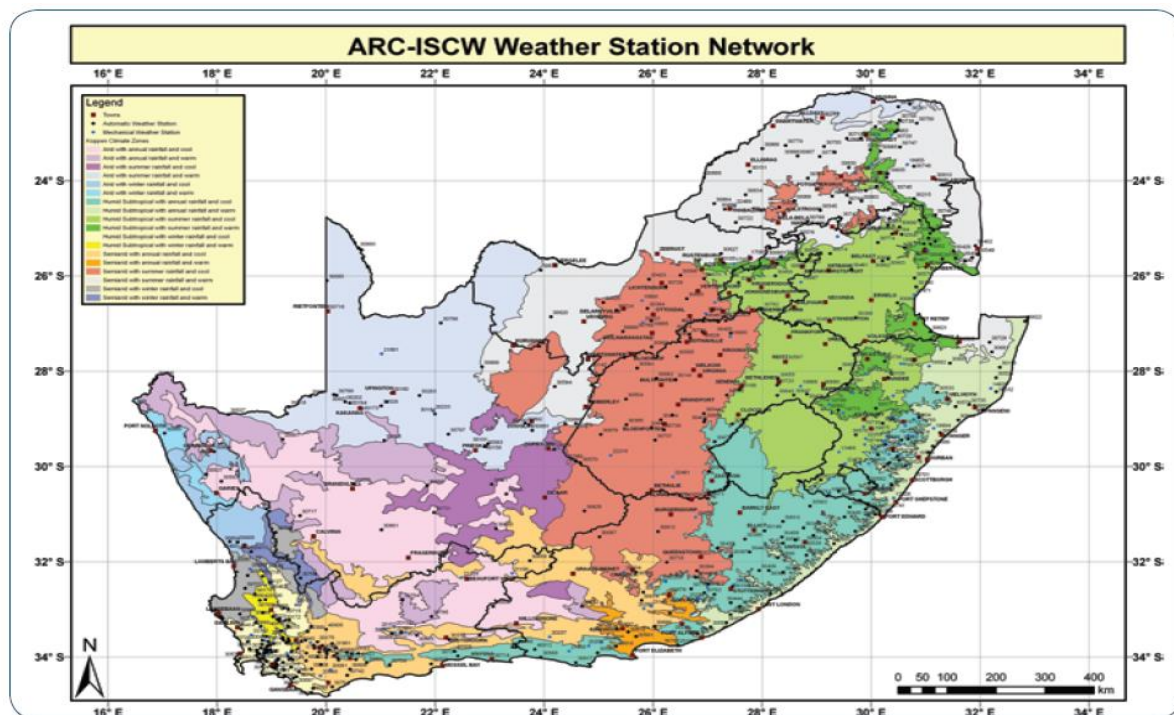


Figure 16: The distribution of ARC-ISW weather station network in SA

Licor-200 pyranometers are installed to measure global solar radiation. The global solar radiation and temperature data used in this study was sourced from ARC. Most of these stations measure the following meteorological data: wind speed, relative humidity, air temperatures (mean, maximum and minimum), rainfall, total evapotranspiration, cold and heat units, and total radiation. Very few ARC stations are called mechanical stations. These stations take measurements of temperatures and bright sunshine hours. Accordingly, the stations are located in the coastal areas.

### 3.8.3 ESKOM

ESKOM has been measuring solar irradiance since 2006. Their measuring equipment are installed at Upington, Aggenies, Tellerie and Paulputs in Northern Cape. These stations measure the following parameters: wind speed, wind direction, air temperature humidity and solar radiation. Since South Africa has nine provinces there is a need for extending these measurements to other provinces and also measure diffuse and direct solar irradiance.

There are the CSPs that are built in the Northern Cape, namely, Khi Solar One (50 MW), Bokpoort (50 MW) and Kaxu Solar one (100 MW) located at Pofadder.



*Figure 17: Kaxu Solar One*

The Kaxu Solar One plant uses the parabolic trough solar collector assemblies [36 & 37]. The plant was commissioned in March 2015 and it supplies energy to an approximately 80 000 homes. It has a storage capacity of 3 hours and the carbon dioxide emissions was estimated to be reduced by 315 000 metric tons.



*Figure 18 : Khi Solar One*

The tower plant consists of the concave solar mirror panels which are tilted at an angle that reflects the sun's rays onto the top of the tower. Each of these panels has an autonomous computerised control system with GPS signal that determines the angle from which the sun is shining. The Khi solar One produces a 50 MW energy and estimated to reduce the South Africa's carbon dioxide emissions by approximately 138 000 metric tons a year. It was the first tower plant to operate for 24 hours with solar energy only. It started to operate fully in October 2016. [36 & 37]



*Figure 19: Bokpoort CSP*

Bokpoort CSP has an output capacity of 200 GWh/year, which serves approximately 21,000 households and approximated to reduce carbon dioxide emissions of about 230,000 tons/ year. The plant has a molten salt storage facility of 1 300 MWh which can provide energy for about 9.3 hours.

## CHAPTER 4: LITERATURE REVIEW

### 4.1 Introduction

Accurate knowledge of the characteristics of solar radiation is of fundamental importance. The determination of the performance of solar energy technologies through photovoltaic cells, solar thermal collectors, etc. for a specific site needs a thorough understanding of solar radiation data at that area. However, not all the weather stations in SA have solar radiation data due to the unavailability of the instruments for radiation measurements. As a result, the classical and artificial neural network models were developed. Classical or empirical models are based on correlations, or relations derived, usually through linear or multilinear regression analysis (curve fitting). This approach assumes that measured solar radiation data can be described as a function of some other independently measured or available variables or parameters. Most of these models were developed outside SA, hence there is a need to evaluate their suitability using the South African data. For the various classical models that can be employed to estimate solar radiation, the scatter plots of the parameters selected such as sunshine duration and solar radiation data give the regression models. It is then that the investigator can fit the regression and hence read the coefficients (constants) that are valid in that specific area. It is also noted that the meteorological data vary with locations.

A variety of solar empirical models have been developed over the years. The most common empirical models are sunshine and temperature. Others involve the combination of parameters such as altitude, humidity, latitude, cloud cover and perspiration. The selection of these classical models usually considers the following features:

- (1) the availability of meteorological data used as input by the model and
- (2) the accuracy of the model.

All these models estimate the global solar radiation as a function of the meteorological parameters such as rainfall, air temperature, sunshine hours, relative humidity, cloudiness, air pollution and precipitation. In this chapter, we will discuss various models that can be used to estimate the global solar radiation. To conduct the feasibility studies for solar energy systems and climatologic studies, the monthly and daily averaged solar radiation data is required. The hourly data is usually needed to simulate the performance of solar devices [21].

## 4.2 Classical models

There are several classical solar models that have been developed using the meteorological parameters at the sites during periods of study. To estimate the solar radiation at any location, the parameters to be used should be taken into consideration as well as the regression coefficients of weather parameters. The availability of ground-based meteorological data which is used as input of the empirical solar models is the most important key for the researcher to select the appropriate model at any site. Accordingly Rawlins, Swartman and Ogunlade, the individual daily solar radiation is more accurately estimated from local sunshine observations than by assignment from the nearby radiometric stations [38]. This encourages the determination of the regression coefficients at a site. Some of the classical models are briefly discussed in this section as follows:

### 4.2.1 Models that depend on the sunshine duration

Sunshine duration is a climatological parameter since it is a measure of cloudiness of a location. Actual sunshine hours at a given location vary significantly due to atmospheric components and it is measured by sunshine recorders. Although both atmospheric and meteorological parameters contribute to the diminishing of the amount of global solar irradiance reaching the surface of the Earth horizontally, bright sunshine hours exert a great influence [39 - 42 & 50].

#### 4.2.2.1 Sen Model

The Sen model is given by [42]:

$$\frac{H}{H_0} = a + b * \left(\frac{S}{S_p}\right)^c \quad 10$$

El-Sebaili et.al [43] determined the regression coefficients  $a$ ,  $b$  and  $c$  using the number of bright sunshine hours ( $S$ ), the monthly average of daily global solar radiation ( $H$ ) on a horizontal surface for the period of 1996 -2004 for Jeddah, Saudi Arabia. The authors employed the determined coefficients to estimate the global solar radiation.  $H_0$  and  $S_p$  are the extra-terrestrial solar radiation and the bright sunshine hours.

#### 4.2.2.2 Glover and McCulloch model

Glover and McCulloch introduced the latitude,  $\varphi$ , dependency to the linear Angstrom- Prescott model. This model considers the effect of latitude of the site under investigation and it is valid only for  $\varphi < 60^\circ$ . The relation is [44]

$$\frac{H}{H_0} = a * \cos \varphi + b * \frac{S}{S_p} \quad 11$$

Ulgen and Hepbasli modified the model to suit Izmir, Turkey [45], such that the regression coefficients,  $a$  and  $b$  become 0.3092 and 0.4931 respectively. For Pakistan, the regression coefficients,  $a$  and  $b$  become 0.388 and 0.367 respectively according to Raja and Twidell [46]

#### 4.2.2.3 Rietveld Model

Rietveld noted that the regression coefficients  $a$  and  $b$  are related linearly and hyperbolically respectively to the mean values of the ratio of the actual number of bright sunshine hours,  $S_a$  and the total number of possible hours or daylength,  $S_p$ , *i. e.*  $\frac{S}{S_p}$ , so, [47]

$$a = 0.10 + 0.24 * \left(\frac{S}{S_p}\right) \quad 12(a)$$

$$b = 0.38 + 0.08 * \left(\frac{S}{S_p}\right) \quad 12(b)$$

By examining several publications of the regression coefficients using equations 12(a) and 12(b), Rietveld concluded that equation  $\frac{H}{H_0} = 0.18 + 0.62 * \frac{S}{S_p}$  is applicable anywhere in the world and it can yield superior results for cloudy conditions, where  $\frac{S}{S_p} < 0.4$ .

#### 4.2.2.4 Swartman and Ogunlade model

The model was proposed to calculate the global solar radiation using the ratio between the actual and the possible sunshine hours and the relative humidity,  $RH$ , at a location under study [48].

$$\frac{H}{H_0} = a + b * \left(\frac{S}{S_p}\right) + c * RH \quad 13$$

#### 4.2.2.5 Sangeeta et al. Model

In this model, the regression coefficients are related to the latitude and bright sunshine hours parameters. The relation is expressed as follows:

$$a = -0.110 + 0.235 * (\cos \varphi) + 0.24 * \left(\frac{S}{S_p}\right) \quad 14(a)$$

$$b = 1.449 - 0.553 * (\cos \varphi) - 0.694 * \left(\frac{S}{S_p}\right) \quad 14(b)$$

#### 4.2.2.6 Ampratwum and Dorvlo model

Ampratwum and Dorvlo's relation is as follows [49]:

$$\frac{H}{H_0} = a + b * \log \left(\frac{S}{S_p}\right) \quad 15$$

The model can be used to estimate the global solar radiation provided the regression coefficients ( $a$  &  $b$ ) at the location under study are known. The extraterrestrial solar radiation is denoted by  $H_0$ .

### 4.2.3 The temperature Models

Sunshine data are not readily available at all sites of interest. The daily maximum and minimum temperature data is available and easy to obtain. Some of the solar radiation models that were proposed in the literature to estimate the global solar irradiation flux with the difference in maximum and minimum temperatures are as follows:

#### 4.2.3.1 Garipey's Model

According to Garipey [40], the empirical coefficients depend on the mean air temperature ( $T$ ) and the amount precipitation ( $P$ ) at the location. The model is expressed as:

$$a = 0.3791 - 0.041 T - 0.0176 P \quad 16(a)$$

$$b = 0.4810 - 0.0043 T - 0.0097 P \quad 16(b)$$

#### 4.2.3.2 Bristow - Champbell Model

Bristow and Champbell [50] suggested the relation whose daily global solar radiation is written as a function of daily extra-terrestrial solar radiation and the change in air temperature.

$$\frac{H}{H_0} = a * [1 - e^{-b\Delta T^c}] \quad 17$$

The coefficient  $a$  represents the amount of maximum radiation expected on a clear day while  $b$  and  $c$  control the rate at which the empirical coefficient  $a$  is approached as the change in temperature increases.

#### 4.2.3.3 Trabea and Shaltout model

The model derived from the Egyptian selected stations relates the mean temperature ( $T$ ), the relative humidity ( $RH$ ), water vapour and precipitation ( $P$ ) [53].

$$\frac{H}{H_0} = a + b * \frac{S}{S_p} + cT + dV + eRH + fP \quad 18$$

#### 4.2.3.4 Hargeaves and Samani model

$$\frac{H}{H_0} = k_r * \sqrt{T_{max} - T_{min}} \quad 19$$

The clearness index,  $\frac{H}{H_0}$  is related to the square root of the change in temperature [54]

$\Delta T = T_{max} - T_{min}$ .  $k_r$  is referred to as the temperature coefficient. Allen has estimated  $k_r$  as a function of elevation to account for the effect of elevation on the volumetric heat capacity of the atmosphere by using the following relation:

$$k_r = k_{ra} * \sqrt{\left(\frac{P}{P_0}\right)} \quad 20$$

where  $k_{ra}$  is assigned the values of 0.17 and 0.2 for inland and coastal regions respectively.  $P$  is the mean atmospheric pressure at that location and  $P_0 = 101.3 \text{ kPa}$  which is the mean atmospheric pressure at the sea level.

Samani has derived the relation that relates the empirical relation  $k_r$  with the maximum and minimum temperature data as follows:

$$k_r = 0.00185 * (T_{max} - T_{min})^2 - 0.0433 * (T_{max} - T_{min})^2 \quad 21$$

#### 4.2.3.5 Donatelli and Campbell model

The model considers the average air temperature and the minimum temperature functions as well as the transmissivity coefficient of the atmosphere for the determination of the global solar radiation. The model is expressed as follows:

$$H = H_0 * A_{D-C} * [1 - \exp(-B_{D-C} * f(T_{avg}) * \Delta T^2) f(T_{min})] \quad 22$$

where

$$T_{avg(i)}(^{\circ}\text{C}) = \frac{T_{max(i)} + T_{min(i)}}{2}$$

$$\Delta T(^{\circ}\text{C}) = T_{max(i)} - \left( \frac{T_{min(i)} + T_{min(i+1)}}{2} \right)$$

$$f(T_{avg}) = 0.017 * \exp * \left( \exp(-0.53 * T_{avg(i)}) \right)$$

$$f(T_{min}) = \exp * \left( T_{min} / C_{D-C} \right)$$

and  $A_{D-C}$  denotes the clear sky transmissivity,  $\Delta T^2$ ,  $f(T_{min})$  and  $f(T_{avg})$  are the functions that are based on the mean and the minimum temperature.  $B_{D-C}$  and  $C_{D-C}$  are the empirical parameters [53]. The determination of these empirical parameters needs the availability of the air temperature and solar radiation data measured at the site.

#### 4.2.4 Latitude or altitude - based model

These are the empirical models in which one of their parameters is either altitude or latitude. They may also include other parameters such temperature, humidity, etc.

##### 4.2.4.1 Kilic and Ozturk model

The authors developed the model using the altitude and latitude in Turkey. The relations take into consideration the altitude, latitude and the declination angle for the calculation of the empirical coefficients of the Angstrom-PreScott-Page model [56]:

$$a = 0.103 + 0.000017 Z + 0.198 * \cos(\varphi - \delta) \quad 23(a)$$

$$b = 0.533 - 0.165 * \cos(\varphi - \delta) \quad 23(b)$$

where  $Z$  is the altitude in kilometres,  $\varphi$  - latitude and  $\delta$  is the declination angle.

#### 4.2.4.2 Gopinathan model

The author took into account the effect of latitude  $\varphi$  of the location, altitude  $Z$  in km and the ratio of sunshine hours at the study area and expressed the relation as follows [57]:

$$\frac{H}{H_0} = \left[ -0.39 + 0.539 \cos \varphi - 0.00693 Z + 0.290 \frac{S_a}{S_p} \right] + \left[ 1.527 - 1.027 \cos \varphi + 0.0926 Z - 0.359 \frac{S_a}{S_p} \right] \quad 24$$

Glover and McCulloch, Almorox and Tymvios, *et al* determined the empirical coefficients in SA, Spain and globally respectively as tabulated in Table 5 [76].

*Table 5: Angstrom – Prescott model coefficients variability by three authors*

Author	Date	Location	Range of $a$	Range of $b$
Glover and McCulloch	1958	South Africa	0.15 to 0.29	0.48 to 0.60
Almorox	2005	Toledo Spain	0.288 to 0.33	0.41 to 0.49
Tymvios	2005	Global	0.17 to 0.43	0.24 to 0.75

### 4.3 Summary

The solar models outlined in this chapter show that the empirical coefficients  $a$ ,  $b$ ,  $c$ , etc. depend on the data of the meteorological and weather parameters such as latitude, elevation, atmospheric pressure, humidity, actual sunshine hours, etc., measured at a site of interest or under investigation. Some of the models are used to compute the empirical coefficients only and later they are employed to predict the amount global solar radiation through different solar models.

## CHAPTER 5: METHODOLOGY

### 5.1 Introduction

Experimentally, it is logical to consider that the global solar radiation is directly proportional to the sunshine duration. The formulation of the proportionality is derived from the measurements of the variables through scatter diagrams and most often by the application of statistical regression methods. The original models in solar energy expressed this relationship between the global solar radiation and the sunshine duration as linear [59 & 60]. The meteorological and climatological data had been collected for the period of 2005 – 2011 and provided by the ARC and SAWS was divided into data sets. A 2006 data is used to evaluate the regression coefficients while for the determination of the regression coefficients, the 2007 – 2011 data has been used as the input. The daily recorded data consist of parameters such as: air temperature, wind speed, global solar radiation, relative humidity, rainfall and actual bright sunshine hours for the few mechanical stations. The ARC mechanical stations measure the bright sunshine hours and all other parameters stated above except the global solar radiation data. Although it is known that in most of the countries, linear Angstrom-PreScott model correlates sunshine and global solar radiation, this is only possible provided the location under study has regression coefficients. In the literature, we have learned that the available weather stations are far much apart with limited measuring instruments hence there is a dire need of estimating this useful parameter in solar systems called global solar radiation. In this research study, an empirical model developed by Angstrom and modified by Prescott (equation 25) with the South African meteorological input parameters was employed to determine the regression coefficients that fit the South African weather conditions whether in the terrain or mountainous locations.

#### *Angstrom – Prescott Model*

The model is given by:

$$\frac{H}{H_0} = a + b * \frac{S}{S_p} \quad 25$$

The coefficients  $a$  and  $b$  depend on the seasonal and regional parameters. The coefficients also depend on the physical characteristics of the atmospheric layer and are influenced by the local latitude and altitude above the sea level, as well as on the seasonal variability of the atmospheric

variables such as rainfall, wind, humidity, and aerosol concentrations. The coefficient  $a$  is interpreted as the fraction of solar radiation,  $\frac{H}{H_0}$ , that enters the atmosphere when there is a complete cloud cover or it can be described as the one which represents the global radiation received at the ground through an overcast sky as a function of extra-terrestrial radiation,  $H_0$  while  $b$  is the rate of change of  $\frac{H}{H_0}$  with respect to  $\frac{S}{S_p}$  and it is an index of the latitudinal variation. The ratio  $\frac{S}{S_p}$  is referred to as cloudless index which gives the information about atmospheric characteristics and conditions of the selected study areas. Generally, the regression coefficients,  $a$  and  $b$  are location specific coefficients that are referred to as fractions of extra-terrestrial radiation on overcast days and clear days respectively. So, this shows that the regression coefficients are not one size fits all. Each country or location must have its own values. Seasonal variability does affect these values, so they need to be evaluated periodically preferably per solar cycle. The sum of the regression coefficients reflects the atmospheric transmission under clear sky conditions [37].

This linear regression model has been used by many researchers to develop empirical correlations. Some of the researchers are: Togrul [68]; Akinoğlu and Ecevit [69]; Gopinathan [55]; Şahin [70]; Paulescu et.al. [73]; Muneer [3]; Menges et.al.[71]; Skeiker [62]; Rietveld [63]; Jin et.al. [72]). The analysis by these researchers from the model have shown that the regression coefficients are site dependent and have suggested regression coefficients in terms of some geographical factors, such as latitude, elevations etc. (Paulescu et.al.; Muneer and Younes, 2006; Menges et.al. 2006; Skeiker, 2006; Rietveld, 1978; Jin et.al. ).

This research study uses the daily global solar radiation,  $H$  in  $\text{MJm}^{-2}\text{day}^{-1}$  and the actual sunshine duration in hours ( $h$ ) measured in 22 South African weather stations. The coordinates of these stations are listed in Table 2. South Africa consists of coastal and inland areas.

For the determination of the regression coefficients,  $a$  and  $b$  in this study, MATLAB codes that involve the employment of various data modelling techniques such as linear regression, curve fitting, statistical data analysis as well as prediction of global solar radiation were written. The regression modelling was done using the MATLAB tools with the help of statistical software package MATLAB 2017b.

The ratio of the global to its extra-terrestrial solar radiation on the horizontal surface in equation 25 is known as the average clearness index (denoted by  $K$ ) per day or monthly. It is very rare for this ratio to exceed 0.9 though it is possible that the ratio can approach 1 during perfectly clear sky [35].  $H_0$  is the component of the extra-terrestrial radiation normal to the horizontal surface obtained using the average day number,  $n$  (a day in the month which best approximates the month's average daily global solar radiation) and integrating over the period of sunrise to sunset. In this study, the daily averages of  $H_0$  and  $S_p$  are computed and in order to determine the regression coefficients per location, the scatterplots were drawn so as to fit the regression lines between  $\frac{H}{H_0}$  and  $\frac{S}{S_p}$ . The parameters  $a$  and  $b$  of the linear Angstrom-Prescott equations are the regression coefficients of the plotted line and are obtained from linear plots. These plots are presented in detail in chapter 6 whereby the regression coefficients  $a$  and  $b$  are identified as the intercept of the  $\frac{H}{H_0}$  axis and the slope of the regression line respectively.

## 5.2 Computation of $H_0$

The basic equation used to compute the average daily extra-terrestrial solar radiation as indicated below is available from standard textbooks on solar engineering, such as Tariq Muneer [3], Muhammad Iqbal [66], Duffie and Beckman [34] and Badescu [25]. A number of researchers such as Srivastava and Pandey [52], Trabea A.A [53], Jamil & Tiwari [59] and others used this basic equation. The extra-terrestrial solar radiation on a horizontal surface  $H_0$  is considered as a function of only latitude,  $\varphi$ . As solar radiation passes through the Earth's atmosphere, it is further modified by the processes of scattering and absorption due to the presence of cloud and atmospheric particles. Consequently the daily global solar irradiation flux incident on a horizontal surface  $H$  is very much location specific and less than the extra-terrestrial irradiation. The mean daily extra-terrestrial solar irradiation on the horizontal surface,  $H_0$  in  $\text{MJm}^{-2} \text{day}^{-1}$  integrated over the period of sunrise to sunset per station under study is computed for each day of the year and it given by the following relation [40 - 50]:

$$H_0 = \frac{24 \times 3600}{\pi} I_{sc} E_0 \left[ \frac{\pi}{180} \omega_s \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_s \right] \quad 26$$

The estimated solar constant,  $I_{SC}$ , which is the energy from the sun per unit time received on a unit area of a surface perpendicular to the direction of the radiation at the mean Earth-Sun distance outside the atmosphere is  $1367 \text{ W/m}^2$  as adopted by the World Meteorological Organization (WMO).  $E_0$  is relative earth-sun distance or the eccentricity correction factor of the Earth's orbit and its value is given by the equation [34 & 40]

$$E_0 = 1 + 0.033 * \cos \frac{360n}{365} \quad 27$$

where  $n$  is the day of the year starting from day 1- 365 and on a leap year the last day of the year is 366.

The variation of the eccentricity is very small but surely it does contribute to the effect of global solar radiation received on the Earth's surface. Muhammad Iqbal [66] indicated that the Earth rotates around the polar axis which is inclined around  $23.45^\circ$  from the normal to the ecliptic plane and results in diurnal changes in the solar radiation that reaches the surface earth. Although the angle between the polar axis and the normal to the ecliptic plane remains the same, the angle of declination defined as the angle between a line joining the centres of the sun and the Earth to the equatorial plane changes every day. This angle is expected to be zero at the vernal and autumnal equinoxes. In the southern hemisphere, the value of the angle of declination is approximately  $-23.45^\circ$  during summer solstice and  $+23.45^\circ$  in winter solstice [68]. The solar declination angle in radians,  $\delta$  and sunset hour angle,  $\omega_s$  are obtained using the following relations respectively,

$$\delta = 23.45 * \frac{\pi}{180} * \sin \left[ 2\pi * \left( \frac{284+n}{365.25} \right) \right] \quad 28$$

and

$$\omega_s = \cos^{-1}(-\tan \delta * \tan \varphi) \quad 29$$

The solar declination angle is the angle that the sun makes with equatorial plane at solar noon. The axis of rotation is tilted at an angle of  $23.45^\circ$  with respect to the plane of the orbit around the Sun.  $\delta$  varies from  $23.45^\circ$  to  $-23.45^\circ$  in a year.  $n$  is the day number from the 1<sup>st</sup> January to the 31 December. Note that the sunset hour angle and the sunrise hour angle are equal except for the sign difference.

In the Southern hemisphere, the variation of solar declination in radians is depicted in the figure below.

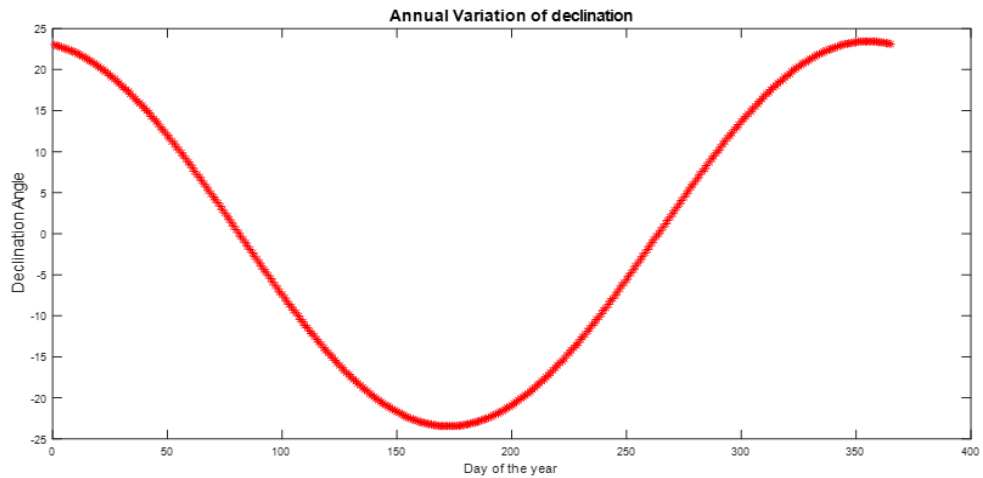


Figure 20: South Africa's solar declination graph

The figure depicts that the sun is away from the Earth during winter season when  $n$  is greater than 120 and less than 240 and closer to the Earth during summer season.

### 5.3 Computation of $S_p$

The maximum possible sunshine duration or astronomical day length in hours,  $S_p$ , is calculated using the relation [4, 25, 37 & 66 ],

$$S_p = \frac{2}{15} \omega_s \quad 30$$

In this study,  $H_0$  and  $S_p$  were calculated using equations (26) and (30) respectively per the selected stations. The ground measurements of the daily average actual bright sunshine hours,  $S$  were obtained from SAWS while the daily average global solar radiation data,  $H$  was requested from ARC for the period of six years.  $S_p$  depends solely on the sunset/rise hour angle. For the atmospheric energy balance studies, analyses of the thermal loads on buildings, climate research, the evaluation of agricultural resources and building the estimation models of the surface solar radiation, bright sunshine duration play a pivotal role. Most of the ARC stations do not measure the actual sunshine duration, so, the closest SAWS stations which measure these data are employed in this research study.

2011 data of the monthly average of the bright sunshine duration of some stations under the present study are tabulated below:

*Table 6: Monthly average bright sunshine hours*

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec.
De Aar	2011	9.1	9.1	8.9	8.7	7.7	7.9	8.9	9.8	10.6	11.2	12.1	11.9
Bloemfontein		7.1	8.6	7.8	7.2	7.1	7.7	8.3	9.1	9.8	9.7	10.7	9
Ermelo		6.1	9.2	7.9	5.7	7.2	8.8	8.7	9.2	9.5	9.2	8.7	7.2
Mafikeng		7.5	9.1	7.8	7	8.8	9.4	9.2	10.4	10.8	10.4	9.8	8.3
Irene		6.1	7.9	7.9	5.8	8.5	9.2	9.1	9.8	10	9.6	9.4	7.4
Thohoyandou		4.2	7.6	8.2	6.1	8.7	8.6	7.4	7.8	8.7	7.1	6.6	5.6
Cape Town		11.4	11.3	8.9	8.8	5.3	5.6	7.6	7.2	7.4	8.5	10.3	11.6
Kimberly		8.2	7.6	7.1	7.7	8.2	8.1	8.7	9.9	10	10.7	11	10

(Sourced from SAWS)

In this study the bright sunshine hours are used as the actual or the observed sunshine hours denoted by  $S$ .

Thohoyandou is observed to have the least bright sunshine hours in January. The data shows that De Aar station has an average of nine hours of bright sunshine throughout the year. The table shows that almost the whole year, South Africa receives an average of more than 70 % bright sunshine. Due to rainfall, Cape Town has the least sunshine hours during winter season. It is evident from the table that cloud cover during rainy season, that is, November, December and January is less than 30 % taking into account that the average day length is thirteen hours. Since researchers have indicated that there is a correlation between the global solar radiation and the bright sunshine duration, there is no doubt that the location is highly suitable for the installation of solar energy applications.

#### 5.4 Computation of the regression coefficients, $a$ and $b$

The regression coefficient  $a$  in equation 25 represents the fraction of the extra-terrestrial solar radiation on overcast days while  $b$  represents the rate of increase of the clearness index with the relative sunshine hours. At the occasions where the bright sunshine hours were the same as the maximum day length hours, the expression  $a + b$  indicates the fraction of radiation received on clear days. For the determination of the regression coefficients, quality of the meteorological data to be used as the input, i.e. global solar radiation and bright sunshine hours are necessary. The regression coefficients were calculated from the values of the daily  $\frac{H}{H_0}$  and  $\frac{S}{S_p}$  annually for the period of five years. By means of MATLAB codes scatter plots were drawn and the statistical software embedded in MATLAB was used to fit the linear regression lines to obtain the values of  $a$  and  $b$ . The outliers were identified at some of the stations where  $\frac{S}{S_p} > 1$ . In very few occasions, the relative sunshine hours whose values were greater than one were disregarded. We only expect that on clear sky days, the values of the ratio  $\frac{S}{S_p}$  approach one. Very few such incidences had occurred in some of the stations and the results were not affected. The average of these yearly regression coefficients were obtained per station to find the modified regression model suitable for a site.

#### 5.5 Area under study

The study is based on the South African provinces. The data for the parameters used in the research study were requested from ARC and SAWS (as stated in 5.1.2). ARC has AgroMet weather station network of approximately 100 mechanical and 530 automatic weather stations throughout SA [36]. The automated weather station data is stored on an hourly and daily basis. The following are the climate parameters that are measured: rainfall, air temperature, global solar radiation, relative humidity, evaporation, wind speed and bright sunshine duration in some of the climatic stations.

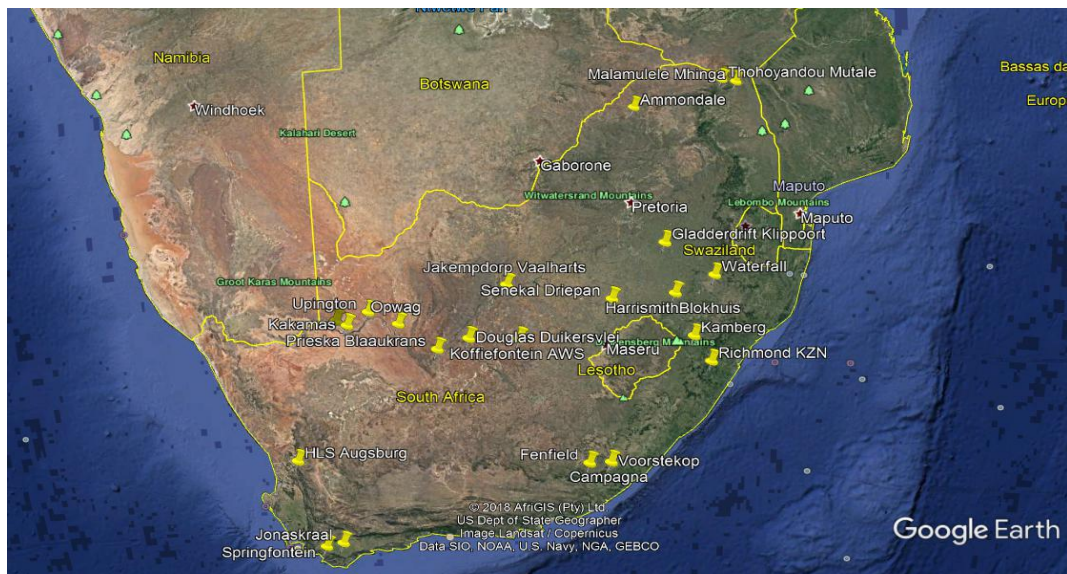


Figure 21: Stations under study

Figure 21 shows the stations under study at different provinces. Table 6 shows the stations' geographic information considered in the present study. The selection of the stations was due to the availability of the data in the period of five years with minimal missing data that do not compromise the results to be determined. Some of the stations were disregarded due to a smaller number of annual data observed after quality control procedures were performed. Only stations with more than two – third of the annual data available were considered. The selected locations from the 24 weather stations in the South African provinces are given in Table 6 on the next page:

Table 7: Geographic information of the stations under study

Site Location	Latitude (°)	Longitude (°)	Altitude (m)
Mutale	-22.73461	30.52188	550
Mhinga	-22.79675	30.84219	460
Ammondale	-23.72619	29.59517	1153
Arcadia	-25.73857	28.20733	1400
Pretoria Botanical	-25.73361	28.30967	1411
Delareyville	-26.72463	25.32766	1379
Koster	-25.99017	26.50456	1534
Ventersdorp	-26.4803	26.61898	1383
Koffiefontein	-29.36199	25.12845	1238
Hoopstad	-27.93916	25.70888	1313
Bloemfontein Glen	-28.92957	26.32633	1227
Hluhluwe	-27.91983	32.36531	25
Weenen	-28.78301	30.08891	699
Bushlands	-28.13938	32.2949	32
Hazyview	-25.04885	31.14449	484
Lydenburg	-25.13169	30.56561	2040
Mzinti	-25.691149	31.72932	265
Upington	-28.46388	21.20541	798
Goudmyn	-33.82939	18.86836	259
Lebourne	-33.82939	18.86836	259
Helderfontein	-33.9233	18.87331	133
Bien Dionne	-33.84272	18.9842	139

It is observed from Table 6 that there is variation of altitude above the sea level which contributes to the variation of the temperature measurements and hence attribute to the amount of global solar radiation received per site on the Earth's horizontal surface. We also notice that the calculation of  $H_0$  includes the latitude which ranges from  $-22.73461^\circ$  to  $-33.9233^\circ$  in the present study, hence,  $H_0$  also varies from one location to the other.

The ratio of the global to its extra-terrestrial solar radiation on the horizontal surface in equation (25) is known as the average clearness index (denoted by  $K$ ) per day and or monthly.  $H_0$  is the component of the extra-terrestrial radiation normal to the horizontal surface obtained using the average day number,  $n$  (a day in the month which best approximates the month's average daily global solar radiation) and integrating over the period of sunrise to sunset.

## 5.6 Data analysis

The statistical analysis gives meaning to numerical data of the observed and estimated global solar radiation. The results are precise only if proper statistical tests are carried out. This section deals with the basic statistical methods involved in the analyses of the research findings. In each province, an annual data is used. There are numerous works in the literature which deal with the comparison of the monthly average daily solar radiation estimated models.

Based on the following statistical error tests, the performance of the modified models is evaluated:

### 5.6.1 The mean percentage error (MPE)

$$MPE = \frac{\sum(H_{i,m} - H_{i,c})}{N} * 100\% \quad 31$$

where,  $H_{i,m}$  is the  $i$ th measured,  $H_{i,c}$  is the  $i$ th estimated global solar radiation data and  $N$  is the total number of observations. The estimated and measured global solar radiation data are the daily averages instead of the monthly averages published in the literature.

### 5.6.2 Root mean square error (RMSE)

$$RSME = \sqrt{\frac{\sum(H_{i,c} - H_{i,m})^2}{N}} \quad 32$$

The RMSE test provides information on the short-term performance of the models by allowing a term by term comparison of the actual deviation between the computed and the measured values. This is the square root of the expected value of the error defined as the amount by which the model estimate differs from the corresponding measured data. The RMSE provides a measured of the squared deviations.

### 5.6.3 Mean bias error (MBE)

$$MBE = \frac{\sum(H_{i,c} - H_{i,m})}{N} \quad 33$$

The MBE test provides information on the long-term performance and a measure of the overall trend of a given model. A low MBE value is desired. Ideally a value of MBE close to zero needs to be obtained in the solar radiation modelling. A positive value gives the average amount of over-estimation in the computed value and vice versa. A drawback of this test is that over-estimation of an individual observation will cancel under-estimation in a separate observation. The above statistical tests are most commonly applied in comparing the models of solar radiation estimations.

### 5.6.4 Nash-Sutcliffe equation (NSE)

$$NSE = 1 - \frac{\sum_1^n (H_{i,m} - H_{i,c})^2}{\sum_1^n (H_{i,m} - \bar{H}_m)^2} \quad 34$$

where  $\sum_1^n (H_{i,m} - H_{i,c})^2 = SSE$  and  $\sum_1^n (H_{i,m} - \bar{H}_m)^2 = SST$ . The Nash-Sutcliffe equation is related to the deterministic coefficient  $R^2$  where

$$R^2 = 1 - \frac{SSE}{SST} \quad 35$$

The NSE or  $R^2$  (the coefficient of determination – a statistical measure of how well the regression line approximates the real data points) value is more efficient if it is closer to 1 since it gives the unexplained variation. This statistic gives information about the goodness of fit of the model [53]. The coefficient of correlation ( $r$ ) is the square root of  $R^2$  which implies the strength and direction of a linear relationship between two variables. In this study, the variables are sunshine hours and global solar radiation data.

## CHAPTER 6: RESULTS AND DISCUSSIONS

### 6.1 Clearness index ( $K_T$ ) and Relative sunshine duration (RSS)

RSS refers to the ratio of the actual (bright) sunshine hours to the possible sunshine hours. The atmospheric components cause the variation of bright sunshine hours at each location. Both the meteorological and climatological parameters affect the incident amount of solar radiation reaching the horizontal surface of the Earth. Since the RSS is a measure of cloudiness in a location, from equation 25, it follows that the higher the ratio, the higher the global solar radiation predicted. It is very crucial to have the knowledge of the relationship between the sunshine hours and the cloudiness for the purpose of the practical forecast of insolation. The duration of real sunshine which is the time that the sun illuminates the Earth's surface is a measurement index of light resources. Accordingly, WMO defines sunshine duration as the number of hours for which direct irradiance is above  $120 \text{ W/m}^2$ .

Daily daylength hours per station under study areas were computed using equation 30. By utilizing MATLAB codes, the ratios were determined.

Relative daily sunshine hours are classified into three cloudy levels, that is,

- (i) Cloudy sky  $0 \leq \frac{S}{S_p} \leq 0.3$
- (ii) Scattered clouds  $0.3 \leq \frac{S}{S_p} \leq 0.7$
- (iii) Fair weather  $0.7 \leq \frac{S}{S_p} \leq 1.0$

Considering Ammondale station in Limpopo Province, the total bright sunshine hour in the year 2011 was 3 078.8 hours. It should be noted that 12% of the relative daily sunshine hours were below 0.400 therefore this province experiences scattered clouds and fair weather throughout the year . The monthly average daily RSS and the clearness indices ( $K_T$ ) were determined for the stations under study and tabulated in Table 7. The region experiences scattered cloudy days with while about 60% of days have fair weather. We expect to harness a good amount of energy in this province.

*Table 8: Ammondale Station – Monthly averages of daily measured and extra-terrestrial solar radiation, bright and possible sunshine hours , clearness index and relative sunshine hours.*

<b>Ammondale Station – 2011</b>						
<b>Month</b>	$H_{meas}$	$H_0$	$S$	$S_p$	$K_T = H_{meas}/H_0$	$RSS = S/S_p$
<b>JAN</b>	21.739	42.349	7.045	13.286	0.514	0.531
<b>FEB</b>	22.323	40.023	8.475	12.799	0.557	0.661
<b>MAR</b>	22.015	35.653	8.913	12.141	0.615	0.733
<b>APR</b>	14.931	29.853	5.983	11.436	0.498	0.523
<b>MAY</b>	15.558	24.705	8.571	10.850	0.633	0.791
<b>JUN</b>	15.967	22.187	9.490	10.561	0.720	0.899
<b>JUL</b>	15.152	23.255	9.187	10.697	0.650	0.858
<b>AUG</b>	19.178	27.538	9.342	11.203	0.697	0.834
<b>SEP</b>	22.776	33.248	9.880	11.883	0.687	0.832
<b>OCT</b>	23.084	38.351	9.235	12.586	0.603	0.734
<b>NOV</b>	22.565	41.586	8.327	13.166	0.543	0.633
<b>DEC</b>	20.72	42.847	6.774	14.440	0.484	0.504

Elevated bright sunshine hours were measured in September, June, August and October. Although the winter season runs from April to July, we did observe that clear sky conditions did occur during this season. Remember, it is very rare to have rainfall during this season and the area becomes cool and warm with maximum temperatures above 22 degrees. According to the classification levels of the cloud formation, the sunshine condition in Polokwane at Ammondale is about 70 % which shows that the site has fair weather. The clearness index ranges from 0.484 – 0.720.

*Table 9: Lydenburg Station – Monthly averages of daily measured and extra-terrestrial solar radiation, bright and possible sunshine hours, clearness index and relative sunshine hours.*

Lydenburg Station 2011						
Month	$H_{meas}$	$H_0$	$S$	$S_p$	$K_T = H_{meas}/H_0$	$RSS = S/S_p$
<b>JAN</b>	19.785	40.510	7.826	11.977	0.488	0.653
<b>FEB</b>	23.218	38.656	9.414	12.108	0.601	0.778
<b>MAR</b>	19.502	34.658	8.455	11.966	0.563	0.707
<b>APR</b>	13.419	29.061	6.590	11.933	0.462	0.552
<b>MAY</b>	14.123	23.731	7.210	12.018	0.595	0.600
<b>JUN</b>	13.716	21.041	8.780	12.084	0.652	0.727
<b>JUL</b>	13.740	22.323	8.706	12.001	0.616	0.727
<b>AUG</b>	16.962	26.949	9.287	11.970	0.629	0.776
<b>SEP</b>	18.636	32.714	9.533	11.928	0.570	0.799
<b>OCT</b>	19.636	37.435	9.181	12.014	0.525	0.764
<b>NOV</b>	22.779	40.172	9.027	12.086	0.567	0.747
<b>DEC</b>	19.728	40.954	8.361	12.006	0.482	0.696

The annual bright sunshine hours measured in Lydenberg station was 3111.3 hours. The table displays that out of the total day length hours of a maximum of 12.1, bright sunshine hours observed were approximately 7 hours monthly. Accordingly the station experienced more than 60 % of clear days in a month. The clearness index provides information about the solar radiation falling at the site as well as the atmospheric changes.

Table 10: Arcadia Station – Monthly averages of daily measured and extra-terrestrial solar radiation, bright and possible sunshine hours , clearness index and relative sunshine hours.

Arcadia Station 2011						
Month	$H_{meas}$	$H_0$	$S$	$S_p$	$K_T = H_{meas}/H_0$	$RSS = S/S_p$
<b>JAN</b>	18.095	40.534	6.094	11.977	0.446	0.509
<b>FEB</b>	20.243	38.605	7.979	12.111	0.524	0.659
<b>MAR</b>	18.457	34.493	7.829	11.965	0.535	0.654
<b>APR</b>	12.297	28.784	5.773	11.932	0.427	0.484
<b>MAY</b>	12.972	23.371	8.471	12.018	0.555	0.705
<b>JUN</b>	12.765	20.645	9.223	12.087	0.618	0.763
<b>JUL</b>	13.097	21.945	9.097	12.001	0.597	0.758
<b>AUG</b>	16.308	26.638	9.777	11.969	0.612	0.817
<b>SEP</b>	19.875	32.507	9.987	11.926	0.611	0.837
<b>OCT</b>	21.211	37.345	9.565	12.014	0.568	0.796
<b>NOV</b>	22.682	40.181	9.373	12.088	0.564	0.775
<b>DEC</b>	19.378	41.002	7.413	12.006	0.473	0.617

The least bright sunshine hours as observed from Table 9 were measured in April which correlates with the clearness index. The annual total bright sunshine hours measured in Arcadia in 2011 were found to be 3059.7 hours. The coefficient of determination (R-squared) was 0.907 which shows that there was a good correlation between the clearness indices and the relative sunshine hours. We conclude that the data gave us the regression correlation value of 0.952.

Table 11: Prieska – Monthly averages of daily measured and extra-terrestrial solar radiation, bright and possible sunshine hours , clearness index and relative sunshine hours.

Prieska Station 2010						
Month	$H_{meas}$	$H_0$	$S$	$S_p$	$K_T = H_{meas}/H_0$	$RSS = S/S_p$
<b>JAN</b>	24.80	41.77	6.62	13.67	0.59	0.70
<b>FEB</b>	25.50	38.88	10.62	13.03	0.66	0.81
<b>MAR</b>	21.56	33.88	10.39	12.18	0.64	0.85
<b>APR</b>	16.49	27.54	9.52	11.27	0.60	0.84
<b>MAY</b>	12.98	22.07	8.45	10.51	0.59	0.80
<b>JUN</b>	13.40	19.47	8.94	10.13	0.69	0.88
<b>JUL</b>	13.39	20.67	8.62	10.31	0.65	0.84
<b>AUG</b>	18.21	25.32	10.47	10.97	0.72	0.95
<b>SEP</b>	19.22	31.60	9.11	11.85	0.61	0.837
<b>OCT</b>	24.72	37.35	10.25	12.76	0.66	0.80
<b>NOV</b>	29.34	41.09	10.89	13.51	0.71	0.81
<b>DEC</b>	25.08	42.53	10.91	13.87	0.59	0.79

Prieska station is in the Northern Province. A number of renewable energy projects have been built in this province. The data in Table 6.4, confirms that there is availability of the natural resource that can be used to produce electricity from solar. During this year, the total sunshine hours measured was 3 581.6 hours. This is the highest value for all the provinces in South Africa. The relative sunshine hours fall within the range of 0.7 and 1, so the area has fair weather which can be used productively.

Table 12: Goudmyn – Monthly averages of daily measured and extra-terrestrial solar radiation, bright and possible sunshine hours , clearness index and relative sunshine hours.

Goudmyn Station 2010						
Month	$H_{meas}$	$H_0$	$S$	$S_p$	$K_T$ $= H_{meas}/H_0$	$RSS$ $= S/S_p$
<b>JAN</b>	22.31	42.72	8.96	13,98	0.52	0.64
<b>FEB</b>	25.58	39.02	8.70	13,22	0.66	0.66
<b>MAR</b>	21.68	32.83	7.53	12,21	0.66	0.62
<b>APR</b>	15.48	25.32	7.16	11,14	0.61	0.64
<b>MAY</b>	11.34	19.09	5.79	10,23	0.59	0.57
<b>JUN</b>	9.61	16.16	5.65	9,78	0.59	0.58
<b>JUL</b>	10.77	17.39	6.10	10,00	0.62	0.61
<b>AUG</b>	13.22	22.51	6.28	10,78	0.59	0.58
<b>SEP</b>	19.23	29.78	7.77	11,82	0.65	0.66
<b>OCT</b>	22.09	36.82	7.15	12,90	0.60	0.55
<b>NOV</b>	25.62	41.69	7.15	13,79	0.61	0.52
<b>DEC</b>	27.02	43.67	7.78	14,22	0.62	0.55

The least global solar radiation value of 9.61 MJ/m<sup>2</sup> was observed in June corresponding to the extraterrestrial solar radiation (16.16 MJ/m<sup>2</sup>). The annual average clearness index was greater than 60 %. The fractional sunshine hours showed that the location receives an abundant amount of bright sunshine i.e. more than 60 % .

## 6.2 Graphical representations

MATLAB software was used to generate the relative sunshine hours (the ratio of the bright sunshine hours and possible sunshine hours) and the clearness indices.

### 6.2.1 Limpopo Province

The variation of clearness indices and the relative sunshine hours are depicted by Figure 22 & 23). In each province the daily fractional solar radiation and sunshine hours were obtained for five years and which means that, if all the graphical representations were to be included in this document, we could have hundred and twenty figures. It can be observed from the figures that there are zero clearness indices values due to the zero measured global solar radiation data sourced from ARC. In the year 2007 and 2011, the regression coefficients  $a$  and  $b$  are 0.199, 0.251 and 0.531 and 0.509 respectively.

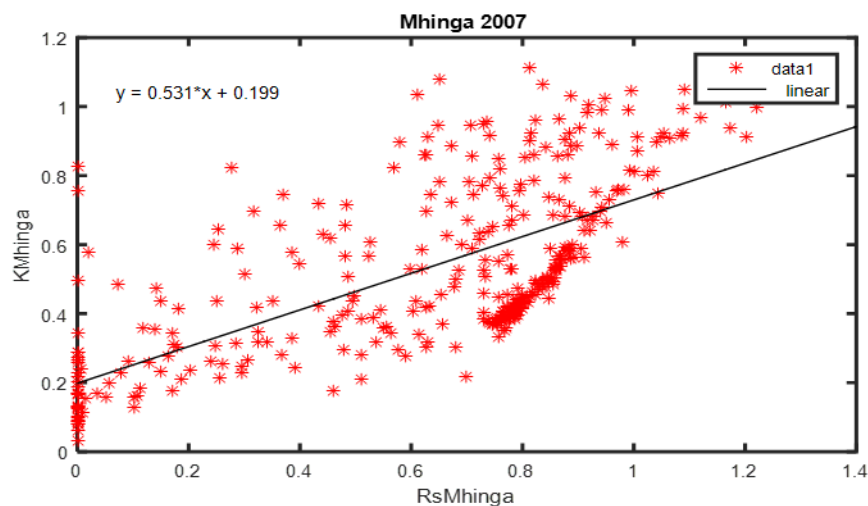


Figure 22: Variation of  $K$  with respect to RSS for Mhinga

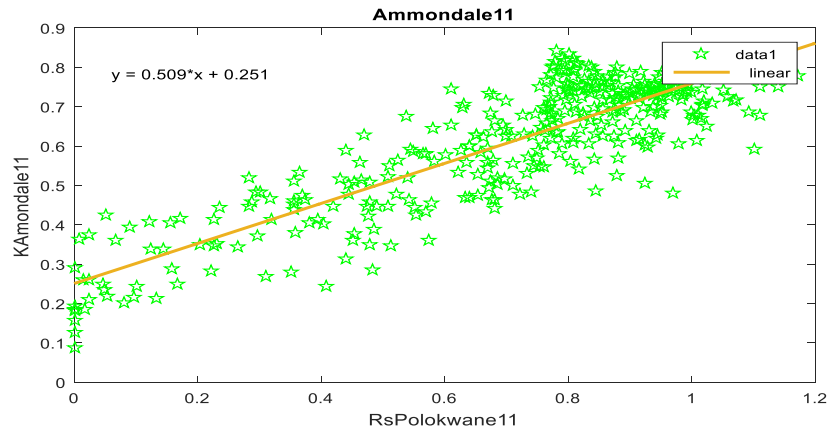


Figure 23: Variation of  $K$  with respect to RSS for Ammondale

There exists the zero  $H$  values at both the stations which might have occurred due to clouds or the radiometers being out of order. Measurements of solar radiation data needs maintenance whereby the radiometers have to be calibrated to ensure World Radiometric Reference (WRR) values. This ensures the acceptance of the measured data worldwide.

### 6.2.2 Western Cape

The average daily global radiation to the corresponding value on a clear day at both Lebourne and Helderfontein and their ratio of the average daily sunshine duration to the maximum possible sunshine were clustered between 0.8 and 1.00 for RSS and 0.55 and 0.75. This confirmed the suitability of renewable energy sources.

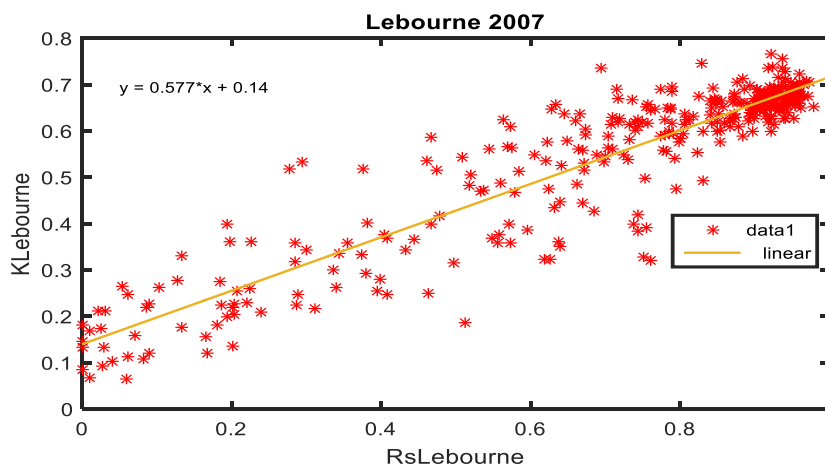


Figure 24: Variation of  $K$  with respect to RSS for Lebourne

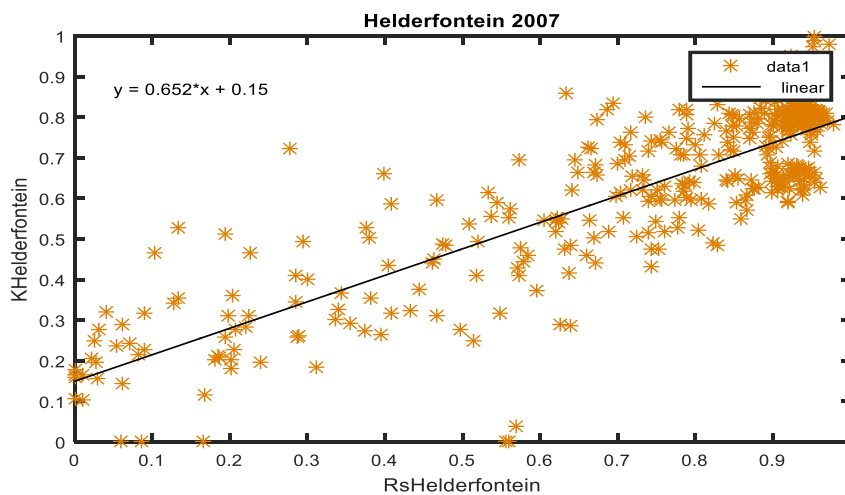


Figure 25: Variation of  $K$  with respect to RSS for Helderfontein

### 6.2.3 Eastern Cape

Figure 26 shows the daily possible sunshine duration. The maximum was observed in summer (November, December and January) and minimum daylengths were in May, June and July.

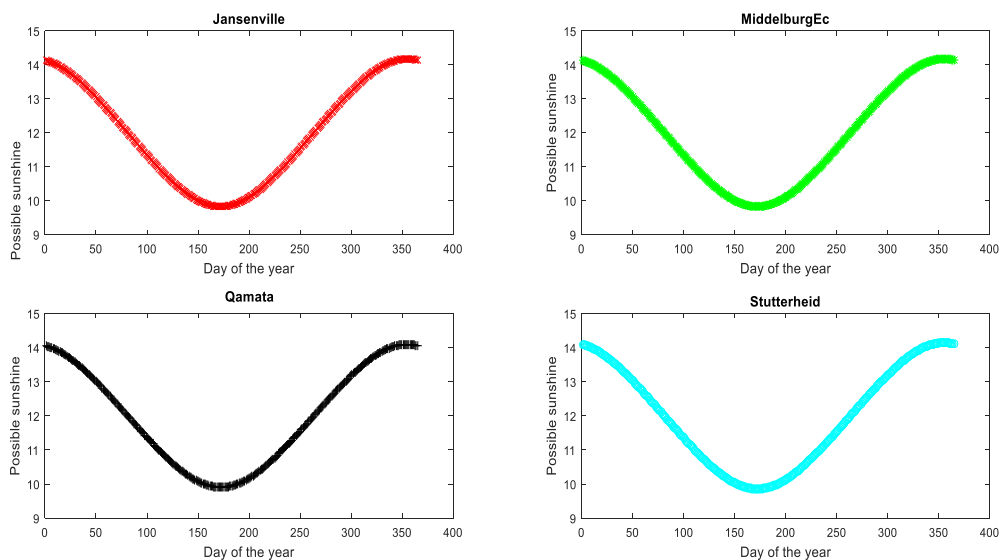


Figure 26: Eastern Cape Daylength

The possible sunshine hours or day length depicted in Figure 26 shows the minimum and maximum values of 10 and 14 hours during winter and summer seasons, respectively.

Although the locations are distant from each other, the day lengths are approximately the same. The more the number of daylengths the higher the global solar radiation expected, taking into account the factors that reduce it. We expect low global solar radiation during this season (winter). Although SA receives its rainfall in summer the maximum of 14 possible sunshine hours are measured.

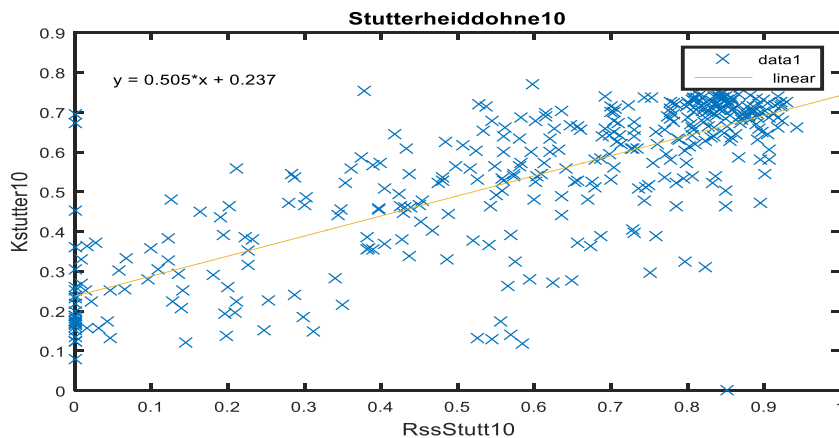


Figure 27: Variation of  $K$  with respect to RSS for Stutterheiddohne 2010

The observed global solar radiation had zero values that might have been caused by cloud cover or the malfunctioning of the measuring instrument. Maintenance of stations is crucial for the reliable solar resource data. There existed only one zero bright sunshine hours.

#### 6.2.4 Northern Cape

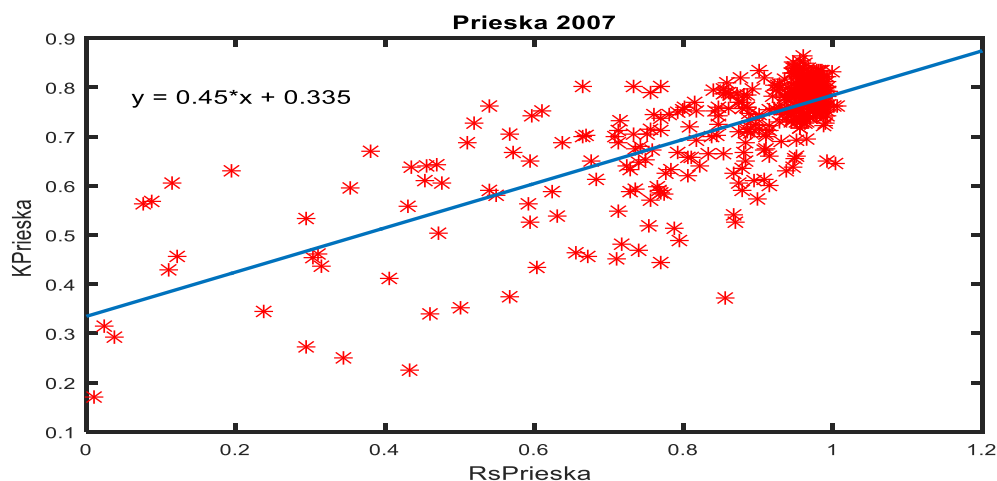


Figure 28: Variation of  $K$  with respect to RSS for Prieska

#### 6.2.5 Mpumalanga

### Comparison of $H$ and $H_0$ , for Lydenberg station in 2007 and 2011.

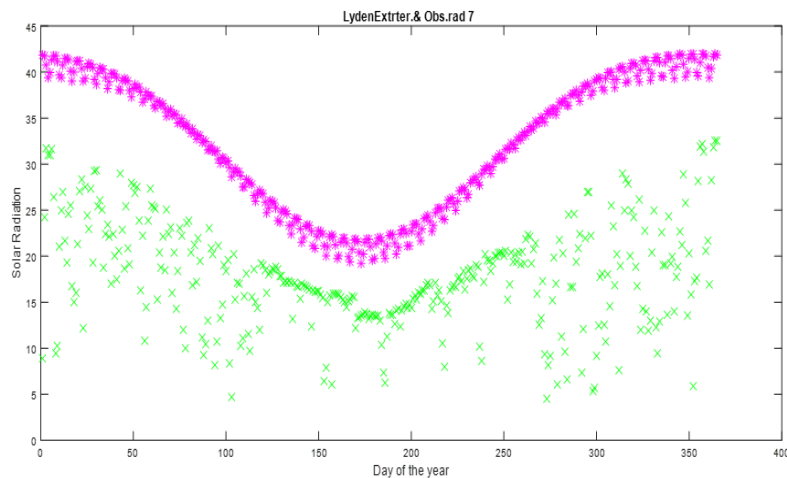


Figure 29: Lydenberg Representation of  $H$  and  $H_0$  2007

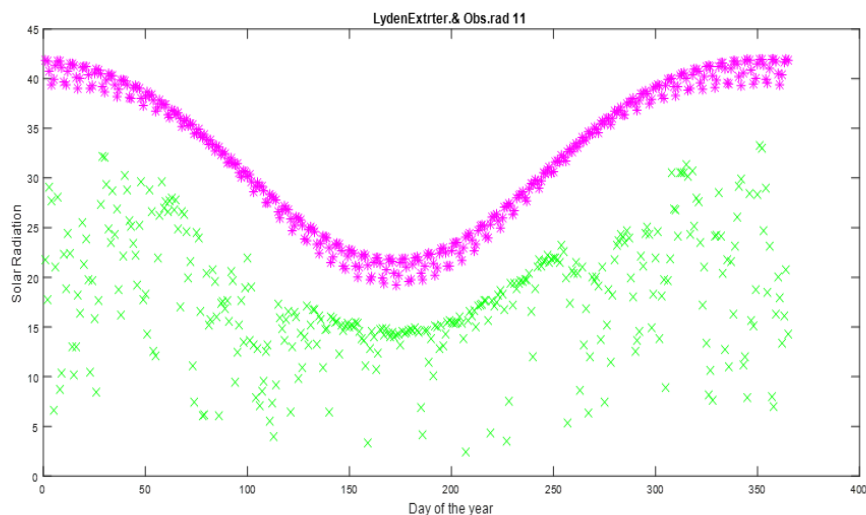


Figure 30: Lydenberg Representation of  $H$  and  $H_0$  2011

The observed global solar radiation ranged from  $5 \text{ MJm}^{-2}\text{day}^{-1}$  to  $32 \text{ MJm}^{-2}\text{day}^{-1}$  while the extra-terrestrial solar radiation ranged from  $22 \text{ MJm}^{-2}\text{day}^{-1}$  to  $43 \text{ MJm}^{-2}\text{day}^{-1}$  during summer seasons. The minimum global solar radiation occurred in June during winter season in SA but we observed that the least measured global solar radiative flux was scattered throughout all the seasons of the year. In April, approximately  $n = 100$ , the country approaches winter season. Although, at  $n = 273$ , August,  $H$  values were at a minimum, this was thought to be due to wind and the Rayleigh scattering of the received global solar radiation due dust. As we approached the rainy season, that is, November and December, the minimum and maximum global solar radiative fluxes were observed. This was due to water drops in the atmosphere

during rainy days. In the year 2011, the minimum was below  $5 \text{ MJm}^{-2}\text{day}^{-1}$ . When compared to 2007, the 2011 winter periods were colder and hence higher humidity.

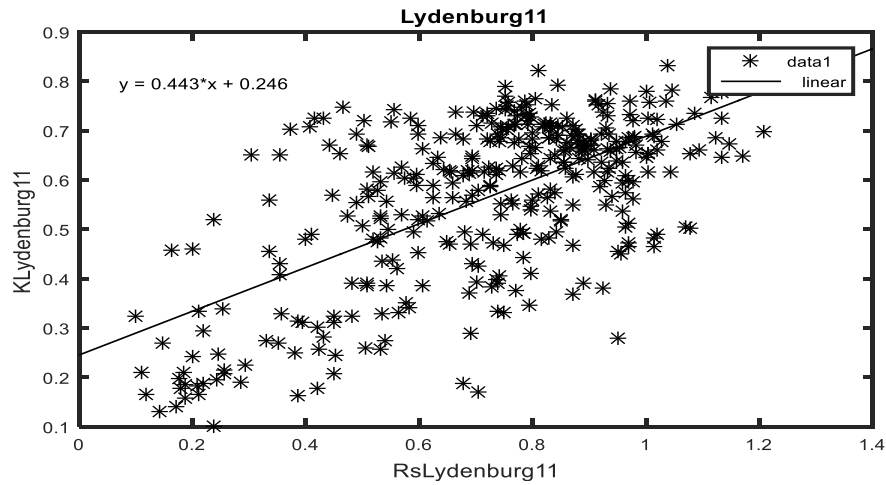


Figure 31: Variation of  $K$  with respect to RSS for Lydenberg.

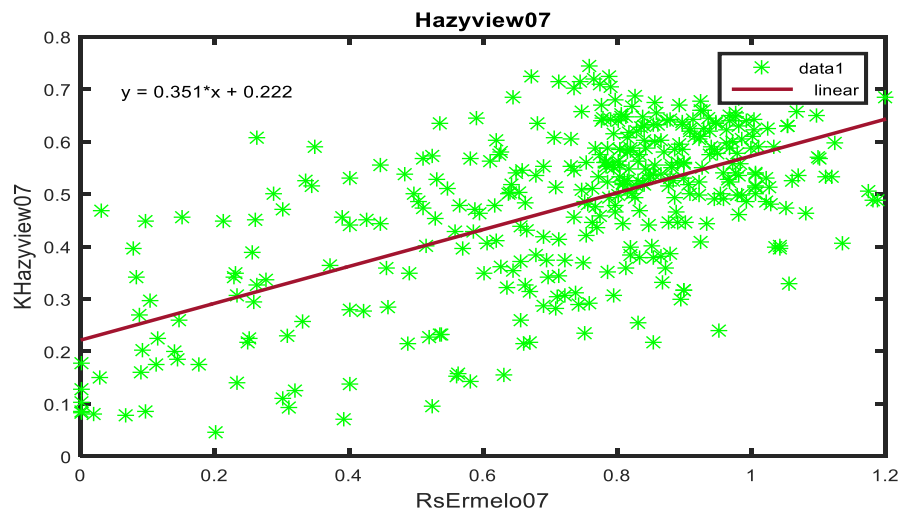


Figure 32: Variation of  $K$  with respect to RSS for Hazyview

## 6.2.6 North West

The stations' data had a relationship between the clearness indices and the proportion of the actual sunshine and the possible sunshine hours. The regression coefficients were determined as 0.168 and 0.406 for Schweizer and 0.113 and 0.455 for Ventersdorp in 2007. On a clear day, both the stations yielded values close to 0.6 ~ 60 % of solar radiation could have been received on the Earth surface at these sites.

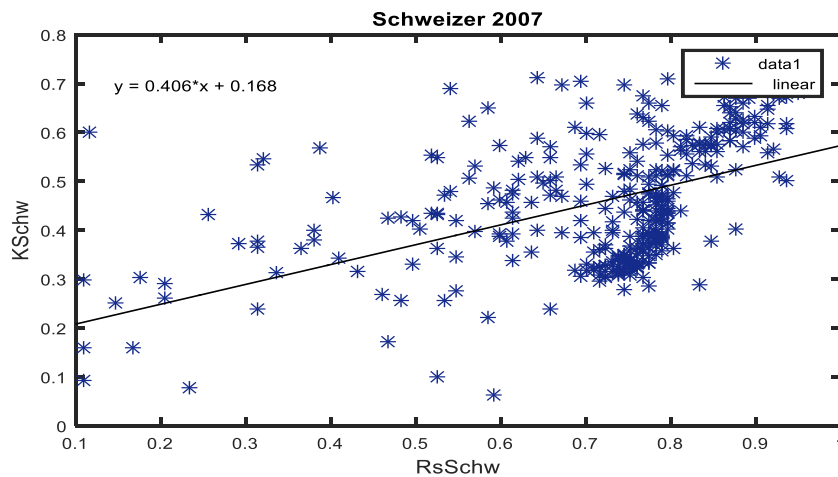


Figure 33: variation of  $K$  with respect to RSS for Schweizer

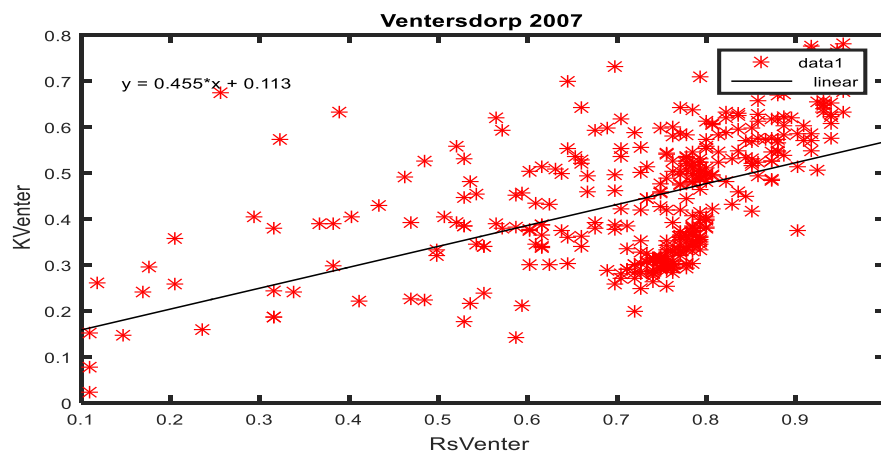


Figure 34: Variation of  $K$  with respect to RSS for Ventersdorp

## 6.2.7 Free State

Free state is the coldest area in South Africa especially during winter. The regression line showed a very good agreement between the clearness indices and relative sunshine hours. The total solar radiation received per station on a clear day where the actual sunshine hours were considered to be equal to the day lengths was more than 78 %. The coldness of the area doesn't rule out the installation of renewable energy systems.

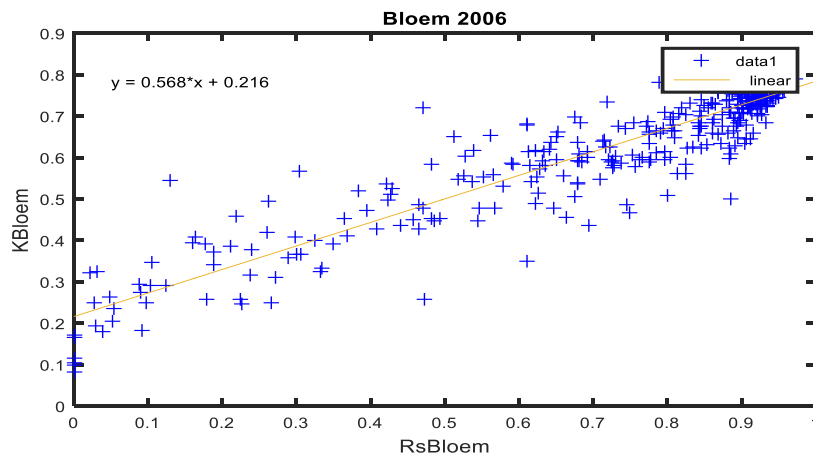


Figure 35: Variation of  $K$  with respect to RSS for Bloemfontein

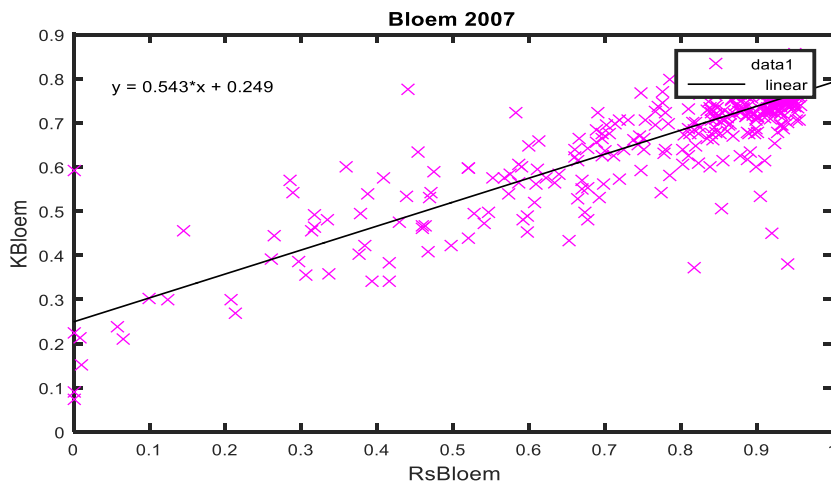


Figure 36: Variation of  $K$  with respect to RSS for Bloemfontein Glen

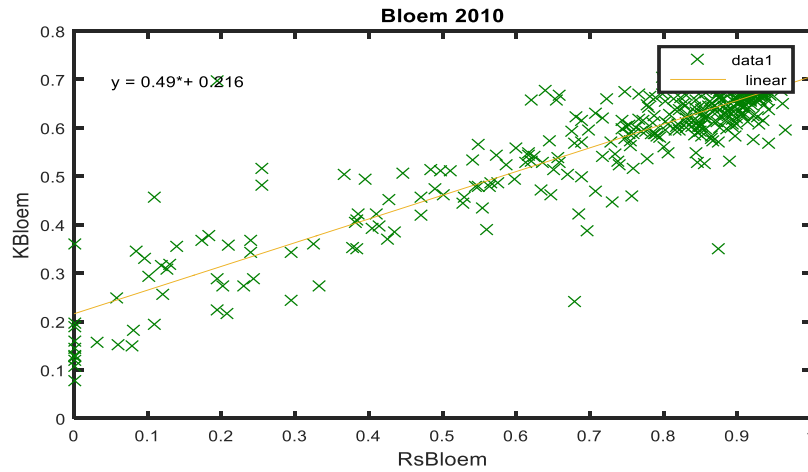


Figure 37: Variation of  $K$  with respect to RSS for Bloemfontein Glen

### 6.2.8 Gauteng

Gauteng province is an industrial area. Due to the huge population in the province, more energy supply is needed. The regression graphs drawn depicted that the use of renewable resources are of paramount importance. About 67 % of global solar radiation was received during the respective period indicated on the figures.

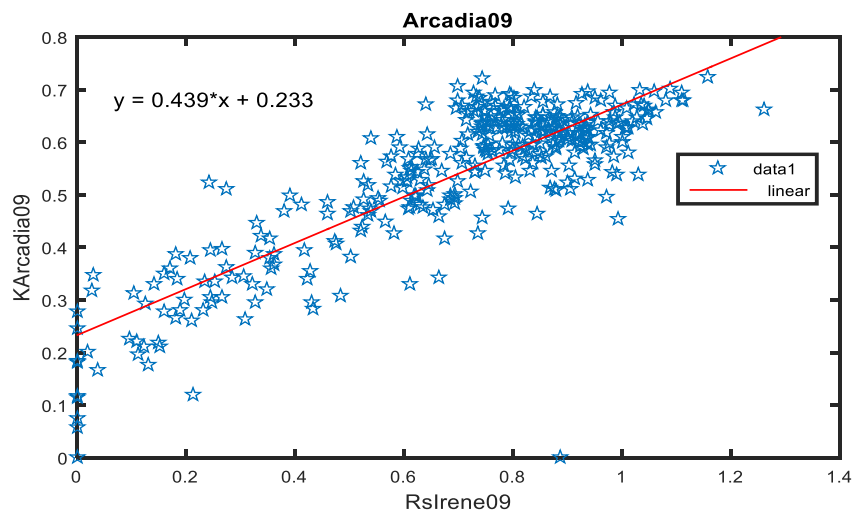


Figure 38: Variation of  $K$  with respect to RSS for Arcadia 2009

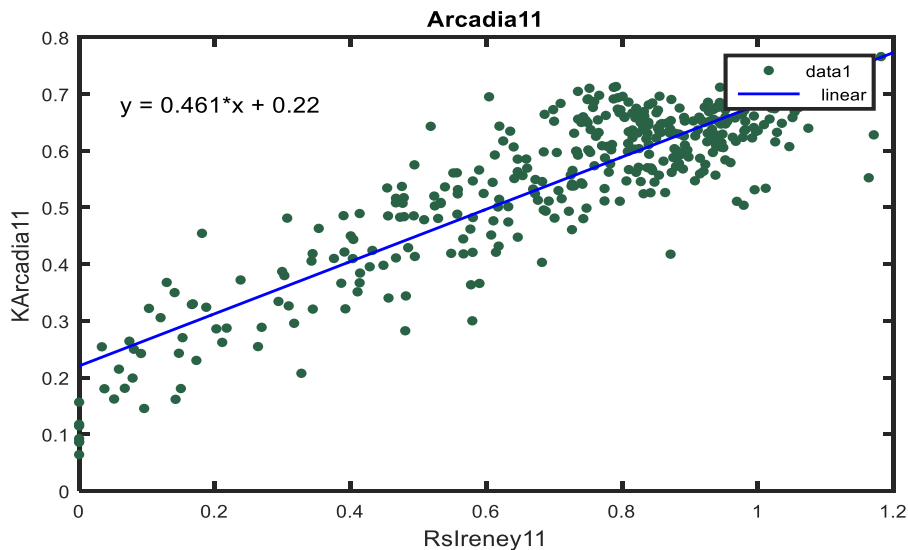


Figure 39: Variation of  $K$  with respect to RSS for Arcadia 2011

The coefficient of determination ( $R^2$ ) was 0.964 which showed a good relationship between the global solar radiation and sunshine hours. Although there were few days in which either the bright sunshine hours or the global solar radiation were zeros, the correlation of the regression line is 0.982. Generally, the maintenance of the stations need to be of priority.

### 6.3 Regression coefficients

The values of the regression coefficients tabulated in Table 13 were obtained from the regression analysis of Prescott-Angstrom first order equation using MATLAB software. The input parameters were the daily bright sunshine hours and global solar radiation at the site. A maximum of three meteorological stations were considered per province such that the 2007 – 2011 data was used to determine the annual regression coefficients. The average of those values are recorded in Table 13.

The parameters,  $\bar{a}$  and  $\bar{b}$  are the provincial regression coefficients determined from the average of the stations under study. On clear days, where the bright sunshine hours were equal to the daylengths/ possible sunshine hours, about 70 % of global solar radiation were received in the Earth. Taking into cognisance the data from Table 6, the geographical coordinates of the stations under study and Table 13, the variation of the regression coefficients were neither influenced by altitude nor latitude. There was no systematic trend found.

Table 13: Regression coefficients per station under study

Limpopo Province	Mutale		Ammondale		Mhinga		$\bar{a}$	$\bar{b}$
	a	b	a	b	a	b		
	0.201	0.432	0.245	0.449	0.202	0.445	0.216	0.442
Mpumalanga	<b>Lydenburg</b>		<b>Hazyview</b>		<b>Mzinti</b>			
	a	b	a	b	a	b	$\bar{a}$	$\bar{b}$
	0.357	0.433	0.247	0.369	0.252	0.341	0.285	0.381
Gauteng	<b>Pretoria Arcadia</b>		<b>Pretoria Botanical</b>		<b>Rodepoort</b>			
	a	b	a	B	a	b	$\bar{a}$	$\bar{b}$
	0.219	0.442	0.223	0.467	0.218	0.603	0.220	0.504
North West	<b>Delareyville</b>		<b>Koster</b>		<b>Ventersdorp</b>			
	a	b	a	b	a	b	$\bar{a}$	$\bar{b}$
	0.216	0.525	0.217	0.524	0.216	0.526	0.217	0.525
Free State	<b>Koffiefontein</b>		<b>Hopetown</b>		<b>Bloemfontein Glen</b>			
	a	b	a	b	a	b	$\bar{a}$	$\bar{b}$
	0.288	0.415	0.395	0.372	0.219	0.533	0.301	0.440
Northern Cape	<b>Prieska</b>		<b>Douglas</b>		<b>Augribies</b>			
	a	b	a	b	a	b	$\bar{a}$	$\bar{b}$
	0.325	0.444	0.291	0.342	0.268	0.433	0.294	0.409
Eastern Cape	<b>Jansenville</b>		<b>Qamata</b>		<b>Middelburg</b>			
	a	b	a	b	a	b	$\bar{a}$	$\bar{b}$
	0.259	0.377	0.289	0.419	0.219	0.459	0.256	0.418
Western Cape	<b>Helderfontein</b>		<b>Goudmyn</b>		<b>Le Bourne</b>			
	a	b	a	b	a	b	$\bar{a}$	$\bar{b}$
	0.167	0.553	0.352	0.422	0.171	0.561	0.230	0.512

From the results highlighted in Table 13, the modified first order Angstrom-PreScott correlation models for the estimation of the global solar radiation  $H$  at the respective meteorological stations under study were expressed as follows:

### 6.2.1 Limpopo Province

$$\text{Thohoyandou Mutale} \quad : \quad \frac{H}{H_0} = 0.201 + 0.432 \frac{S}{S_p}$$

$$\text{Polokwane Ammondale} \quad : \quad \frac{H}{H_0} = 0.245 + 0.449 \frac{S}{S_p}$$

$$\text{Malamulele Mhinga} \quad : \quad \frac{H}{H_0} = 0.202 + 0.445 \frac{S}{S_p}$$

$$\text{In general:} \quad \frac{H}{H_0} = 0.216 + 0.442 \frac{S}{S_p}$$

where  $H$ ,  $H_0$ ,  $S$  and  $S_p$  are the global solar radiation, the extraterrestrial solar radiation on the upper atmosphere, the bright sunshine hours and the possible sunshine hours respectively.

### 6.2.2 Mpumalanga Province

$$\text{Lydenburg} \quad : \quad \frac{H}{H_0} = 0.357 + 0.433 \frac{S}{S_p}$$

$$\text{Hazyview} \quad : \quad \frac{H}{H_0} = 0.247 + 0.369 \frac{S}{S_p}$$

$$\text{Mzinti} \quad : \quad \frac{H}{H_0} = 0.252 + 0.341 \frac{S}{S_p}$$

$$\text{In general:} \quad \frac{H}{H_0} = 0.285 + 0.381 \frac{S}{S_p}$$

### 6.2.3 Gauteng Province

$$\text{Pretoria Arcadia} \quad : \quad \frac{H}{H_0} = 0.219 + 0.442 \frac{S}{S_p}$$

$$\text{Pretoria Botanical} \quad : \quad \frac{H}{H_0} = 0.223 + 0.467 \frac{S}{S_p}$$

$$\text{Roodepoort} \quad : \quad \frac{H}{H_0} = 0.218 + 0.602 \frac{S}{S_p}$$

$$\text{In general:} \quad \frac{H}{H_0} = 0.220 + 0.504 \frac{S}{S_p}$$

#### 6.2.4 North West Province

$$\text{Delareyville} \quad : \quad \frac{H}{H_0} = 0.216 + 0.525 \frac{S}{S_p}$$

$$\text{Koster} \quad : \quad \frac{H}{H_0} = 0.217 + 0.524 \frac{S}{S_p}$$

$$\text{Ventersdorp} \quad : \quad \frac{H}{H_0} = 0.216 + 0.526 \frac{S}{S_p}$$

$$\text{In general:} \quad \frac{H}{H_0} = 0.220 + 0.504 \frac{S}{S_p}$$

#### 6.2.5 Free State

$$\text{Koffiefontein} \quad : \quad \frac{H}{H_0} = 0.288 + 0.415 \frac{S}{S_p}$$

$$\text{Hopetown} \quad : \quad \frac{H}{H_0} = 0.395 + 0.372 \frac{S}{S_p}$$

$$\text{Bloemfontein Glen} \quad : \quad \frac{H}{H_0} = 0.219 + 0.533 \frac{S}{S_p}$$

$$\text{In general:} \quad \frac{H}{H_0} = 0.301 + 0.440 \frac{S}{S_p}$$

#### 6.2.6 Northern Cape:

$$\text{Prieska} \quad : \quad \frac{H}{H_0} = 0.3255 + 0.444 \frac{S}{S_p}$$

$$\text{Douglas} \quad : \quad \frac{H}{H_0} = 0.291 + 0.342 \frac{S}{S_p}$$

$$\text{Augribies} \quad : \quad \frac{H}{H_0} = 0.268 + 0.433 \frac{S}{S_p}$$

$$\text{In general:} \quad \frac{H}{H_0} = 0.294 + 0.409 \frac{S}{S_p}$$

### 6.2.7 Eastern Cape

$$\text{Jansenville} \quad : \quad \frac{H}{H_0} = 0.259 + 0.377 \frac{S}{S_p}$$

$$\text{Qamata} \quad : \quad \frac{H}{H_0} = 0.289 + 0.419 \frac{S}{S_p}$$

$$\text{Middelburg} \quad : \quad \frac{H}{H_0} = 0.219 + 0.459 \frac{S}{S_p}$$

$$\text{In general:} \quad \frac{H}{H_0} = 0.256 + 0.418 \frac{S}{S_p}$$

### 6.2.8 Western Cape

$$\text{Helderfontein} \quad : \quad \frac{H}{H_0} = 0.67 + 0.553 \frac{S}{S_p}$$

$$\text{Goudmyn} \quad : \quad \frac{H}{H_0} = 0.352 + 0.422 \frac{S}{S_p}$$

$$\text{LeBourne} \quad : \quad \frac{H}{H_0} = 0.171 + 0.561 \frac{S}{S_p}$$

$$\text{In general:} \quad \frac{H}{H_0} = 0.230 + 0.512 \frac{S}{S_p}$$

## 6.4 Comparison of the observed and the estimated global solar radiation

The performance of the modified Angstrom-Prescott linear equations were tested using the 2006 data in some of the provinces, namely Limpopo, Northern Cape and Western Cape. The results are reported graphically, where the average daily observed and the estimated global solar radiation were compared. Stations with full data were selected in order to evaluate the performance of the model.

The graphical representations of the comparison of the average daily measured and estimated global solar radiation are shown in Figures (40 – 42) in the following pages:

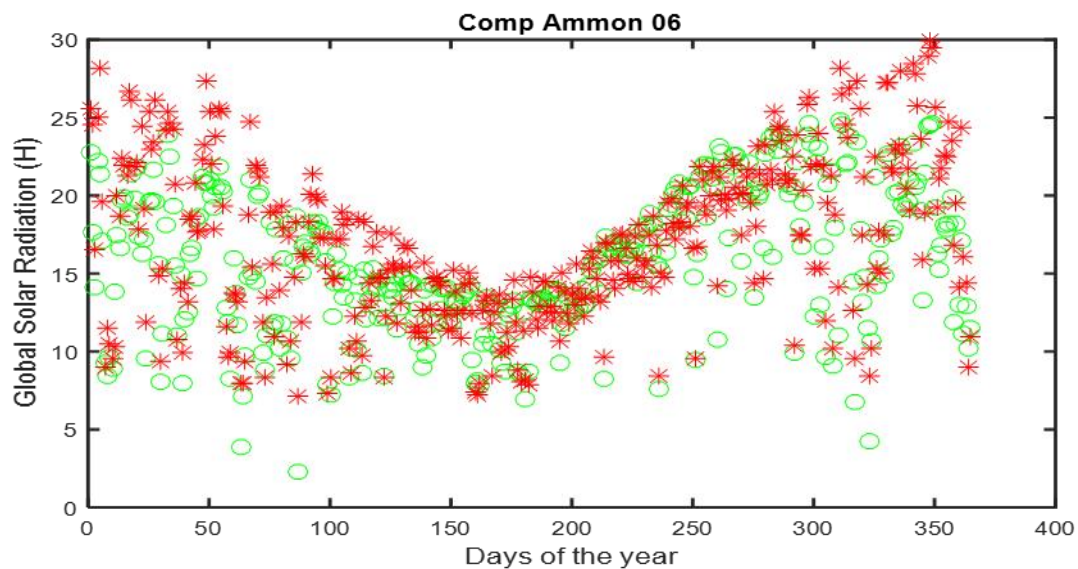


Figure 40: 2006 Observed data and the estimated H for Ammondale station.

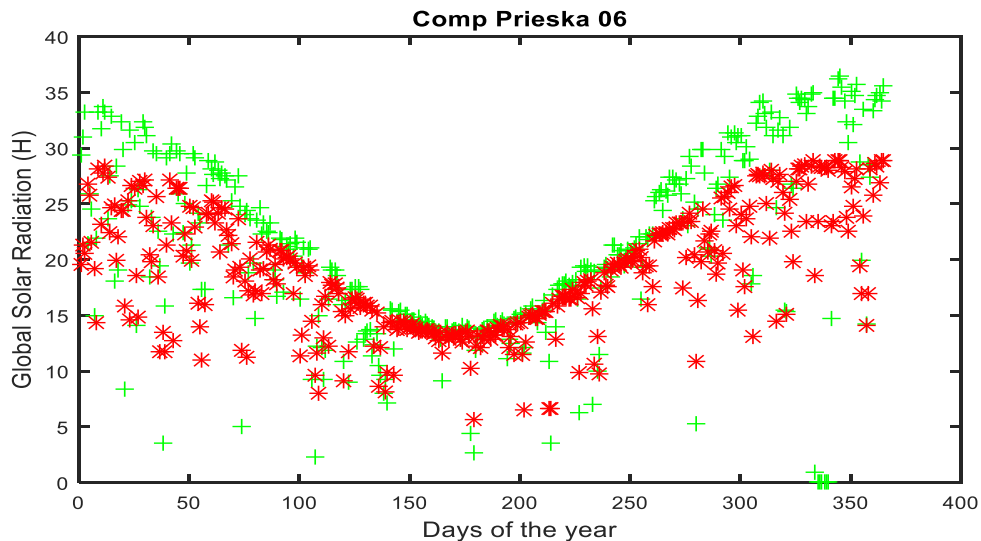


Figure 41: 2006 Observed data and the estimated H for Prieska station.

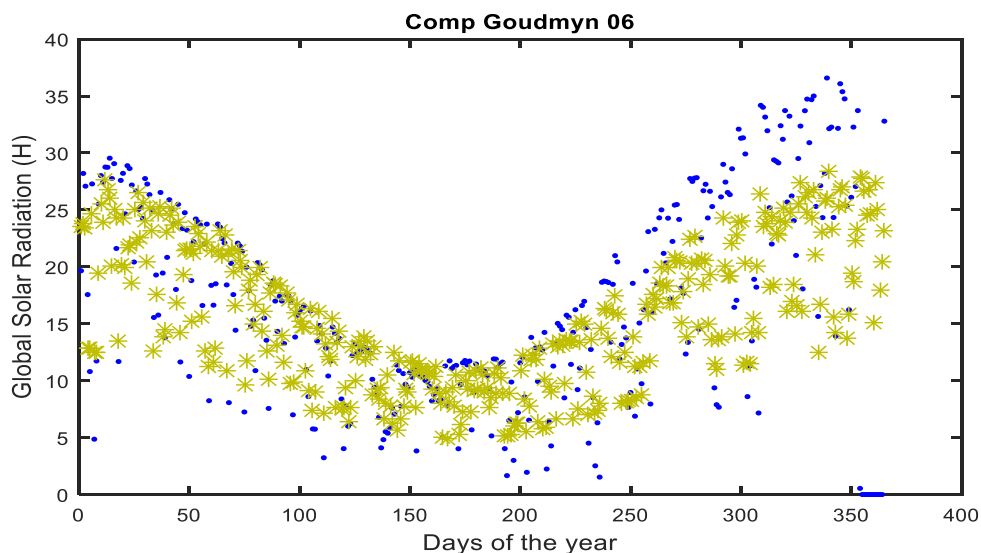


Figure 42: Comparison of the measured and estimated daily global solar radiation for Goudmyn 2006

The plots show the comparison of the daily measured and estimated global solar radiation through Angstrom-Prescott linear regression model modified using the local data and a fairly good relation was observed throughout the year. The 2006 meteorological data was used for the estimated data. Minor underestimations occurred in November and December for both stations Prieska in Northern Cape and Goudmyn in Western Cape. Taking into consideration that South Africa experiences rainfall during November and December, the variation would have occurred due to the aerosols in the atmosphere. The model predicted the daily global solar radiation data equivalent to the measured data in Limpopo province, Ammondale.

The maximum measured and estimated global solar radiation ( $\text{MJ}/\text{m}^2\text{day}$ ) were (24.54, 29.96); (35.56, 28.94) and (27.51, 21.80) during November 2006 for Ammondale, Prieska and Goudmyn respectively. Western Cape is the only province that receives rainfall during winter season and due to low temperatures, global solar radiation reached the minimum of  $5 \text{ MJ}/\text{m}^2\text{day}$  at Goudmyn.

The estimated and measured global solar radiation fluxes for the stations under study are tabulated in Table 14 and 15. These were determined using the evaluated regression coefficients in sections 6.2.1 – 6.

*Table 14: Estimated and Observed monthly global solar radiation flux in  $\text{MJ}/\text{m}^2$  2006*

Month	Ammondale		Lydenberg		Pretoria Botanical	
	Hest.	Hobs.	Hest.	Hobs.	Hest.	Hobs.
<b>January</b>	19.42	16.62	22.03	16.29	14.61	12.63
<b>February</b>	19.22	17.22	22.43	16.67	16.25	13.23
<b>March</b>	14.86	13.51	19.56	14.61	14.77	11.61
<b>April</b>	15.40	13.87	19.23	15.07	12.35	10.83
<b>May</b>	13.58	12.87	16.98	13.69	12.11	9.73
<b>June</b>	11.25	11.25	15.94	11.70	10.56	8.68
<b>July</b>	13.36	13.27	17.34	15.79	10.34	9.23
<b>August</b>	15.97	16.59	19.08	18.38	10.27	11.19
<b>September</b>	19.34	19.42	23.62	21.29	15.78	13.86
<b>October</b>	20.76	20.04	23.46	18.83	18.74	14.04
<b>November</b>	19.38	16.95	24.20	18.46	18.13	13.69
<b>December</b>	21.01	18.15	20.62	16.72	17.82	14.18

Table 15: Estimated and Observed monthly global solar radiation flux in MJ/m<sup>2</sup> 2006

Month	Prieska		Bloemfontein Glen		Goudmyn	
	Hest.	Hobs.	Hest.	Hobs.	Hest.	Hobs.
<b>January</b>	23.01	26.68	21.98	22.62	21.65	24.10
<b>February</b>	20.32	23.99	19.93	20.04	19.95	20.63
<b>March</b>	20.07	22.93	19.21	19.05	17.29	17.45
<b>April</b>	16.44	17.16	16.31	16.80	12.78	12.71
<b>May</b>	14.00	13.62	13.65	14.99	10.01	9.36
<b>June</b>	12.90	12.92	13.69	14.03	9.06	9.52
<b>July</b>	13.54	14.13	13.12	14.00	8.73	9.23
<b>August</b>	15.66	16.40	15.65	16.28	11.93	12.69
<b>September</b>	20.84	23.11	21.45	22.21	14.64	17.47
<b>October</b>	21.62	26.68	21.77	22.38	17.83	22.21
<b>November</b>	24.79	29.11	26.55	27.16	21.80	27.59
<b>December</b>	25.61	25.01	25.93	26.93	22.27	18.29

Table 16: Comparison between the monthly average daily measured and estimated values of  $H$  with the associated annual MBE, MPE, RMSE and  $R^2$

	Ammondale LP		Lydenburg MP		Botanical GP		Bloemfontein Glen		Prieska NC		Goudmyn WC	
<b>JAN</b>	16,62	19,42	16,29	22,04	18,83	16,65	22,63	21,98	26,68	23,01	24,10	21,65
<b>FEB</b>	17,22	19,22	16,67	22,44	24,88	20,67	20,04	19,93	23,99	20,32	20,63	19,95
<b>MAR</b>	13,51	14,86	14,61	19,57	18,44	16,40	19,05	19,22	22,93	20,07	17,45	17,29
<b>APR</b>	13,87	15,40	15,07	19,24	18,51	19,26	16,81	16,30	17,16	16,44	12,71	12,78
<b>MAY</b>	12,87	13,58	13,69	16,99	16,04	17,80	15,00	13,65	13,62	14,00	9,36	10,01
<b>JUN</b>	11,25	11,51	11,70	15,95	16,82	19,23	14,04	12,69	12,92	12,90	9,52	9,06
<b>JUL</b>	13,27	13,36	15,79	17,34	13,46	18,66	14,00	13,12	14,13	13,54	9,23	8,73
<b>AUG</b>	16,59	15,97	18,38	19,08	16,21	19,35	16,28	15,65	16,40	15,66	12,69	11,93
<b>SEP</b>	19,42	19,34	21,29	23,62	20,55	20,13	22,21	21,45	23,11	20,84	17,47	14,64
<b>OCT</b>	20,04	20,76	18,83	23,47	21,89	20,49	22,39	21,77	26,68	21,62	22,21	17,83
<b>NOV</b>	16,95	19,38	18,46	24,20	12,49	18,93	27,17	26,56	29,11	24,79	27,59	21,80
<b>DEC</b>	18,15	21,62	16,73	20,62	24,18	21,65	26,94	25,93	25,01	25,61	18,29	22,27
<b>avgH</b>	<b>11,5400</b>	<b>10,9700</b>	<b>16,7359</b>	<b>20,6318</b>	<b>27,7700</b>	<b>26,4600</b>	<b>19,7100</b>	<b>19,0100</b>	<b>20,9900</b>	<b>19,0600</b>	<b>16,7400</b>	<b>15,6300</b>
<b>RMSE</b>	<b>0,0297</b>		<b>0,5672</b>		<b>0,0683</b>		<b>0,3224</b>		<b>0,3466</b>		<b>0,5058</b>	

<b>MBE</b>	<b>0,0160</b>		<b>-</b> <b>0,0454</b>		<b>-</b> <b>0,0068</b>		<b>0,0169</b>		<b>0,0181</b>		<b>0,0265</b>	
<b>MPE</b>	<b>0,0135</b>		<b>0,0418</b>		<b>0,0129</b>		<b>0,0498</b>		<b>0,0510</b>		<b>0,0807</b>	
<b>R-squared</b>	<b>0,9820</b>		<b>0,6121</b>		<b>0,9730</b>		<b>0,8108</b>		<b>0,7934</b>		<b>0,6400</b>	
<b>r</b>	<b>0,9910</b>		<b>0,7820</b>		<b>0,9860</b>		<b>0,9000</b>		<b>0,8910</b>		<b>0,8000</b>	

$H_{meas}$  and  $H_{est}$  denote the measured and estimated global solar radiation respectively.

Table 15 depicts the comparison of the monthly average daily global solar radiation of the estimated and measured values. The accuracy of the estimated global solar radiation values were tested by computing the statistical errors enlisted in Table 15. The MBE values obtained were close to zero in agreement with Almorox et al. [65] and Che et.al. (2004). The actual deviation between the measured and the estimated (RMSE) values were low and this confirms that the model's performance is good. According to Merges et al. (2006), the model is said to perform relatively well if low MPE values are low and lie between -10.0 % and +10.0 %. The coefficients of determination,  $R^2$  and the coefficients of correlation,  $r$  range from 0.6124 – 0.9820 and 0.7820 – 0.9910 respectively. This is indeed a good model to predict the global solar radiation in the whole of South Africa irrespective of the climatic zones.

## CHAPTER 7: CONCLUSIONS AND RECOMMENDED FUTURE WORK

### 7.1 CONCLUSIONS

A simple linear empirical linear equation proposed by Angstrom and modified by Prescott due to the identification of clear days was modified in this study. The meteorological parameters were measured in South Africa. The total daily irradiation income on the horizontal surface is denoted by  $H$  and  $H_0$ . In order to find the regression coefficients, the bright sunshine hours ( $S$ ) and the global solar radiation ( $H$ ) measured on the horizontal surface were sourced from SAWS and ARC. The computed parameters were the possible sunshine hours ( $S_p$ ) and the global solar radiation on the upper surface of the Earth ( $H_0$ ). With the help of MATLAB coding, the daily  $S_p$  and  $H_0$  for the locations under study were computed. The measured and the computed values of the parameters used in the linear Angstrom -Prescott equation were critically analysed in order to identify the outliers. The annual regression coefficients per station were obtained through the curve fitting tool in MATLAB. Since a five year data was used to determine the regression coefficients, so, the average was taken. We have also computed the provincial regression coefficients. The regression coefficients determined showed no systematic manner in relation to the geographical coordinates. The provincial regression coefficients,  $a$  and  $b$ , range from 0.216 – 0.325 and 0.381 – 0.512 respectively. These values are in the agreement with those determined by Drummond in 1957 for Pretoria which is now called Tshwane in Gauteng.

The highest total bright sunshine hours were observed in the Northern Cape province. From the modified linear regression model derived in this study, on clear days where  $S = S_p$ , the sum of Angstrom regression coefficients,  $a + b$  (the transmissivity of the atmosphere for global solar radiation under clear sky conditions) values were greater than 0.7. Thus, one could conclude that, South Africa receives more than 70 % of solar radiation that can be harnessed for the energy use especially towards electricity and solar water heating.

Comparison of the observed and estimated global solar radiation showed a maximum error of about 4.00 % which proved a good performance of the model. The performance was evaluated using the statistical errors such as RMSE, MBE, MPE and  $R^2$ . Good agreement of the measured

and estimated global solar radiation was shown through the small values of RMSE and MBE while the coefficients of determination and correlation coefficients were close to 1.

## 7.2 FUTURE WORK

It is of vital importance that large data for more than 50 years has to be used to develop some new models that are strictly suitable for South Africa. This is possible provided our country has reliable solar resource data. At Vuwani Science Resource Centre, the flagship of University of Venda, a weather station has been installed. It can be of benefit if a permanent personnel is assigned to take care of the station. Due to lack of funds, SA cannot install enough solar radiation instruments hence modelling in the fourth industrial revolution plays an important part. Introduction of computational module to the postgraduate students is a priority since this knowledge will assist students who are working with data. The regression models for the prediction of solar radiation need to be developed taking into consideration the escarpments available in our country. For future studies, satellite data needs to be employed to evaluate the performance of the model. The regression coefficients may be determined for the plateau areas in South Africa to check their variability in the interior and coast lands. The seasonal values may be computed in consideration of the temperature data at the site of study. It is of paramount importance to assess the air quality at the study area since greenhouse gases and aerosols affect the amount of solar radiation that reaches the Earth hence the regression coefficients. Climate change is real, so enough meteorological data needs to be collected and analysed for public domain.

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