GLOBAL, DIRECT AND DIFFUSE SOLAR INSOLATION ANALYSIS ON HORIZONTAL AND TILTED SURFACES AT COLOMBO, SRI LANKA

Wasala W.A.M.L

(118362H)

Degree of Master of Engineering

Department of Mechanical Engineering

University of Moratuwa

Sri Lanka

January 2015

GLOBAL, DIRECT AND DIFFUSE SOLAR INSOLATION ANALYSIS ON HORIZONTAL AND TILTED SURFACES AT COLOMBO, SRI LANKA

Wasalamuni Arachchillage Manjula Laksiri Wasala

(118362H)

Thesis submitted in partial fulfillment of the requirements for the degree

Master of Engineering

Department of Mechanical Engineering

University of Moratuwa

Sri Lanka

January 2015

DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: .... Date: ....

W.A.M.L Wasala

The above candidate has carried out research for the Masters Thesis under my supervision.

Signature: .... Date: ....

Prof. R.A Attalage

ABSTRACT

An analysis of global, direct and diffuse solar radiation on horizontal and tilted surfaces at Colombo was carried out to assess the solar resource potential on horizontal and tilted surfaces. The calculated monthly average global horizontal solar resource potential varied between 4.00 to 5.95 kWh/m^2/day while 5.00 kWh/m^2/day was the calculated annual average global horizontal solar resource potential at Colombo. Estimated annual average diffuse solar radiation component on horizontal surface was 1.82 kWh/m^2/day and the direct solar radiation component was 3.18 kWh/m^2/day which was about 63.6% of the global horizontal insolation at Colombo. Solar resource assessment was then carried out for tilt angles 15°, 17.5°, 22.5°, 30°, 40° and 6.9° for the tilted surfaces in due south orientation. The derived maximum solar resource potential was 1830 kWh/m^2 per annum for the surface tilt angle of 6.9° which is equal to the local latitude. The solar resource potential was decreased with increased surface tilt angle. The percentage decrements compared to the global horizontal solar radiation were 0.7%, 1.4%, 3.0%, 6.8% and 14.3% for surface tilt angles of 15°, 17.5°, 22.5°, 30°, and 40° respectively. According to the results of the analysis, it is required to tilt the surface maximum of 30° towards the south and maximum of 25° towards the North during a year to maximize the solar resource potential on the tilted surface free to rotate about its East-West axis, placed at zero surface azimuth angle. 1918 kWh/m^2 per annum was the estimated maximum possible solar resource potential on tilted surface which is 5.1% greater than that of horizontal surface. With the availability of Solar Radiation data, it may possible to assess the Solar Resource Potential of any other location of the country in future by using the same procedure.

Key Words: Global Horizontal Solar Radiation, Direct & Diffuse Solar Radiation, Solar Radiation Model, Colombo

ACKNOWLEDGEMENT

I am very much grateful to Prof. R.A Attalage, Deputy Vice Chancellor of the University of Moratuwa for giving me his utmost support and guidance on this research. I would be very much grateful to Mr. Gayan Sirimanne, Lecturer, Department of Mechanical Engineering, University of Moratuwa, for giving his fullest support in every stage of this research. I wish to thank Dr. Himan Punchihewa and Dr. Inoka Manthilake, for their support as the resource persons for the research. This research was carried out under the supervision of Prof. R.A Attalage, senior professor, Department of Mechanical Engineering, University of Moratuwa. I am indebted to him for the valuable guidance, and kind hearted co-operation and encouragement extended throughout the study. Finally, I would appreciate everybody, who helped me in numerous ways at different stages of the research, which was of utmost importance in bringing out this effort a success.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ASHRAE	American Society of Heating Refrigerating and Air conditioning Engineers
CEB	Ceylon Electricity Board
CSR	Climatological Solar Radiation
DNI	Direct Normal Irradiation
ESD	Energy Services Delivery
GHI	Global Horizontal Irradiation
HDKR	Hay-Davis-Klucher-Reindl
LECO	Lanka Electricity Company
MBE	Mean Bias Error
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
PV	Photo Voltaic
RERED	Renewable Energy for Rural Economic Development
RMSE	Root Mean Square Error
WMO	World Metrological Organization
SLSEA	Sri Lanka Sustainable Energy Authority
SSE	Surface metrology and Solar Energy
SWERA	Solar and Wind Energy Resource Assessment

CHAPTER 1. INTRODUCTION

1.1. Background

Sri Lanka, while being an upper middle income earning country fulfills its energy needs either directly by primary energy sources such as biomass and petroleum or by secondary sources such as electricity generated using coal, petroleum, hydro power and biomass. Sri Lanka's energy sector experienced a severe strain owing to the increasing international oil prices and droughts in 2012 (Sri Lanka Sustainable Energy Authority, 2012). Reduced rainfall exerted more demand on petroleum imports with severe economic impact on the industry. Under this circumstance, the country had to depend on expensive petroleum based thermal power generation to fulfill the rising energy demand during last few years. Also the international oil prices too increased owing to the geopolitical disturbances in crude oil producing countries, Euro zone debt crisis and the slow phase of global economic recovery. As a result of this unfavorable situation, the country had to spend about 51.5% (Sri Lanka Sustainable Energy Authority, 2012) of its export earnings on petroleum importation. Hence this situation is emphasizing the fact that exploration of indigenous energy sources such as renewable energy derived from solar, wind, biomass, hydro and mini hydro is vital to survive through the crisis as well as to enhance the energy security in the country.

Solar energy is probably the most important renewable energy source available in present day. Most of other renewable energy sources are also derived directly or indirectly from the solar energy. There are many advantages of solar energy such as its cleanliness, free availability, accessibility from most of the urbanized geographical locations of the country throughout almost the entire year, capability to operate independently or in conjunction with traditional energy sources and being remarkably renewable. Many applications of solar energy are presently in use for meeting electrical loads in most of the remote non-electrified regions of Sri Lanka. Still good potential exists in the country for significant expansion of the use of solar energy.

In present day, there are two commonly used methods for harnessing solar energy practiced widely over the world. The first one is the conversion of solar energy into electricity by solar photovoltaic modules and the convenient use according to the end user requirement. Other method is the conversion of solar energy into thermal energy by using solar thermal collectors and utilization for thermal energy applications. Photovoltaic systems convert solar radiation into electricity via a variety of methods. The most common approach is using silicon panels, which generate an electric current when solar energy irradiate upon it. Solar thermal systems are used to store heat from the sun which can be used for a variety of purposes. Many different approaches exist for solar thermal energy utilization, including active systems such as solar hot water heaters and also passive systems such as greenhouses which store and utilize solar energy.

A good, quantitative knowledge about distribution and the extent of solar energy resources in Sri Lanka is essential in order to make accurate decisions on the application of solar technologies, and to properly size the systems to be designed to meet desired loads. So an accurate prediction of incident solar radiation at a given location is of prime importance for any solar energy based application such as sizing modules in photovoltaic and thermal power systems, building design applications, agriculture etc. A study of this nature is important for a tropical country like Sri Lanka, where the annual average solar radiation is about 5.58 kWh/m^2/day (Surface meteorology and Solar Energy, 2005) and solar energy being readily available throughout the year with low seasonal variations. Solar energy harnessing by solar photovoltaic modules or flat plate collectors is usually done on tilted surfaces to maximize the energy conversion. Therefore analyzing the energy harnessing potential at a tilted surface is also of great importance to find out the optimum tilt angle for each month of the year.

1.2. Solar Energy Potential in Sri Lanka

Sri Lanka is located within the equatorial belt, a region where a substantial amount of solar energy resources exist throughout the year in adequate quantities for many of the solar energy applications including solar water heating, electricity generation etc. The extent of solar resources in Sri Lanka has been estimated by several parties in the past based on the daily total solar radiation recorded at number of weather stations throughout the country and also based on the satellite observations. Recently National Renewable Energy Laboratory (NREL) which is a Laboratory of U.S Department of Energy developed a model called Climatological Solar Radiation (CSR) model which can be used to predict monthly and annual average daily total solar radiation. CSR model provides monthly average daily total solar radiation estimates for the seven years period from 1985 to 1991. The results of this study indicate that the distribution of solar resources measured in terms of annual average daily insolation (on tilted surface where the tilt angle equals to the local latitude) varies from 4.5 to 6.0 $kWh/m^2/day$ across the country, with the lowest values occurring in the hill country in the Central Province (George, Gueymard, Heimiller, Marion, & Renne, 2003). The seasonal variation in solar resources in Sri Lanka lies between 4.5 and 6.5 $kWh/m^2/day$ (on tilted surface where the tilt angle equals to the local latitude) (George et al., 2003). The CSR model predicts that the highest resources are available during the hot dry period between March and April when the transition from the northeast to southwest monsoons occurs.

Most of the solar energy application devices such as photovoltaic modules and flat plate solar thermal collectors are fixed at an angle to the horizontal plane for maximizing the solar energy harnessing process. Also, concentrated type solar collectors are employed to obtain direct normal irradiation (DNI) with the aid of solar tracking systems. Figure 1.1 and 1.2 show the solar resource potential of direct normal irradiation on horizontal plane and annual average daily total irradiance at tilted surface where the tilt angle equal to the local latitude angle.

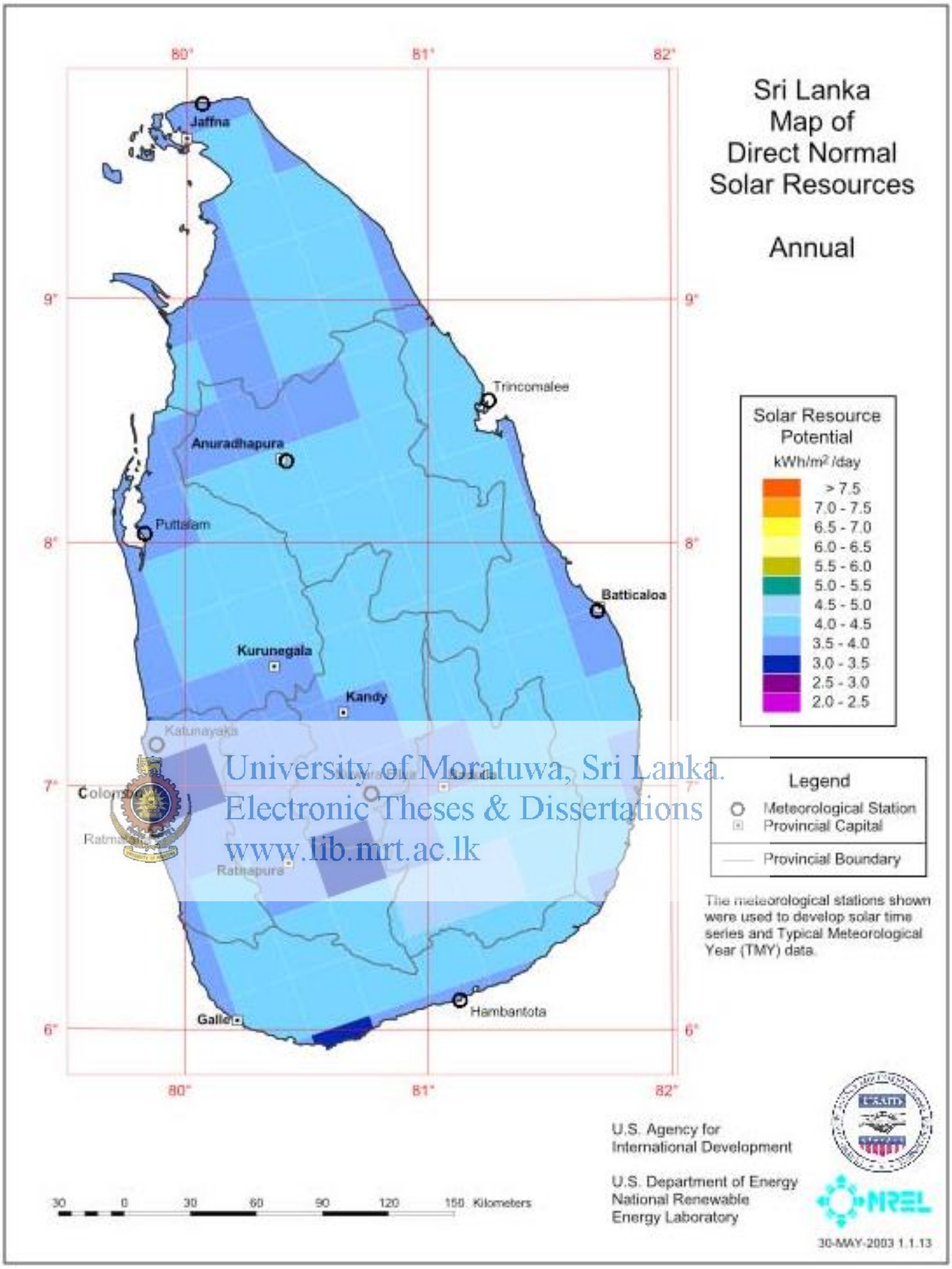

Figure 1.1: Direct Normal Irradiation (DNI) data for horizontal plane
Source: Solar Resource assessment for Sri Lanka and Maldives by NREL

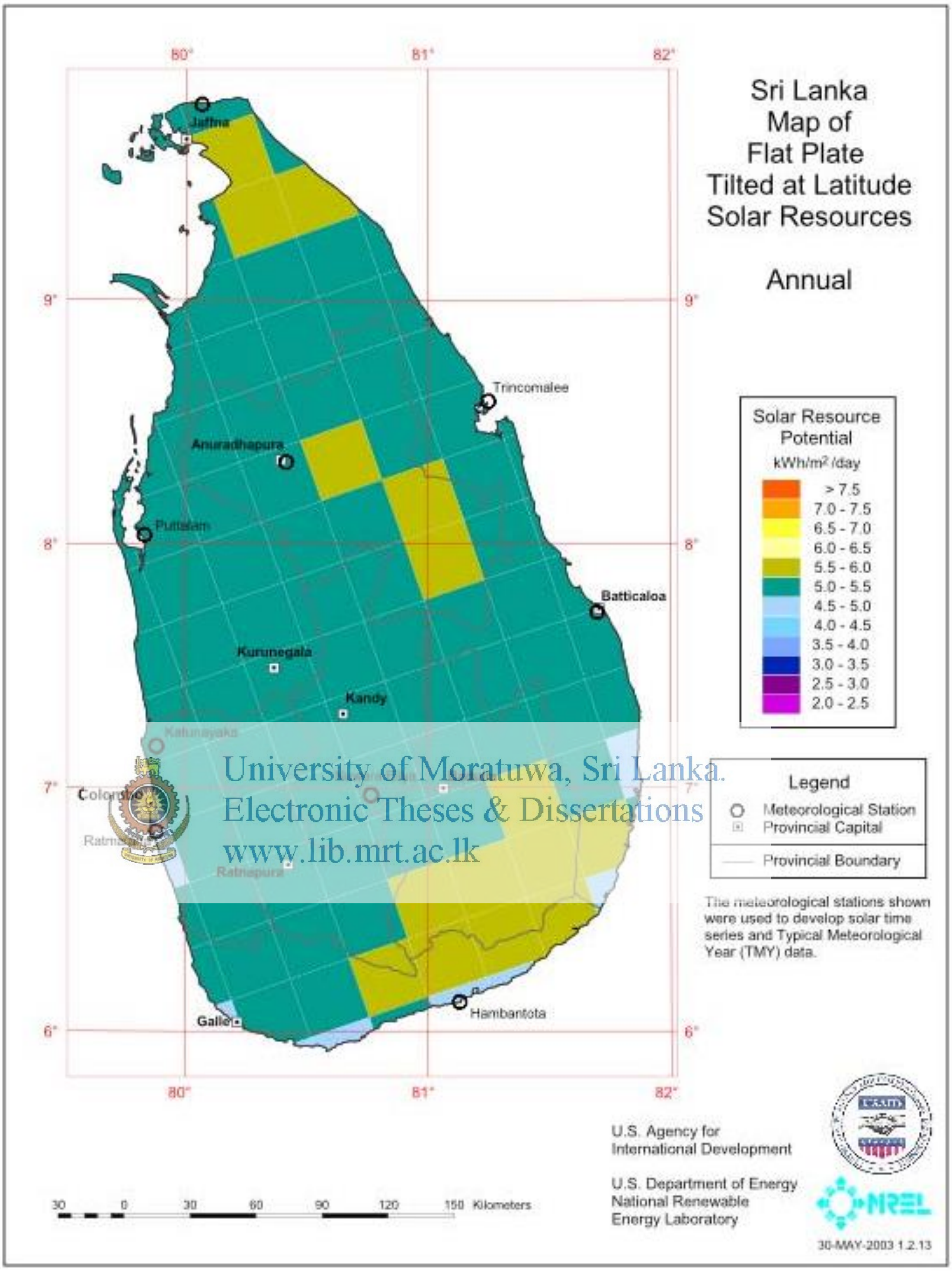

Figure 1.2: Annual average daily total solar irradiance at surface tilted at latitude angle
Source: Solar Resource assessment for Sri Lanka and Maldives by NREL

According to the figure 1.2, it can be concluded that harnessing of annual average daily solar radiation of 5.0-5.5 kWh/m^2/day (on tilted surface where the tilt angle equals to the local latitude angle) is possible in most parts of the country. Also it indicates that there exists a substantial solar energy harnessing potential in the dry zone of Sri Lanka

Another solar radiation model developed to estimate monthly average daily insolation data for Colombo, averaged for the 22 years from 1983 to 2005 is available at the Atmospheric Science Data Center web site of National Aeronautics and Space Administration (NASA). The particular solar radiation model is called NASA-SSE model which is totally based on satellite measurements. This model estimates that 6.67 kWh/m^2/day as the maximum insolation value which estimated in March while 4.93 kWh/m^2/day as the minimum insolation value which occurs in November (Surface meteorology and Solar Energy, 2005). The estimated annual average global horizontal solar insolation at Colombo is about 5.58 kWh/m^2/day (Surface meteorology and Solar Energy, 2005).

Table 1.1: 22-year averaged (1983-2005) monthly average daily global horizontal insolation at Colombo (kWh/m^2/day) derived by NASA-SSE model

Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Avg**
5.50	6.27	6.67	5.96	5.29	5.30	5.40	5.65	5.65	5.29	4.93	5.16	5.58

Source: NASA Atmospheric Science Data Center

Utilizing solar energy for off grid and grid applications in Colombo, the capital city of Sri Lanka, is economically viable for both in industrial and domestic sectors. Since a large amount of built up area is available in the capital city, an ample number of roof tops is available for solar energy harnessing systems. According to the measured solar radiation data for Colombo for the period from year 2000 to 2003 as illustrated in Figure 1.3, solar energy is available with sufficient intensity for more than six hours in the day time throughout the year. Hence, both solar photovoltaic modules and solar thermal collectors can efficiently operate during major part of the day time in Colombo.

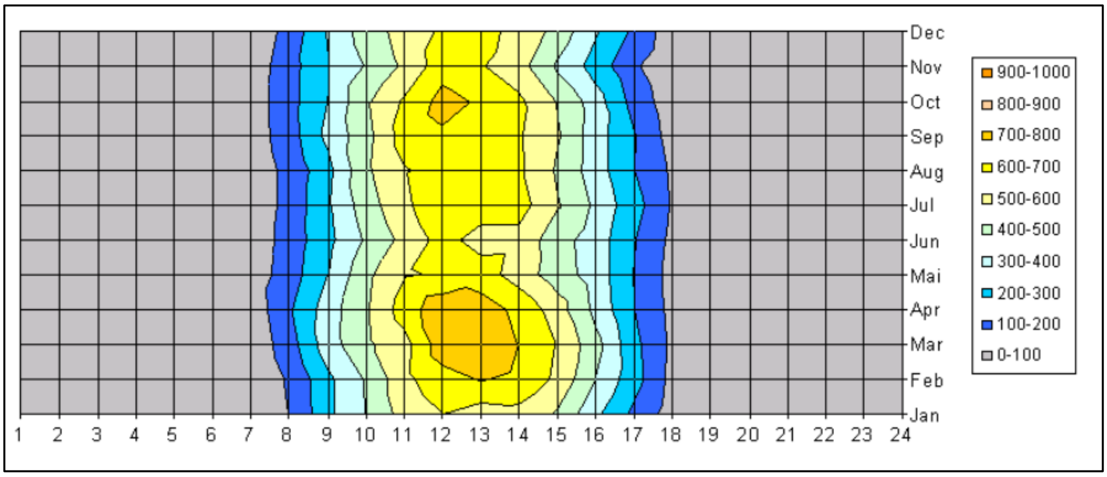

Figure 1.3: Monthly average hourly global horizontal irradiation (W/m^2) in Colombo for the duration from year 2000 to 2003
Source: Solar and Wind Energy Resource Assessment (SWERA) Report

1.3. Present Status of Solar Energy Applications in Sri Lanka

Sri Lanka's first solar power plant, worth LKR 412 million, has been commissioned and operates at Hambantota which adds 500 kW to the national grid (Sri Lanka Sustainable EnergyAuthority, 2010). Another solar power plant which costs LKR 1024 million was also installed at Hambanthota, and it contributes 737 kW to the national grid (Sri Lanka Sustainable EnergyAuthority, 2010). These pilot solar power projects operating in Hambantota completed a full weather cycle in 2012, derived annual plant factors of 16.02% and 17.49% for the 500 kW plant and the 737 kW plant respectively (Sri Lanka Sustainable Energy Authority, 2012). Ceylon Electricity Board (CEB) has also embarked on a 10 MW solar photovoltaic (PV) project, which will be interconnected to the medium-voltage network (CEB, 2012). The project will consist of five solar PV farms each generating 2 MW. They are expected to be commissioned by the end of 2014 and another 15 MW solar PV plant project is also under consideration.

Stand-alone PV systems make an important contribution in providing electricity to rural areas which are not served by the national grid. One example is the Renewable Energy for Rural Economic Development (RERED) project executed from 2002 to 2011. Also there were Energy Services Delivery (ESD) Projects executed in between 1997 and 2002. Under ESD and RERED projects, electricity has been given to

110,575 households using solar PV systems (Renewable Energy For Rural Economic Development Project, 2003). Figure 1.4 indicates the growth of the installed capacity of solar PV systems for domestic usage and the number of households facilitated by the ESD and RERED projects during the period from 1998 to 2011.

Presently net metering facility is available to all electricity customers in Lanka Electricity Company (LECO) areas (Siyambalapitiya, 2009). Customers can sell electricity to the grid at any time of the day. Solar net metering schemes gained much attention of the public in 2012 and created a dynamic industry.

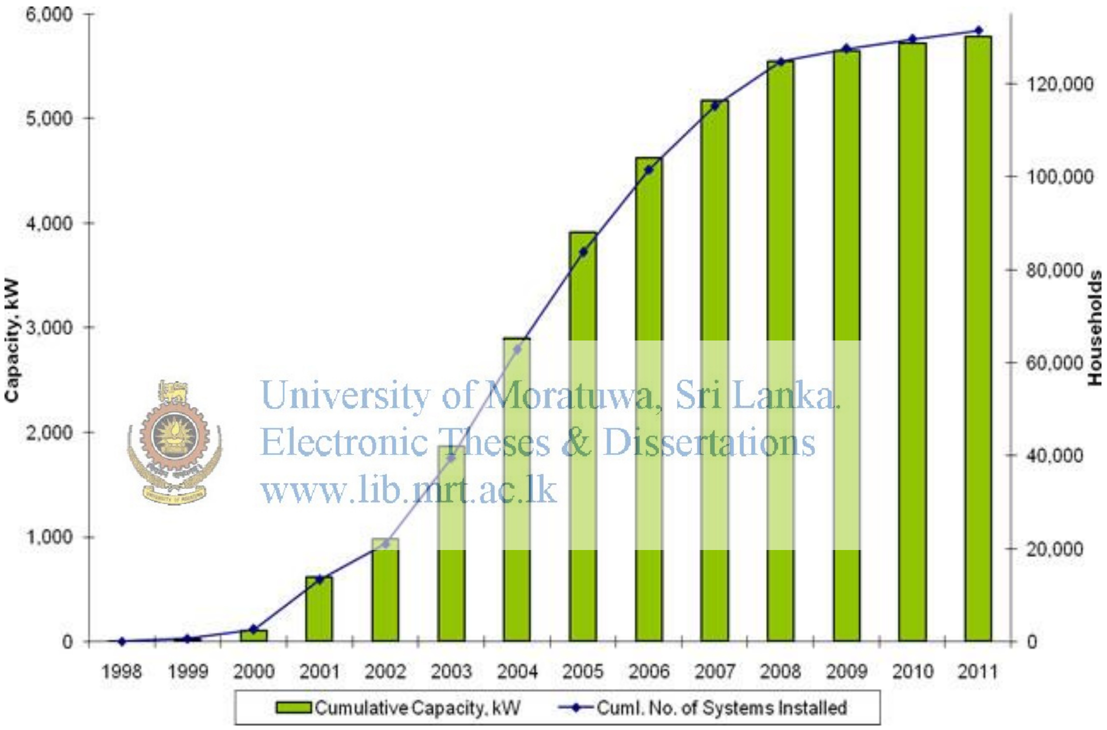

Figure 1.4: Solar home systems installed under ESD (1997-2002), RERED (2003-2007) & RERED Additional Financing (2008-2011) projects

Source: http://www.energyservices.lk/statistics/esd_rered.htm

Since the solar energy is used mostly in non-commercial forms, the total usage of energy is not yet quantified properly. However, solar energy is the most frequently used form of energy in day to day life and its supply is unrestricted and persistent throughout the year in most parts of Sri Lanka. Drying, heating and electricity production are the most common uses of solar energy in the country.

Table 1.2: Solar energy utilization in Sri Lanka

Typical User Groups	Typical Applications	Scale of use by end 2012
Solar photovoltaic	Household lighting	About 120,000 units
Grid connected PV	For sale to utility	4 power plants
Solar Thermal	Hot water systems (Commercial and domestic scale)	widespread
Informal use	Household and agricultural use	widespread

Source: Sri Lanka Sustainable Energy Authority

By the end of year 2012, it is generated 2 GWh of energy had been generated by 1.4 MW of installed capacity at four solar power plants. It is about 0.3% of the total non-conventional renewable energy generation of year 2012 (SLSEA, 2012).

Table 1.3: Solar energy generation from non-industrial solar PV modules

	2000	2005	2009	2010	2011	2012
No: of solar PV modules	10,000	97,105	147,737	157,342	166,947	120,000
Aggregate Peak Capacity (kW)	400.0	4264.2	6281.3	6659.7	7038.1	7416.5
Estimated Energy (MWh)	432	4605.3	6783.8	7192.5	7601.1	8009.8

Source: Sri Lanka Sustainable Energy Authority

Table 1.3 indicates that the non-industrial aggregate peak demand and the estimated energy generation had been remarkably increasing during the last decade. However the number of installed non-industrial PV modules has got reduced during 2011 to 2012. It may be due to some previously used and newly added PV modules counts under the industrial category.

Figure 1.5: Sri Lanka's first solar power plant at Hambantota

1.4. Problem Statement

Colombo, the capital of Sri Lanka receives ample amount of solar radiation consistently throughout the year. The received solar radiation has sufficient intensity for use in solar energy applications such as solar PV systems and solar thermal systems. An accurate estimation about the solar resource potential at Colombo is of prime importance to make accurate decisions and for properly sizing the solar energy systems being designed.

Earlier, two well-known US based organizations called NREL and NASA developed two solar radiation models called CSR model and NASA-SSE model respectively for the assessment of solar resource potential in Colombo. Both of these solar radiation models have used satellite data to predict the solar resources in terms of Direct Normal Irradiance (DNI) and Global Horizontal Irradiance (GHI). CSR solar radiation model provides monthly average daily total solar radiation estimates for the seven year period from 1985 to 1991 whereas NASA-SSE model estimates the monthly average daily total solar radiation for the twenty two year period from 1983 to 2005.

The estimation of solar resource potential from the CSR model is twenty four years old and the NASA-SSE model is almost ten years old. Therefore, the reliability of such obsolete models is now becoming questionable. Due to the inadequacy of data, it is undesirable to use those available from those two models for sizing solar energy system and equipment on tilted surfaces especially for roof top installations. Hence, development of a new model to predict solar resource potential from recent solar radiation data is of great importance since ground measurements of daily solar radiation for Colombo are available for recent years from the Meteorological Department of Sri Lanka.

The available data of solar radiation for Colombo is limited to ground measured Global Horizontal Irradiation. Direct and diffuse solar radiation components for Colombo have not been measured where it requires expensive instrumentation. Simple but accurate solar radiation models can be used to derive direct and diffuse solar radiation components from existing global solar radiation data and subsequently the results can be used to estimate solar resource potential on horizontal and tilted surfaces.

Diffuse solar radiation plays a vital role regarding the assessment of solar resource potential on tilted surfaces. Many isotropic and anisotropic sky models have already been developed to estimate the diffuse solar radiation component on tilted surfaces and it is a challenging task to select a suitable sky model to make accurate solar energy estimations. Also the opportunity is available to maximize the solar energy resource potential on tilted surface by selecting the optimum surface tilt angle which is possible to be derived using an accurate sky model.

1.5. Key Objectives

1. Estimate the monthly average daily global, direct and diffuse horizontal solar resource potential in Colombo
2. Estimate the annual average global, direct and diffuse solar resource potential on tilted surfaces suitable for roof top solar energy system installations in Colombo.
3. Estimate the monthly average optimum surface tilt angle which maximize the solar resource potential in Colombo.

1.6. Other Objectives

1. Identify the different meteorological parameters affecting the global solar radiation.
2. Identify the relative importance of different meteorological parameters affecting the global solar radiation.
3. Study about different solar radiation models which can be used to estimate solar radiation on horizontal and tilted surfaces.
4. Study about solar resource potential on tilted surfaces under isotropic and anisotropic sky conditions.

1.7. Outcomes

1. Mathematical model to predict the monthly average daily global solar radiation using sunshine hours in Colombo.
2. Estimation of monthly average daily global, direct and diffuse horizontal solar radiation in Colombo.
3. Estimation of the monthly average clearness index for horizontal surfaces in Colombo.
4. Estimation of monthly average daily global solar radiation on selected tilted surfaces suitable for roof top solar energy system installations.
5. Derivation of monthly average optimum tilt angle which maximize the solar resource potential on tilted surfaces in Colombo.
6. Estimation of maximum solar resource potential in Colombo.

1.8. Scope of the Study

The scope of this study is limited to analyze the solar radiation on horizontal and tilted surfaces in order to derive the monthly average daily global, direct and diffuse radiation on both horizontal and tilted surfaces and derive the optimum monthly average surface tilt angle for maximum solar energy harnessing.

1.9. Outline of the Study

In the first chapter of this study, describes the solar energy utilization characteristics in Sri Lanka and the potential for solar energy harnessing, particularly in Colombo. Present status of solar energy generation and its trends are also highlighted. Fundamental theories which describe solar geometry and basic concepts of solar radiation are discussed in Chapter 2. A literature review on correlations developed by various scientists and engineers is included in the same chapter. The research methodology is described in detail in Chapter 3. The results of the study are discussed in Chapter 4 and finally Chapter 5 is dedicated to present the findings and conclusions of this study.

CHAPTER 2. REVIEW OF LITERATURE

2.1. Fundamentals of Solar Radiation

2.1.1. General introduction to solar radiation

Energy from the sun is transmitted to the earth by radiation and in broad sense, solar radiation refers to the total spectrum of the electromagnetic radiation emitted by the sun. The sun, a large sphere of intensely hot gaseous matter is having a diameter of 1.39×10^9m while earth is having a diameter about 1.27×10^7m (Kalogirou, 2014). The mean distance between the sun and the earth is about 1.5×10^8km (Kalogirou, 2014). Due to this large distance between the sun and the earth, sun subtends an angle of just 32 minutes on the earth's surface (Kalogirou, 2014). So the earth receives almost parallel beam radiation from the sun and it takes 8min and 20sec for the radiation to reach the earth with the traveling speed of 3×10^8 m/s in the vacuum (Kalogirou, 2014). The sun's total energy output is 3.8×10^{20}MW, which is equal to 63 MW/m^2 of the sun's surface (Kalogirou, 2014). This energy radiates outward in all directions and the earth receives only a small fraction of the total radiation emitted, which is equal to 1.7×10^{14}kW (Kalogirou, 2014). Sun's brightness varies from its center to the edge. However, for engineering applications it is customary to assume that the brightness all over the solar disc is uniform. Radiation outside the earth's atmosphere is called as extraterrestrial solar radiation whereas within the atmosphere is called terrestrial radiation. Radiation coming from the sun is equivalent to blackbody radiation coming from a black surface at a temperature of 5762K (Kalogirou, 2014). The World Meteorological Organization (WMO) defines sunshine as direct irradiance from the sun measured on the ground of at least of 120 Wm^{-2}. Direct sunlight gives about 93 lux of illumination per watt of electromagnetic power including infrared, visible and ultraviolet radiation. Bright sunlight provides illumination of approximately 100 000 lux per square metre at the earth's surface (Kalogirou, 2014).

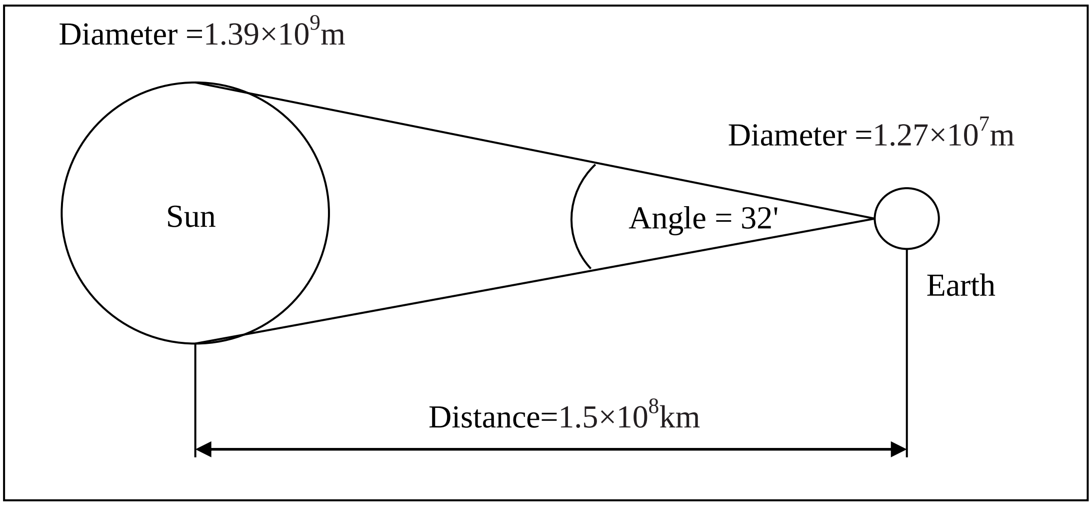

Figure 2.1: The Sun-Earth relationship

2.1.2. Solar geometry

In order to study about the solar energy received at the earth's surface, a clear understanding on solar geometry is essential. There are some parametric angles defined under solar geometry to make this effort more convenient. Climate zones, seasonal temperature changes and daily temperature changes are largely determined by changes in the amount of energy received by the earth from sun. The angle at which solar radiation strikes a surface dramatically affects the amount of energy received by the particular surface. Therefore the amount of energy received at earth's surface is a function of the angle at which solar radiation strikes the surface.

Solar declination angle (δ) illustrated in Figure 2.2 is the angle between a plane perpendicular to incoming solar radiation and the rotational axis of the earth. The earths' axis of rotation is always inclined an angle of 23.5^0 from the ecliptic axis, normal to the ecliptic plane. The ecliptic plane is the plane of orbit of the earth around the sun. The solar declination angle varies from +23.45° on June 21 when the earths' axis tilts toward the sun, to -23.45° on December 21 when the earths' axis tilts away from the sun. The solar declination angle is 0° on equinox dates which are March 21 and September 21.

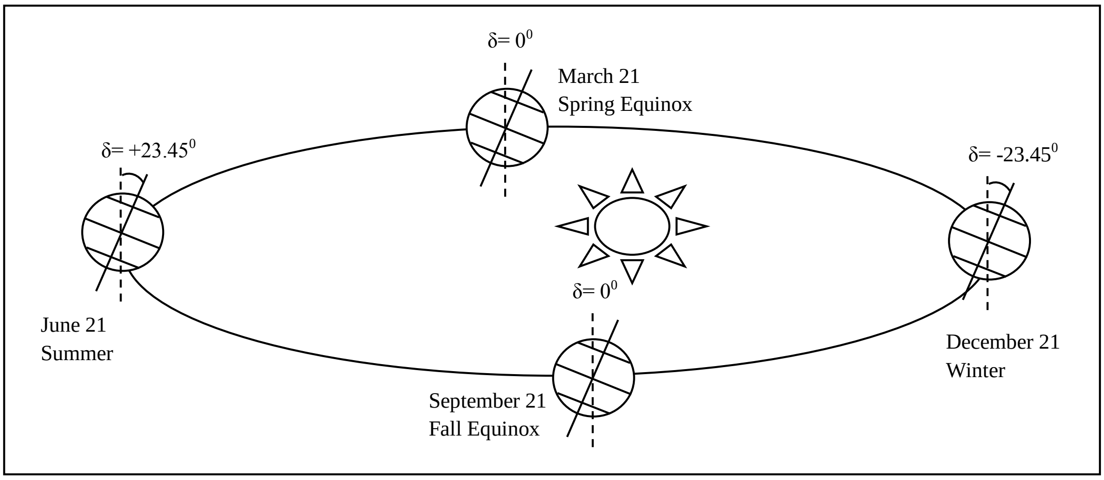

Figure 2.2: Solar declination angle

Changes in the solar declination angle as the earth revolves around the sun create cyclic changes in solar radiation. These radiation changes contribute to cyclic weather changes that are referred to seasons. The variation of the solar declination throughout the year is shown in figure 2.3 and the declination angle (δ) in degrees for any day of the year (N) can be calculated approximately by the Equation 2.1.

$$\delta^{\circ} = 23.45 \sin\left[\frac{360}{365}(284 + N)\right] \quad (2.1)$$

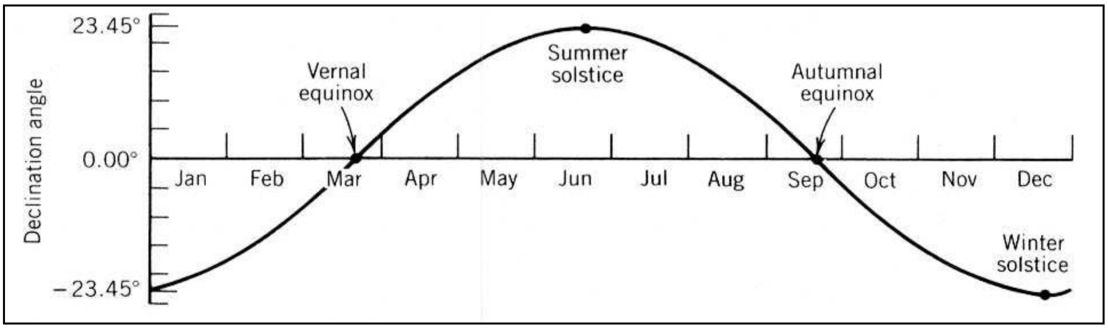

Figure 2.3: Variation of the solar declination angle throughout the year
(Source: www.powerfromthesun.net)

Any location of the earth can be described by using the Latitude (ϕ) and the Longitude (L). The Latitude (ϕ) of a location is the angle made by the radial line joining the given location to the center of the earth with its projection on the equatorial plane. This angle indicates how far a particular location from the equatorial plane.

The earth is a sphere that rotates about its rotational axis 15^0 per hour relative to the sun. An angle called the hour angle (ω) is defined which is the angle through which the earth has to rotate to bring the meridian plane of any place or location under the sun.

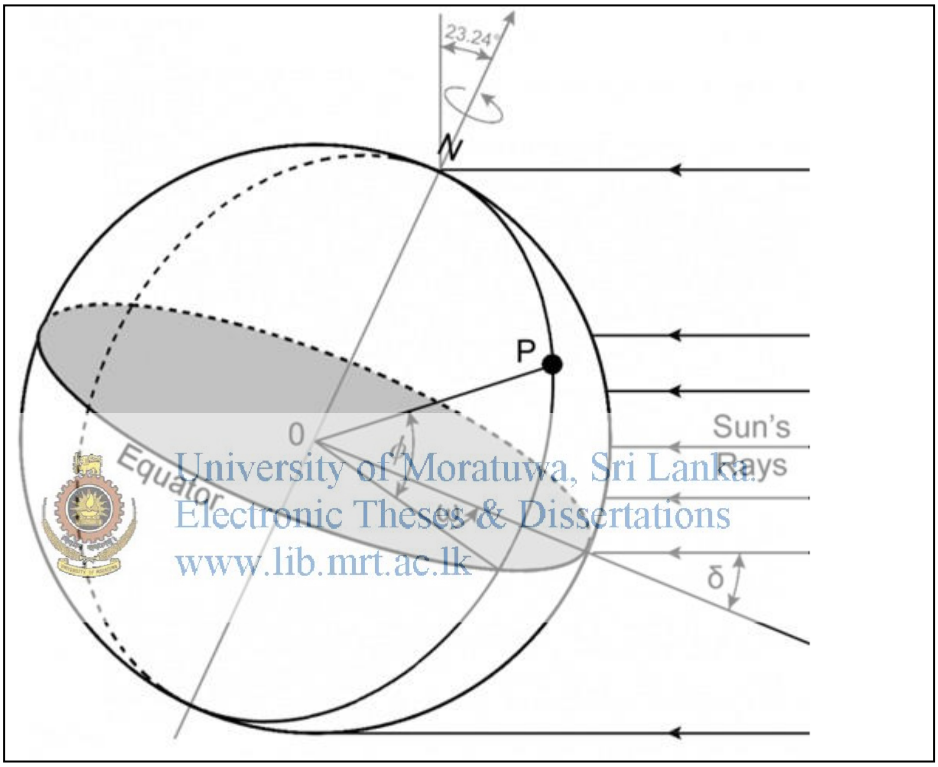

Figure 2.4: Illustration of the Latitude (ϕ) and Hour angle (ω)
Source: www.itacanet.org

The Zenith Angle (θ_z) is the angle from the observers' zenith point to the sun's position in the sky. According to the Equation 2.2, the zenith angle can be calculated with aid of the local latitude, solar declination angle and the hour angle.

$$\cos\theta_Z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \tag{2.2}$$

The solar altitude angle (α) is the angle between the sun's rays and the horizontal plane. It is related to the solar zenith angle and can be expressed mathematically as shown in Equation 2.3.

$$\theta_Z + \alpha = \frac{\pi}{2} \quad (2.3)$$

The solar azimuth angle (A_z) is the angle of the sun's rays measured in the horizontal plane from the due south for the northern hemisphere or due north for the southern hemisphere. Westward is designated as positive. The mathematical expression for the solar azimuth angle is shown in Equation 2.4.

$$\sin A_z = \frac{\cos \delta \sin \omega}{\cos \alpha} \quad (2.4)$$

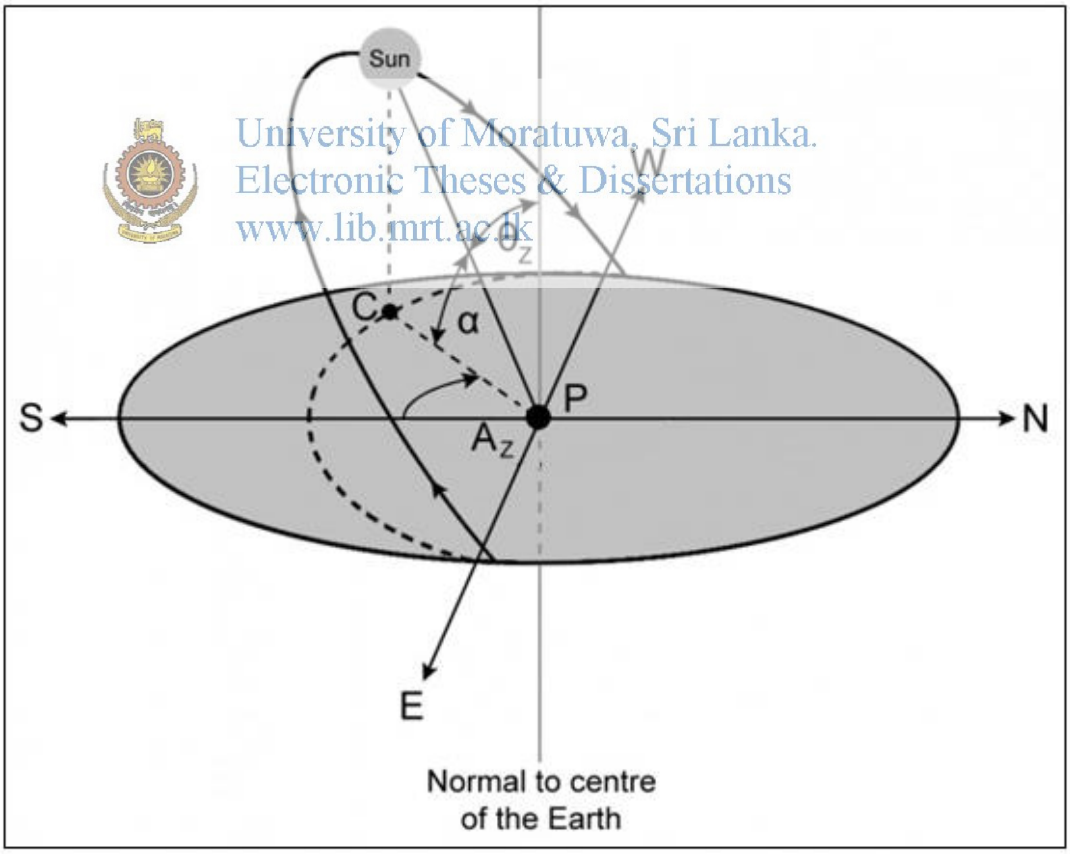

Figure 2.5: Solar Zenith angle (θ_z), Altitude (α) and Azimuth angle (A_z**)**

Source: www.itacanet.org

The solar incidence angle (θ_i) is the angle between the sun's rays and the normal on the striking surface. For a horizontal plane, the incidence angle (θ) and the zenith angle (θ_z) are same. A general expression expressed in Equation 2.5 for the angle of incidence can be derived by using previously defined terms.

$$\cos\theta_i = \sin\phi\sin\delta\cos\beta - \cos\phi\sin\delta\sin\beta\cos Azs + \cos\phi\cos\delta\cos\omega\cos\beta + \sin\phi\cos\delta\cos\omega\sin\beta\cos A_{zs} + \cos\delta\sin\omega\sin\beta\sin A_{zs} \quad (2.5)$$

Where β is the surface tilt angle from the horizontal and A_{zs} is the surface azimuth angle, the angle between the normal to the surface and true south, with westward designated as positive. Figure 2.6 illustrates the inter relation of the above discussed sun-earth angles.

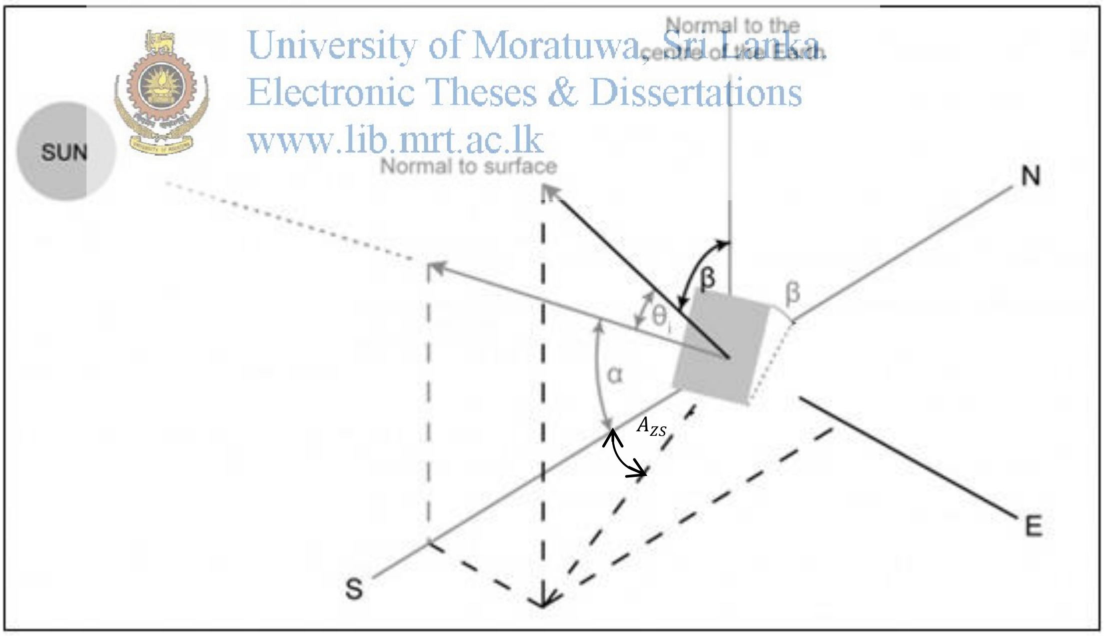

Figure 2.6: Solar radiation incident on a south faced tilted surface
Source: www.itacanet.org

The Equation 2.5 can be simplified for different conditions as follows.

- For horizontal surfaces, $\beta = 0°$ and $\theta_i = \theta z$, Then the Equation 2.5 becomes Equation 2.2
- For vertical surfaces, $\beta = 90°$ Then the Equation 2.5 becomes the mathematical expression shown in Equation 2.6

$$\cos\theta_i = -\cos\phi\sin\delta\sin\beta\cos A_{zs} + \sin\phi\cos\delta\cos\omega\cos A_{zs} + \cos\delta\sin\omega\sin A_{zs} \tag{2.6}$$

- For a south facing, tilted surface in the northern hemisphere $A_{zs} = 0°$. Then the Equation 2.5 simplifies to the Equation 2.7.

$$\cos\theta_i = \sin(\phi - \beta)\sin(\delta) + \cos(\phi - \beta)\cos(\delta)\cos(\omega) \tag{2.7}$$

- For a north facing tilted surface in the southern hemisphere, $Azs = 180°$ Then the Equation 2.5 becomes the mathematical expression shown in the Equation 2.8.

$$\cos\theta_i = \sin(\phi + \beta)\sin(\delta) + \cos(\phi + \beta)\cos(\delta)\cos(\omega) \tag{2.8}$$

Table 2.1 summarizes the above discussed solar angles

Table 2.1: Summary of solar angles

Symbol	Name	Definition	Limits
θ_i	Angle of incidence	Angle between the beam of solar radiation incident on a surface and the normal to that surface	$0° \leq \theta_i \leq 90°$
θ_z	Zenith angle	Angle subtended by a vertical line to the point directly overhead and the line of sight to the sun	$0° \leq \theta_z \leq 90°$
α	Solar altitude	Angle subtended by the line of sight to the sun and its projection on the horizontal plane	$0° \leq \alpha \leq 90°$
A_{zs}	Surface azimuth angle	Angular deviation of the projection on a horizontal plane of the normal to the surface from the local meridian	$-180° \leq A_{zs} \leq 180°$
β	Tilt angle	Angle between a plane surface and the horizontal	$0° \leq \beta \leq 180°$
ϕ	Latitude	Angular location relative to the equator (+ north, -south)	$-90° \leq \phi \leq 90°$
δ	Declination	Angular position of the sun at solar noon relative to the plane of equator (+north, -south)	$-23.45° \leq \delta \leq 23.45°$
ω	Hour angle	Angular displacement of the sun east or west of the local meridian (+afternoon, -morning)	

2.2. Extra-Terrestrial & Terrestrial Solar Radiation

2.2.1. Extra-terrestrial solar radiation

The solar radiation which is found outside the earth's atmosphere is called extra-terrestrial solar radiation. The solar radiant power intensity at a plane held normal to the direction of solar radiant flux at the mean sun-earth distance in extra-terrestrial region is held almost constant throughout the year. This constant value is termed as solar constant (I_{SC}) and its value is adopted to be 1367 W/m^2 (Gowsami, Kreider, & Krieth, 1999). However, this extra-terrestrial radiation is subject to variations due to the fact that the earth revolves around the sun not in a circular orbit but follows an elliptic path, with sun at one of the foci. According Gowsami et al (1999) the intensity of extra-terrestrial radiation measured on a plane normal to the radiation (I_{ON}) on the nth day of the year is given in terms of solar constant (I_{SC}) by Equation 2.9.

$$I_{ON} = I_{SC}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] \quad (2.9)$$

When considering a plane which is placed in extraterrestrial region, parallel to the ground, the rate of solar radiation incident on this plane (I_{OH}) at a given nth day of the year is given by the relationship expressed in the Equation 2.10.

$$I_{OH} = I_{ON}\cos\theta_i = I_{SC}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right][\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega] \quad (2.10)$$

2.2.2. The earth's atmosphere

The atmosphere of the earth is a blanket that entirely envelops the earth and it contains various gaseous constituents, suspended dust, minute solid and liquid particulate matter and various types of clouds. It extends as far as 9600 km above the earth's surface (Gowsami et al., 1999) and this gaseous cover of the earth is held around it by gravitational attraction. The density of the atmosphere decreases rapidly with altitude. About 97% of the air is concentrated within the lower 29 km and the weight of the upper layer is exerted on the lower layers (Gowsami et al., 1999).

Temperature of the Earth's atmosphere varies with altitude among five different atmospheric layers called exosphere, thermosphere, mesosphere, stratosphere and troposphere. The stratosphere contains the ozone layer. Troposphere is the lowest layer of the atmosphere and it begins at the Earth's surface and extends up to 7 km at the poles and 17 km at the equator with some variation due to weather factors (Gowsami et al., 1999). The troposphere contains approximately 80% of the total mass of the atmosphere and 50% of the total mass of the atmosphere is contained within the lower 5.6 km of the troposphere (Gowsami et al., 1999). The average temperature of the atmosphere at the surface of Earth is about 15℃. The average atmospheric pressure at the sea level is about 101.3 kPa (Gowsami et al., 1999).

Total atmospheric mass is about 5.1480×10^{18} kg (Gowsami et al., 1999) and the atmospheric pressure is a direct result of the total weight of the air above the point at which the pressure is measured. The air pressure varies with location and time because of the amount of air above the earth varies with location and time. The density of air at the sea level is about 1.2 kgm^{-3}.

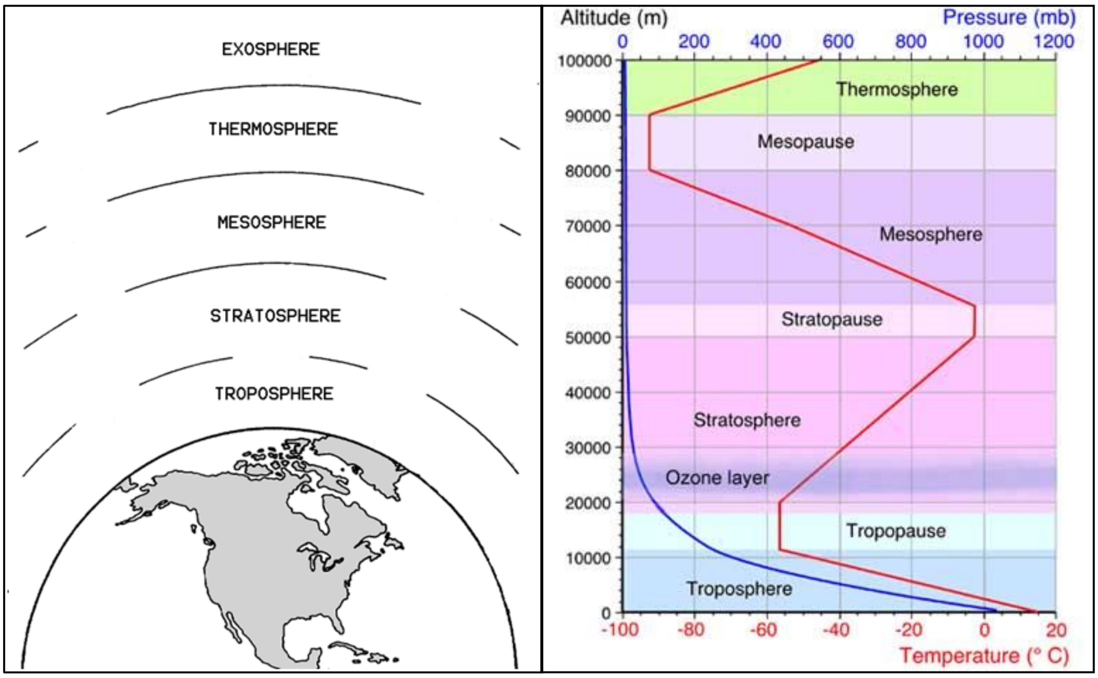

Figure 2.7: Temperature & pressure variation at the different layers of the Earth's atmosphere

Source: www.survivalworld.com (Not to scale)

Source: www.weatheronline.co.nz

2.2.3. Atmospheric attenuation

Solar radiation passing through the earth's atmosphere is subjected to the mechanisms of atmospheric absorption and scattering. It is the reason for attenuation of the amplitude of solar radiation during propagation through the atmosphere which is generally referred to as atmospheric attenuation. When solar radiation collides with gas molecules and other particles while transmitting through the earth's atmosphere, part of its energy incident is absorbed by those molecules and particles by electronic transitions, molecular vibrations and molecular rotations. It is called atmospheric absorption. When solar radiation transmits through the atmosphere in a certain direction, it is redirected by reflection and refraction when it collides with particles. This phenomenon is called atmospheric scattering. Atmospheric scattering is a function of the wave length (λ) of incident radiant energy and the size of the gas molecule, dust particle or vapour droplet encountered.

The X–rays and extreme ultraviolet radiations of the sun are highly absorbed by nitrogen (N_2), oxygen (O_2) and other atmospheric gases in the ionosphere which is located within the thermosphere (Gowsami, Kreider, & Krieth, 1999). The ozone (O_3) and water vapour (H_2O) largely absorb ultraviolet ($\lambda<0.40\mu m$) and infrared radiations ($\lambda>2.3\mu m$) (Gowsami et al., 1999). Also there is almost complete absorption of short wave radiations ($\lambda<0.29\mu m$) in the atmosphere (Gowsami, Kreider, & Krieth, 1999). Hence the solar radiant energy incident on the earth's surface in wavelength below 0.29µm and above 2.3µm of the electromagnetic spectra is negligible.

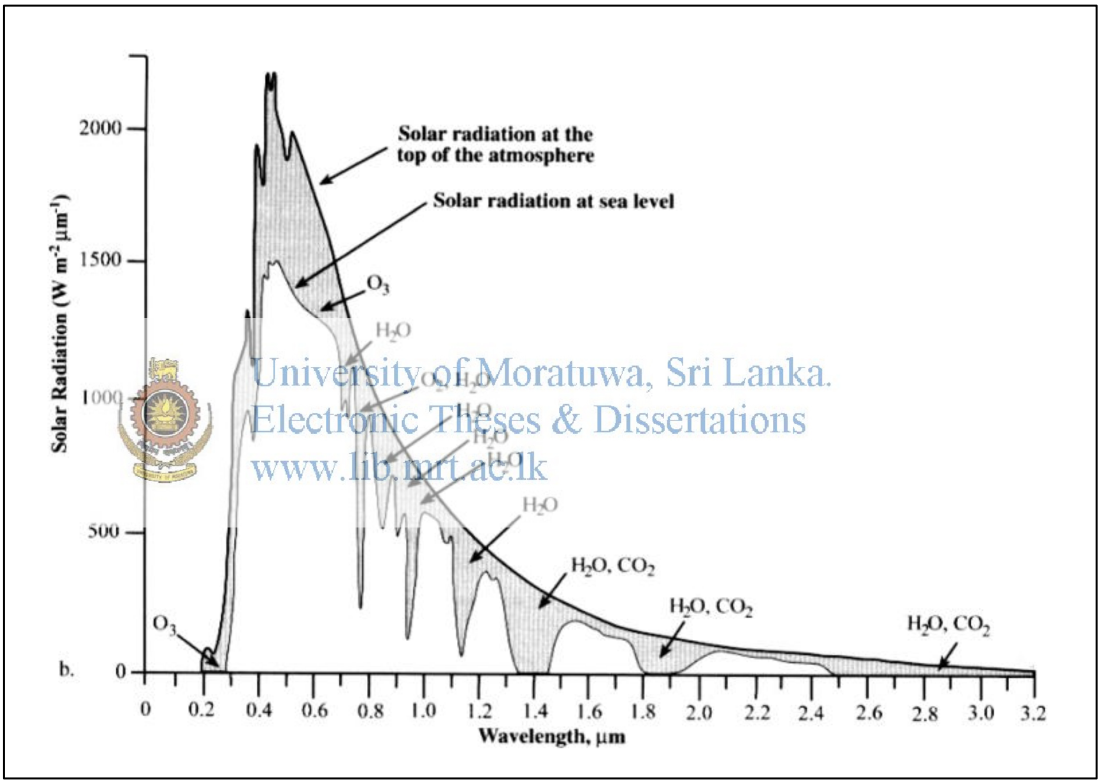

Figure 2.8: Atmospheric absorption due to different types of gas molecules
Source: https://jpjustiniano.wordpress.com

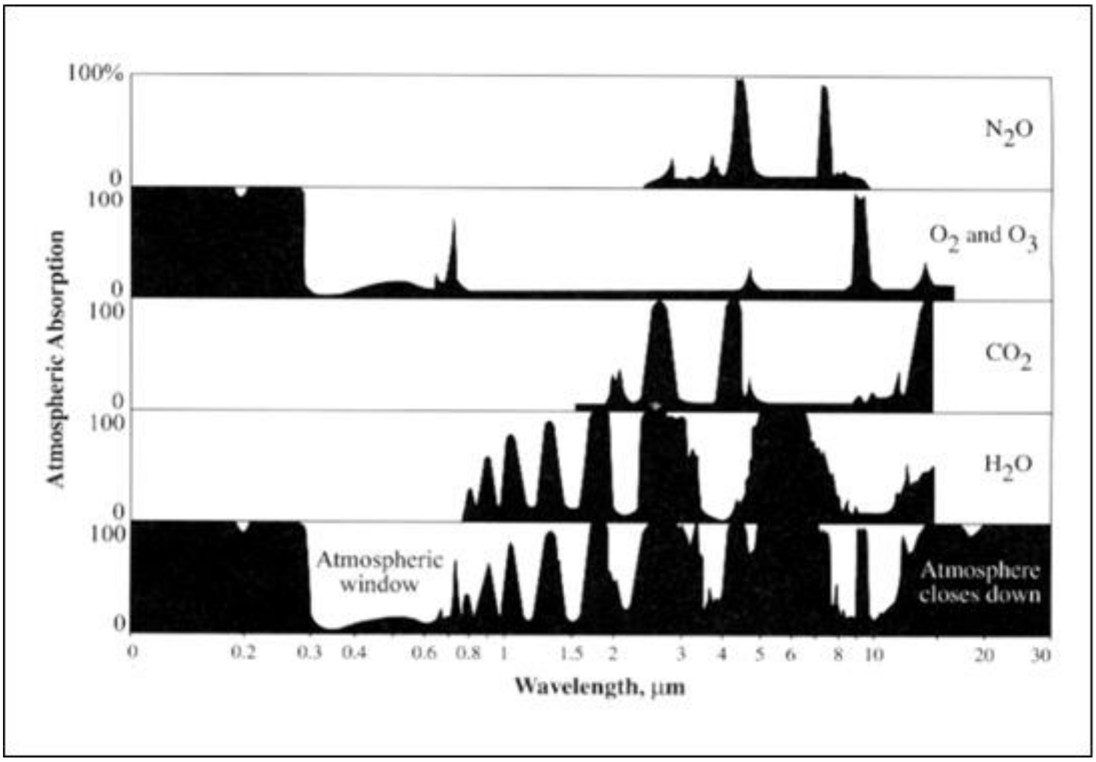

Figure 2.9: Effect on atmospheric absorption on terrestrial solar radiation

Source: https://jpjustiniano.wordpress.com

The re-distribution of incident energy during scattering depends strongly on the ratio of particle size to wavelength of the incident wave. If the particle is isotropic, the scattering pattern is symmetric about the direction of incident wave. Particles with sizes very small compared to the wavelength of the incident radiation, cause the radiation to scatter almost equally both in the forward and backward directions. As the particle size becomes comparable with the wavelength of incident radiation, more energy is scattered in the forward direction and secondary maxima and minima appear at various angles. However the overall scattering increases with the increase in particle size and ultimately depends on the ratio of refractive index of the particle relative to that of the surrounding medium. When scatterers are very small compared to the wavelength of incident radiation (radius $< \lambda/10$), the intensity of the radiation scattered both forward and backward directions are equal. This type of scattering is called Rayleigh scattering. With regards to the scattering of this type, the scattered radiation intensity varies inversely proportional to the fourth power of the wavelength. Air molecules are the principal Rayleigh scatterers in the atmosphere.

The total intensity of the scattered unpolarized solar radiation incident on a molecules in the direction θ is given by the Equation 2.11.

$$I = \frac{I_0}{r^2}\alpha^2\left(\frac{2\pi}{\lambda}\right)^4\frac{1+\cos^2\theta}{2} \quad (2.11)$$

Where,

I: Total intensity of scattered unpolarized solar radiation incident on a molecules in the direction θ

I_0: Incident intensity

α: Polarizability of the molecule

r: Distance between the molecule and the point of observation

λ: Wave length of the incident radiation

A large portion of the solar energy is contained in the visible spectrum from blue (λ ~0.425 μm) to red (λ~0.65 μm) (Gowsami et al., 1999). According to the Equation 2.11, the blue light scatters about 5.5 times more than the red light.

It is also apparent that the dependence of $1/\lambda^4$ causes more blue light to be scattered than the other lights in the visible spectrum. Thus, when viewed from a distance, the sky appears blue. As the sun approaches horizon (at sunrise or sunset), solar radiation transmits a much more distance through the atmosphere compared to the zenith direction and more and more blue light is scattered out of the beam and the red colour dominates. Because of the energy contained in the violet spectrum (λ~0.405 μm) is much smaller than that contained in the blue spectrum and also human eye has a much lower response to the violet colour, sky does not appear violet.

For larger particles (radius > λ) with a mean diameter of 0.1 to 10 times the wave length of incident solar radiation, the angular distribution of intensity of the radiation scattered becomes more complex with more energy scattered in the forward direction. This type of scattering is called Mie scattering. The proportionality between the radiation intensity of Mie scattering and wave length varies from λ^{-4} to λ^0 depending on the particle diameter.

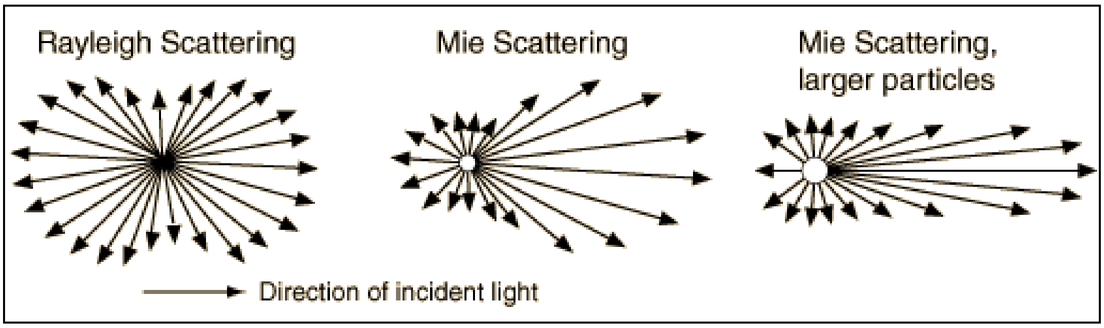

Figure 2.10: Illustration of the Reyleigh scattering and Mie scattering

Source: http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html

With regard to Rayleigh and Mie scattering, both the scattered and incident radiation has the same wavelength and hence this two scattering processes are called elastic scattering. As the diameters of the aerosol particles (such as water droplets, ice crystals and smog) are much larger than the wave length of the incident radiation, the scattering does not depend upon the wave length and it is called non-selective scattering of the atmosphere.

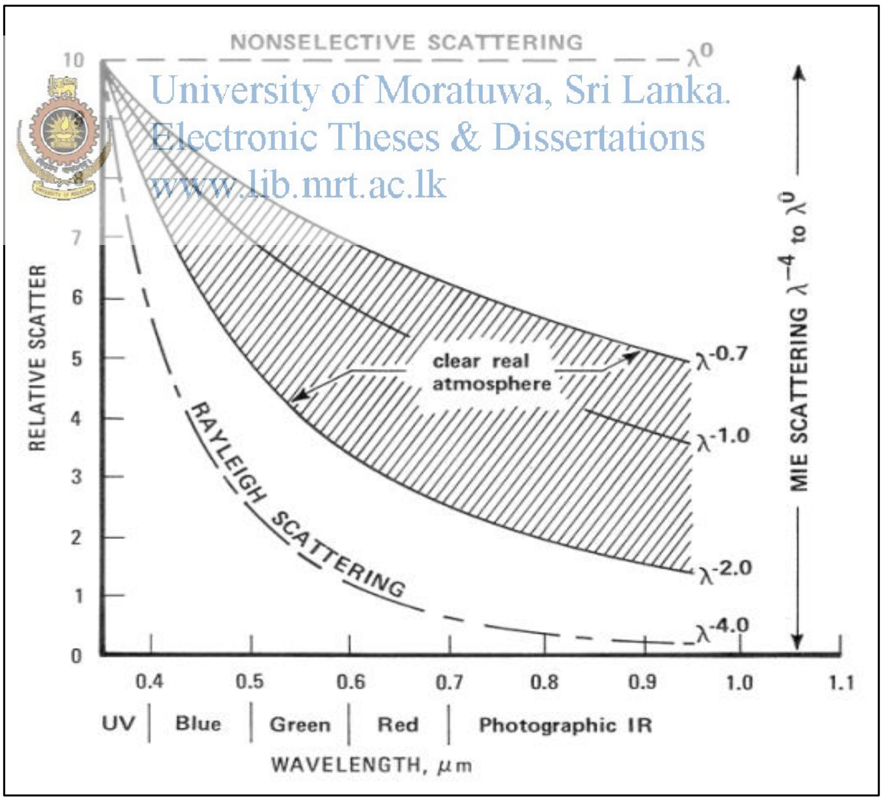

Figure 2.11: Relative scatter of solar spectrum in earth’s atmosphere

Source: http://www.udel.edu

Roughly 50% of the scattered radiation is lost to space and the remaining part is directed to the earth's surface from different directions as diffuse radiation. Scattering of radiation due to dust particles which are much larger than air molecules is difficult to compute since such particles vary in size and concentration from location to location, according to height and from time to time.

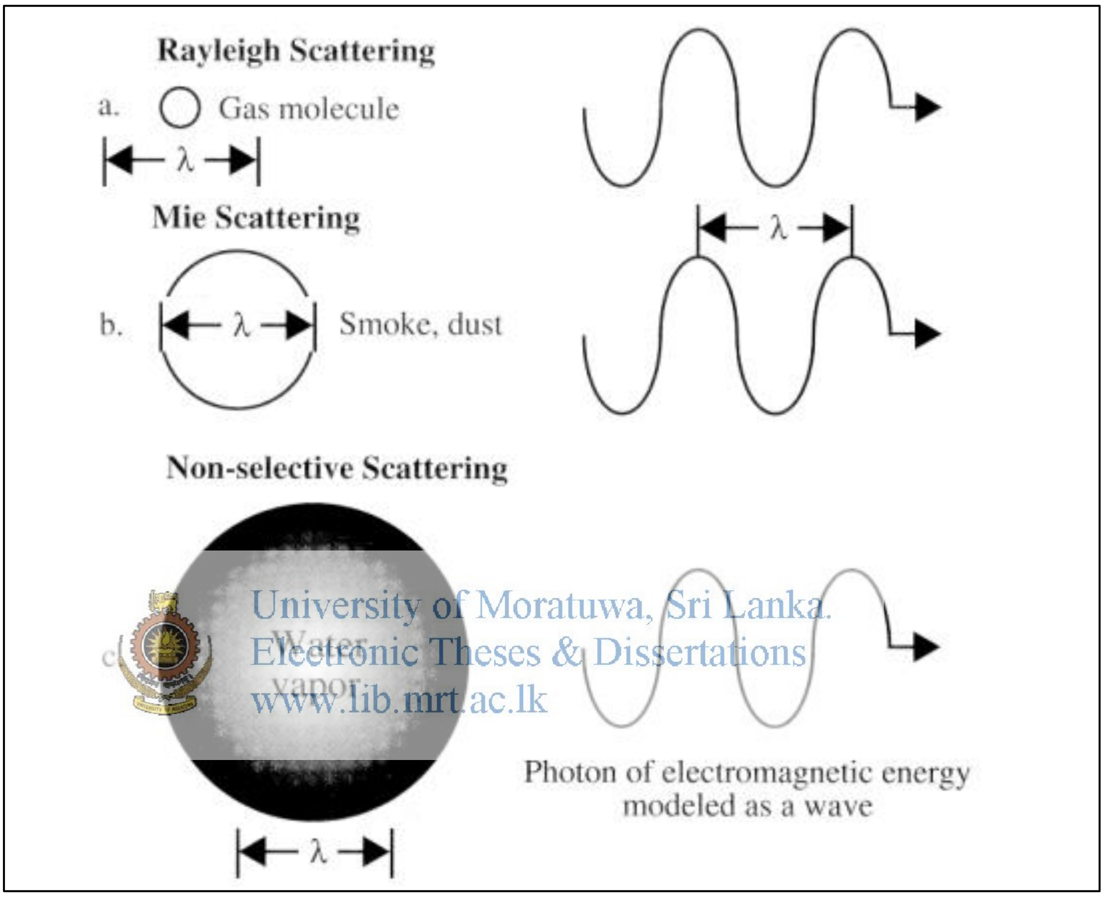

Figure 2.12: Types of solar radiation scattering due to different types of particles in Earth’s atmosphere

Source: http://www.udel.edu

In a cloudy atmosphere, a considerable depletion of the direct solar radiation takes place. Most of the solar radiation is reflected back into the space, another part is absorbed by the clouds and the rest is transmitted downwards to the earth as diffuse radiation. The fraction of the total solar radiant energy reflected back to the space by reflection from the clouds, scattering by the atmospheric gases and dust particles, and by reflection from the Earth's surface is called the albedo of the earth atmosphere system and has a value of about 0.30 for the earth as a whole.

When solar radiation passes through the atmosphere, the decrease in intensity is described by Bouger's law that assumes that the attenuation is proportional to the local intensity in the medium.

If $I_\lambda(x)$ is the monochromatic intensity after radiation has travelled a distance x, the Bouger's law is expressed by the Equation 2.12.

$$-dI_\lambda = I_\lambda(x)K_\lambda dx \tag{2.12}$$

Where;

K_λ is the monochromatic extinction coefficient, which is assumed to be a constant for the medium. If the radiation has to travel a distance L in atmosphere and the intensity at $x = 0$ is designated by the symbol $I_{\lambda,o}$, the monochromatic transmittance τ_λ is equal to the ratio of the intensity at $x = L$ to $I_{\lambda,o}$. An expression for $I_\lambda(L)$ can be obtained by the integration of Equation 2.12 between 0 and L, which results in the Equation 2.13.

$$I_\lambda(L) = I_{\lambda,o} e^{-K_\lambda L} \tag{2.13}$$

Then the Equation 2.13 can be re arranged as Equation 2.14

$$\tau_\lambda = \frac{I_\lambda(L)}{I_{\lambda,o}} = e^{-K_\lambda L} \tag{2.14}$$

The extinction co-efficient (K_λ) is a complex property of the atmosphere since it combines the effects of absorption, emission and scattering by the molecules and particles that make up the medium.

2.2.4. Terrestrial solar irradiation

Solar radiation received by the earth's surface is called terrestrial irradiation where irradiance is the process by which a surface is radiated by any radiation including visible light. Solar radiation received by the earth's surface can be divided into two basic components called direct and diffuse radiation. Direct solar radiation (I_N) is a measure of the rate of solar energy arriving at the earth's surface from the sun's direct beam (I_b), on a plane perpendicular to the beam. Diffuse radiation (I_d) is the result of atmospheric attenuation and it is a measure of the rate of incoming solar energy on a horizontal plane at the earth's surface resulting from scattering of the sun's beam radiation due to atmospheric constitutes. Absorption occurs only at specific wave lengths, for example Ultra-Violet (UV) solar energy is absorbed by ozone in the stratosphere. But scattering occurs at all wavelengths. The combination of both forms of solar energy incident on a horizontal plane at the earth's surface is referred to as global solar radiation (I_G) and it can be mathematically expressed by Equation 2.15, 2.16 & 2.17.

$$I_G = I_b + I_d \quad (2.15)$$

$$\text{Since, } I_b = I_N \cos\theta_Z \quad (2.16)$$

$$I_G = I_N \cos\theta_Z + I_d \quad (2.17)$$

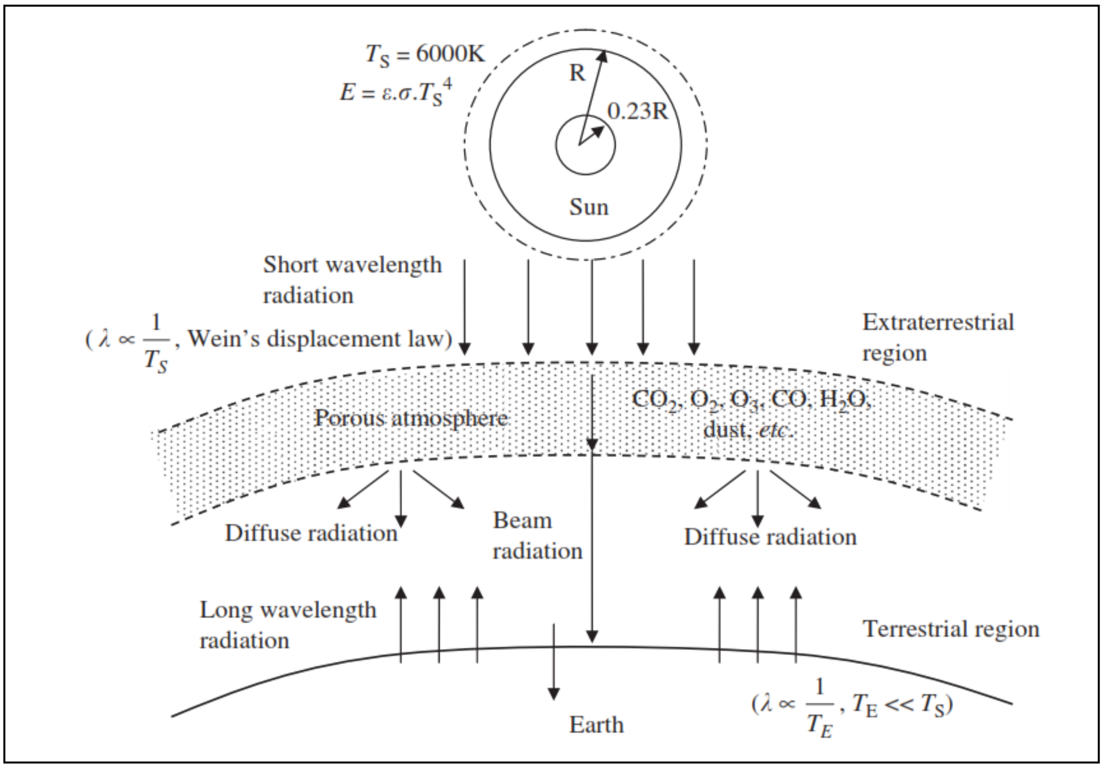

Figure 2.13: Direct and Diffuse Solar radiation received on earth's surface

Source: (Tiwari, 2013)

Evaluating I_N and I_d is generally done by using empirical equations that incorporate factors affecting solar irradiation on earth's surface. The expression for the rate of beam radiation in extraterrestrial region given by Equation 2.18 is proposed by Threlkeld and Joardan (2005) by considering the Bouger's law for the radiation transmission through a transparent medium.

$$I_N = C_n I_{ON} e^{-(k/\sin\alpha)} \qquad (2.18)$$

Where,

k is the optical depth of the atmosphere, which is a measure of the number of scattering events that occur between a source of light and the observer. k is measured for average atmospheric conditions at sea level and C_n is a parameter called clearness number to account for the differences in local condition from the average sea level conditions. α is the solar altitude angle.

According to the Threlkeld and Jordan (2005) model, the sky diffuse radiation (I_d) on a clear day is proportional to the beam normal solar radiation (I_N) and can be estimated by using an empirical sky diffuse factor "C". Therefore I_G can be estimated by Equation 2.19, 2.20 and 2.21

$$I_G = I_N \cos\theta_Z + I_d \tag{2.19}$$

$$I_G = I_N \sin\alpha + \mathrm{C}I_N \text{ ; Since}(\alpha = 90° - \theta_Z) \tag{2.20}$$

$$I_G = C_n I_{ON} e^{-\left(k/\sin\alpha\right)} (\mathrm{C} + \sin\alpha) \tag{2.21}$$

Available data can be used to evaluate C_n, k and C. These values can then be used in Equation 2.20 to estimate the total global solar radiation on earth's surface(I_G). Many other empirical models are also available to estimate total global solar irradiation.

2.3. Solar Irradiation on Horizontal Surface

Solar radiation on horizontal surface consists of two radiation components called direct and diffuse solar radiation and they are related to the total or global solar radiation as given in the Equation 2.15 which describes earlier. The relationship given by the equation 2.15 describes the instantaneous terms of solar radiation. It requires knowing about the long term monthly averaged daily insolation rather than looking for instantaneous global solar irradiation since it is quite important to evaluate the long term performance of global horizontal solar resource. Solar insolation is defined as the total amount of radiant solar energy received by a given surface area during a given time.

Although measurements of the solar radiance provide the most accurate information about the solar resource, these measurements are difficult and expensive to obtain. But some simple and accurate solar radiation models are available in present context to make quite accurate estimations of solar resource potential on a horizontal surface by use of different weather parameters which are easily measureable. Some of these weather parameters are daily sunshine hours (S), daily average temperature (T), daily maximum and minimum temperatures (T_{max}, T_{min}), daily average relative humidity (R_h) and daily average cloud amount (C_ω). One of the earliest methods of estimating solar radiation on a horizontal surface was proposed by the pioneer spectroscopist Angstrom (Badescu, 2008). It was a simple linear model which is illustrates in Equation 2.22, relating average horizontal radiation to clear day radiation to the sunshine level, that is, percentage of proportion of actual hours of sunshine out of the possible hours of sunshine.

$$\frac{\overline{H}}{\overline{H_o}} = \left(a + b\frac{\bar{S}}{\overline{S_o}}\right) \tag{2.22}$$

Where,

$\overline{H}$: Monthly averaged daily radiation on horizontal surface of terrestrial region

$\overline{H_o}$: Monthly averaged daily radiation on horizontal surface of extra-terrestrial region

$\bar{S}$: Monthly averaged hours of sunshine

S_o : Monthly averaged maximum possible hours of sunshine

a,b: Site specific constants

$\overline{H_o}$ can be obtained by integrating the Equation 2.10 over the period from sunrise to sunset.

The resulting expression is given by Equation 2.23,

$$\overline{H_o} = \frac{24 \times 3600 \times I_{SC}}{\pi}\left[1 + 0.033cos\left(\frac{360N}{365}\right)\right] \times \left[\cos L \cos\delta \sin h_{ss} + \left(\frac{\pi h_{ss}}{180}\right)\sin L \sin\delta\right] \quad (2.23)$$

Where,

h_{ss} is the sunset hour

It is quite easy to attribute rough physical meanings to the coefficients *a* and *b* in Equation 2.22 using the extreme values of $\frac{\bar{S}}{S_o}$. If there are no clouds obscuring the sun within a day, then $\frac{\bar{S}}{S_o} = 1$ and $\frac{\bar{H}}{H_o} = a + b$ can be interpreted as the monthly average daily value for the transmittance of a clear day. Note that clear day ($\frac{\bar{S}}{S_o} = 1$ in this case) does not always mean a perfectly clear day without appearance of any cloud all the day. Even sometimes the presence of clouds that do not obscure the sun may increase the irradiation reaching the site due to high reflections. Another fact is that the days without any cloud may have different solar irradiation reaching the earth due to differences in the air mass and also due to some atmospheric conditions such as dense turbidity. For a completely overcast day, $\frac{\bar{S}}{S_o} = 0$ and $\frac{\bar{H}}{H_o} = a$, which essentially accounts for the diffuse component. It may represent the average daily transmission of an overcast sky at the site under consideration. Plenty of researchers have found values for *a* and *b* for specific locations and results illustrates in the Table 2.2.

Table 2.2: Coefficients *a* and *b* for the Angstrom regression equation

		Sunshine hours in percentage of possible			
Location	**Climate***	**Range**	**Avg.**	***a***	***b***
Albuquerque. NM	BS-BW	68-85	78	0.41	0.37
Atlanta. GA	Cf	45-71	59	0.38	0.26
Blue Hill. MA	Df	42-60	52	0.22	0.50
Brownsville. TX	BS	47-80	62	0.35	0.31
Buenos Aires. Arg.	Cf	47-68	59	0.26	0.50
Charleston. SC	Cf	60-75	67	0.48	0.09
Dairen, Manchuria	Dw	55-81	67	0.36	0.23
El Paso, TX	BW	78-88	84	0.54	0.20
Ely, NV	BW	61-89	77	0.54	0.18
Hamburg, Germany	Cf	11-49	36	0.22	0.57
Honolulu, HI	Af	57-77	65	0.14	0.73
Madison, WI	Df	40-72	58	0.30	0.34
Malange, Angola	Aw-BS	41-84	58	0.34	0.34
Miami, FL	Aw	56-71	65	0.42	0.22
Nice, France	Cs	49-76	61	0.17	0.63
Poona, India (monsoon), (dry)	Am	25-49 65-89	37 81	0.30 0.41	0.51 0.34
Stanleyville, Congo	Af	34-56	48	0.28	0.39
Tamanrasset, Algeria	Bw	76-88	83	0.30	0.43

Source: Gowsami et al., (1999)

*Af = tropical forest climate, constantly moist, rainfall all through the year
Am = tropical forest climate, monsoon rain, short dry season, bur total rainfall sufficient to support rain forest
Aw = tropical forest climate, dry season in winter
BS = steppe or semiaraid climate
BW = dessert or arid climate
Cf = mesothermal forest climate, constantly moist, rainfall all through the year
Df = mesothermal snow forest climate, constantly moist, rainfall all through the year
Dw = mesothermal snow forest climate, dry season in winter

Recently Jayasinghe & Sendanayake (2008) used the values 0.28 and 0.47 for the two coefficients a and b respectively as shown in Equation 2.24 to estimate global solar radiation of Sri Lanka which is originally developed for Vishakapatnam (9°50’N and 79°25’E) in South India.

$$\frac{\bar{H}}{\bar{H}_o} = \left(0.28 + 0.47\frac{\bar{S}}{\bar{S}_o}\right) \tag{2.24}$$

Al-Ghamdi, Al-Hazmi, El-Sebaii and Yaghmour (2010) used relationships given in Equation 2.25 thru 2.32 to estimate the global solar radiation on a horizontal surface at Jeddah, Saudi Arabia. The same relationships are also used by Khatib, Mahmoud, Mohamed and Sopian (2011) and also Beckman and Duffie (1991) to estimate the global solar radiation.

$$\frac{\bar{H}}{\bar{H}_o} = a + b\frac{\bar{S}}{\bar{S}_o} + c\left(\frac{\bar{S}}{\bar{S}_o}\right)^2 \tag{2.25}$$

$$\frac{\bar{H}}{\bar{H}_o} = a + b\frac{\bar{S}}{\bar{S}_o} + cT \tag{2.26}$$

$$\frac{\bar{H}}{\bar{H}_o} = a + b\frac{\bar{S}}{\bar{S}_o} + cR_h \tag{2.27}$$

$$\frac{\bar{H}}{\bar{H}_o} = a + bT + cR_h \tag{2.28}$$

$$\frac{\bar{H}}{\bar{H}_o} = a + b(T_{max} - T_{min}) + cC_\omega \tag{2.29}$$

$$\frac{\bar{H}}{\bar{H}_o} = a + b(T_{max} - T_{min})^{0.5} + cC_\omega \tag{2.30}$$

$$\frac{\bar{H}}{\bar{H}_o} = a + b\frac{\bar{S}}{\bar{S}_o} + cC_\omega \tag{2.31}$$

$$\frac{\bar{H}}{\bar{H}_o} = a + b\left(\frac{\bar{S}}{\bar{S}_o}\right)^c \tag{2.32}$$

Akinagolu and Ecevit (1993) proposed the values 0.145, 0.845 and -0.416 for the coefficients a,b and c respectively in Equation 2.25. This results the Equation 2.33.

$$\frac{\overline{H}}{\overline{H_o}} = 0.145 + 0.845\frac{\bar{S}}{\overline{S_o}} - 0.416\left(\frac{\bar{S}}{\overline{S_o}}\right)^2 \tag{2.33}$$

The values of $\overline{H_o}$ for each month at latitude 5^0 N and 10^0 N are tabulated in Table 2.3. Also the table indicates the recommended dates of each month that would give the mean daily extra-terrestrial solar insolation values on horizontal surface.

Table 2.3: Monthly average daily extraterrestrial insolation on horizontal surface (MJ/m^2)

Latitude	**Jan 17**	**Feb 16**	**Mar 16**	**Apr 15**	**May 15**	**Jun 11**	**Jul 17**	**Aug 16**	**Sep 15**	**Oct 15**	**Nov 14**	**Dec 10**
5^0 N	34.2	36.1	37.5	37.5	36.3	35.3	35.6	36.7	37.3	36.3	34.5	33.5
10^0 N	32.0	34.6	36.9	37.9	37.5	37.0	37.1	37.5	37.0	35.1	32.5	31.1

The values of the Table 2.2 are often used for the engineering calculations and derived based on the day number (N) and the relevant declination (δ) given in Table 2.4

Table 2.4: Day number and recommended average day for each month

Month	Day Number	Average day of the month		
		Date	**N**	**δ (deg)**
January	i	17	17	-20.92
February	31+i	16	47	-12.95
March	59+i	16	75	-2.42
April	90+i	15	105	9.41
May	120+i	15	135	18.79
June	151+i	11	162	23.09
July	181+i	17	198	21.18
August	212+i	16	228	13.45
September	243+i	15	258	2.22
October	273+i	15	288	-9.60
November	304+i	14	318	-18.91
December	334+i	10	344	-23.05

The ratio $\frac{\overline{H}}{\overline{H_o}}$ described in previous paragraphs is also referred to as monthly average clearness index $\overline{K_T}$ where expressed in Equation **(2.34)** is a very useful term when estimating the diffuse solar radiation from global solar radiation.

$$\overline{K}_T = \frac{\overline{H}}{\overline{H}_0} \tag{2.34}$$

Since the clearness index is a direct measurement of cloudiness of the sky, Iqbal (1978) propose following classification of days based on the clearness index as illustrate in Table 2.5.

Table 2.5: Classification of the days according to the clearness index

Day Type	K_T
Clear	$0.7 \leq K_T \leq 0.9$
Partly Cloudy	$0.3 \leq K_T \leq 0.7$
Cloudy	$0 \leq K_T \leq 0.3$

It is essential to quantify the beam and diffuse radiation of a particular location of interest, in solar engineering applications. The amount of global horizontal solar insolation on a terrestrial region is the sum of beam and diffuse radiation as discussed earlier. Several empirical solar radiation models are available in literature which are capable of estimating the diffuse solar insolation from monthly average daily global solar radiation. A numbers of researchers have proposed many different solar radiation models by breaking the global solar radiation into beam and diffuse components. Basically, two types of solar radiation models called Parametric Models and Decomposition Models have been developed.

Parametric models require comprehensive information on atmospheric conditions. Meteorological parameters frequently used as predictors in parametric models include the type, amount and distribution of clouds, fraction of sunshine, atmospheric turbidity and perceptible water content. Decomposition models usually use information on global radiation to predict the beam and diffuse solar radiation components. The relationships in decomposition models are usually expressed in terms of the irradiations which are the time integrals (usually over one hour) of the radiant flux or irradiance. Decomposition models are developed to estimate direct and diffuse irradiance from global irradiation data.

Theoretical determination of the direct, diffuse and directional intensities of diffuse irradiation require data on cloud which include the type, optical properties, amount, thickness, position and the number of layers. These data are rarely collected on routine basis. However, sunshine hours and total cloud cover data are widely and conveniently available. When combined with the knowledge of local atmospheric conditions, the number of sunshine hours can be used to estimate the available monthly average solar radiation.

Jordan and Liu (1979) proposed the empirical solar radiation model given in Equation 2.35 to predict the monthly average daily diffuse solar radiation from monthly average global solar radiation.

$$\frac{\overline{H}_D}{\overline{H}} = 1.390 - 4.027\overline{K}_T + 5.531\overline{K}_T^2 - 3.108\overline{K}_T^3 \tag{2.35}$$

Collares-Pereira and Rabel (1979) proposed the following empirical solar radiation model expressed in Equation 2.36 to predict the monthly average daily diffuse radiation from monthly average global solar radiation by incorporating sunset hour angle (h_{ss}).

$$\frac{\overline{H}_D}{\overline{H}} = 0.775 + 0.00653(h_{ss} - 90) - [0.505 + 0.00455(h_{ss} - 90)] \cos 115\overline{K}_T - 103) \tag{2.36}$$

With the monthly average daily total radiation ($\overline{H}$) and monthly average diffuse radiation ($\overline{H}_D$) known, the monthly average beam radiation ($\overline{H}_B$) on a horizontal surface can be calculated by using the Equation 2.37.

$$\overline{H} = \overline{H}_B + \overline{H}_D \tag{2.37}$$

After estimating the global and diffuse solar radiation on a horizontal surface by using a suitable empirical solar radiation model, it is possible to estimate radiation solar radiation on a tilted plane as well.

2.4. Solar Irradiation on a Tilted Surface

Usually in solar energy applications the equipment such as solar PV modules and solar thermal collectors are not installed horizontally but at an angle to increase the amount of radiation intercepted and to reduce reflection and cosine losses. In some cases those equipment have to be installed in accordance with the roof geometry resulting in a tilt angle to the horizontal plane.

The amount of radiation on a terrestrial surface at a given location at a given time depends on the orientation and the slope of the surface. There exists direct and diffuse solar radiation components as in the case of solar radiation of a horizontal surface. Additionally another new solar radiation component exists due to the ground reflection radiation on the tilted surfaces. The total insolation (H_t) on a tilted flat surface is the sum of the direct insolation (H_{Bt}) diffuse insolation (H_{Dt}) and ground reflected insolation (H_{Gt}) as expressed in Equation 2.38.

$$H_t = H_{Bt} + H_{Dt} + H_{Gt} \tag{2.38}$$

The Equation 2.38 can be re-written in terms of H_B and H_D as in the Equation 2.9

$$H_t = H_B R_B + H_D R_D + \rho_g (H_B + H_D) R_G \tag{2.39}$$

Solar radiation tilt factor is defined as the ratio of total radiation on a tilted surface to that on a horizontal surface(R_t), as shown in Equation 2.40.

$$R_t = \frac{H_B R_B + H_D R_D + \rho_g (H_B + H_D) R_G}{H_B + H_D} \tag{2.40}$$

As shown in the Figure 2.14, the beam radiation component on a tilted surface can be written as Equation 2.41,

$$H_{Bt} = H_{Bn} \cos\theta \tag{2.41}$$

And the beam radiation component on a horizontal surface is given by Equation 2.42,

$$H_B = H_{Bn} \cos\emptyset \tag{2.42}$$

Where

H_{Bt} : Beam radiation component on a tilted surface (W/m^2)
H_{Bn}: Beam normal radiation component (W/m^2)
H_B : Beam radiation component on a horizontal surface (W/m^2)

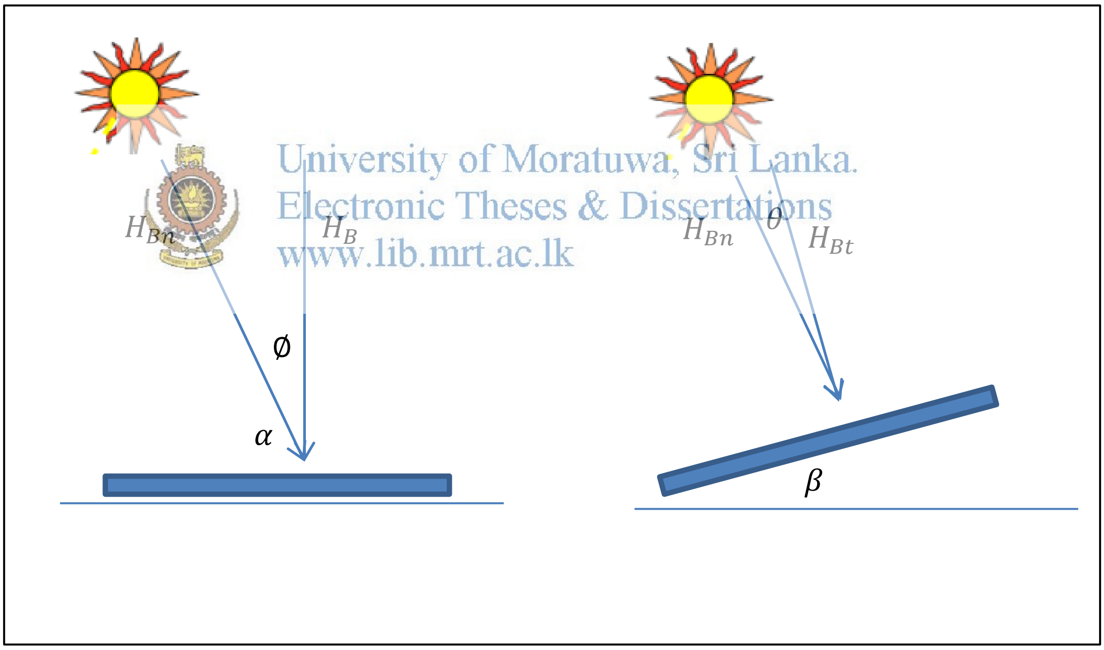

Figure 2.14: Beam radiation on Horizontal and Tilted surfaces

It follows Equation 2.43,

$$R_B = \frac{H_{Bt}}{H_B} = \frac{\cos\theta}{\cos\emptyset} \tag{2.43}$$

Where R_B is called the beam radiation tilt factor. Therefore the beam radiation component for any tilted surface is given by the Equation 2.44.

$$H_{Bt} = H_B R_B \tag{2.44}$$

Where, R_B is the ratio of the daily beam radiation incident on an inclined plane to that on horizontal plane for the northern hemisphere and south facing surfaces. It is expressed in Equation 2.45.

$$R_B = \frac{H_{Bt}}{H_B} = \frac{\cos(\emptyset - \beta)\cos\delta\sin\omega_s' + \omega_s'\sin(\emptyset - \beta)\sin\delta}{\cos\emptyset\cos\delta\sin\omega_s' + \omega_s\sin\emptyset\sin\delta} \tag{2.45}$$

Where,

ω_s : Sunset hour angle

ω_s' : Sunset hour angle at the tilted plane

ω_s and ω_s' is expressed by Equation 2.46 and 2.47.

$$\omega_s = (\cos^{-1} - \tan\emptyset\tan\delta) \tag{2.46}$$

$$\omega_s' = min\{\cos^{-1}(-\tan\emptyset\tan\delta), \cos^{-1}(-\tan(\emptyset - \beta)\tan\delta)\} \tag{2.47}$$

Two distinct types of solar radiation models can be identified in literature, called isotropic radiation models and anisotropic radiation models based on the behavior of the diffuse solar radiation component of global solar radiation. The isotropic model assumes that the intensity of the sky diffuse radiation is uniform over the entire sky dome. The assumption of isotropy of the sky provides a good fit to empirical data at low intensity conditions found during overcast skies. Isotropic models generally underestimate the amount of solar radiation falling on tilted surfaces at higher solar intensities and in clear or partly clear sky situations. In anisotropic conditions, circumsolar and horizon brightening are considered to be prevalent.

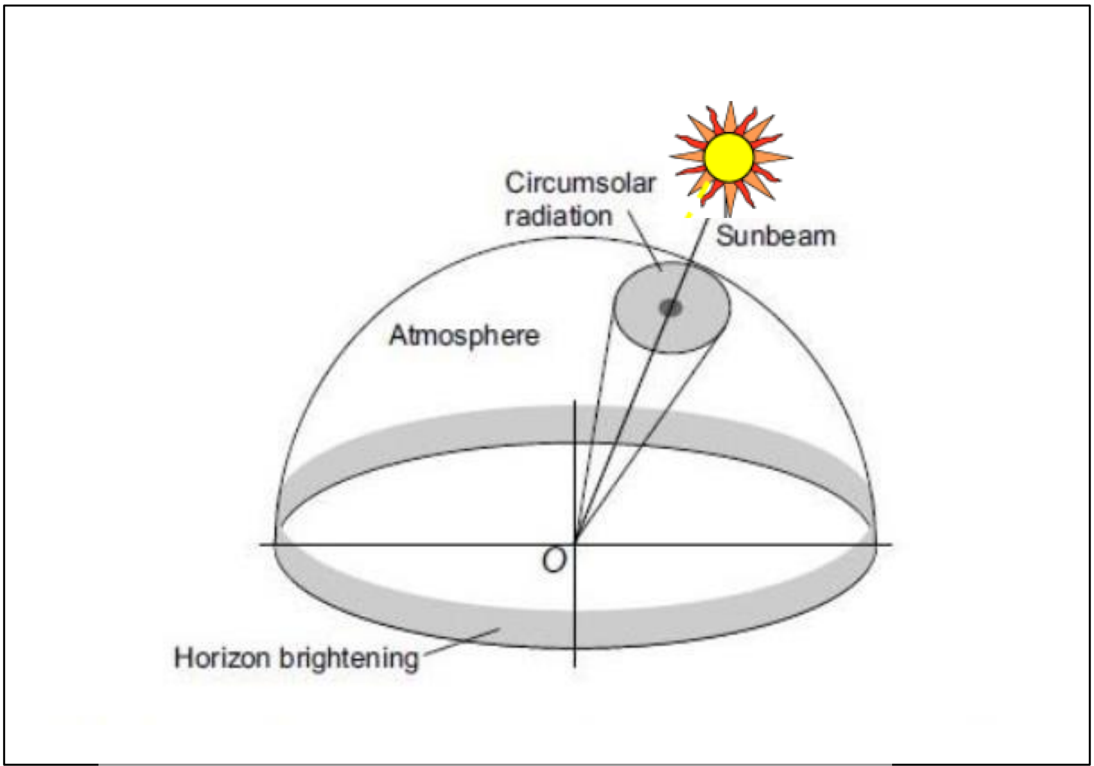

Figure 2.15: Anisotropic Solar Radiation Model

Source: www.assignmentpoint.com

According to the isotropic sky model originally developed by Hottel and Woertz (1942) and refined by Liu and Jordan (1960) sky diffuse solar radiation component is calculated as follows,

According to the Liu and Jordan (1960) diffuse radiation on a horizontal surface is given by the Equation 2.48.

$$H_D = 2\int_0^{\frac{\pi}{2}} H_R \cos\emptyset d\emptyset = 2H_R \quad (2.48)$$

Where,

H_R : Diffuse sky radiance (w/m^{2}rad)

Therefore diffuse radiation on tilted surface is given by Equation 2.49.

$$H_{Dt} = \int_{0}^{\frac{\pi}{2}-\beta} H_R \cos \emptyset d\emptyset + \int_{0}^{\frac{\pi}{2}} H_R \cos \emptyset d\emptyset \tag{2.49}$$

Where,

β is the surface tilt angle. The second term of the equation becomes H_R which is equal to $\frac{H_D}{2}$ according to the Equation 2.48. Then Equation 2.49 can be re arranged as Equation 2.50.

$$H_{Dt} = \frac{H_D}{2} \int_{0}^{\frac{\pi}{2}-\beta} \cos \emptyset d\emptyset + \frac{H_D}{2} = \frac{H_D}{2} \left[\sin\left(\frac{\pi}{2} - \beta\right) \right] + \frac{H_D}{2} \tag{2.50}$$

Further Equation 2.50 can be simplified to Equation 2.51

$$H_{Dt} = H_D \left[\frac{1 + \cos \beta}{2} \right] = H_D R_D \tag{2.51}$$

Where R_D is called the diffuse solar radiation tilt factor and R_D for the model of Liu and Jordan (1960) can be expressed by Equation 2.52.

$$R_D = \left[\frac{1 + \cos \beta}{2} \right] \tag{2.52}$$

R_D for the isotropic model proposed by Badescu (2002) can be expressed by Equation 2.53.

$$R_D = \left[\frac{3 + \cos 3\beta}{4} \right] \tag{2.53}$$

R_D for the isotropic model proposed by Tian et al. (2001) can be expressed by Equation 2.54

$$R_D = \left[1 - \frac{\beta}{180} \right] \tag{2.54}$$

R_D for the isotropic model proposed by Koronakis (1996) can be expressed by Equation 2.55.

$$R_D = \left[\frac{1}{3(2 + \cos \beta)} \right] \tag{2.55}$$

Klucher (1979) found that the isotropic models give satisfactory results for overcast skies but underestimates irradiance under clear and partly overcast conditions, when there is increased intensity near the horizon and in the circumsolar region of the sky.

Klucher (1979) proposed R_D as expressed in Equation 2.56.

$$R_D = \left[\frac{1+\cos\beta}{2}\right]\left[1+\acute{F}\sin^3\left(\frac{\beta}{2}\right)\right]\left[1+\acute{F}\cos^2\beta\sin^3\emptyset\right] \tag{2.56}$$

Where $\acute{F}$ is the clearness index which can be expressed by Equation 2.57.

$$\acute{F} = 1 - \left[\frac{I_D}{I_B + I_D}\right]^2 \tag{2.57}$$

The first of modifying factors in the sky diffuse component given by Equation 2.56 takes into account horizon brightening. The second modifying factor takes into account the effect of circumsolar radiation. Under overcast skies, the clearness index $\acute{F}$ becomes 0 and the model reduces to the isotropic model.

Hay and Davis (1980) proposed a solar radiation model considering only isotropic sky and circumsolar component, but horizon brightening was not taking into account. R_D for the anisotropic model proposed by Hay and Davis (1980) is expressed by Equation 2.58.

$$R_D = AR_B + (1-A)\left[\frac{1+\cos\beta}{2}\right] \tag{2.58}$$

Where A is the anisotropy index, defined by Equation 2.59

$$A = \frac{H_{Bn}}{H_{On}} \tag{2.59}$$

The anisotropy index is used to quantify the portion of the diffuse radiation treated as circumsolar, with the remaining portion of diffuse radiation is assumed isotropic. By using the same definition for anisotropy index, Reindl et al. (1990) proposed a solar radiation model which also accounts for the horizon brightening.

R_D for the anisotropic model proposed by Hay and Davis (1980) is expressed by Equation 2.60.

$$R_D = AR_B + (1 - A)\left[\frac{1 + \cos\beta}{2}\right]\left[1 + \sqrt{\frac{I_B}{I_B + I_D}}\sin^3\left(\frac{\beta}{2}\right)\right] \qquad (2.60)$$

Duffie and Beckman (2006) proposed an integrated model by combining the models developed by Hay and Davis (1980), Klucher (1979) and Reindl et al. (1990) which is referred to as HDKR model.

R_D for the anisotropic HDKR model proposed by Duffie and Beckman (2006) is given by Equation 2.61

$$R_D = AR_B + (1 - A)\left[\frac{1 + \cos\beta}{2}\right]\left[1 + \sin^3\left(\frac{\beta}{2}\right)\right] \qquad (2.61)$$

The ground reflected solar radiation component on a tilted surface can be estimated by the Equation 2.62.

$$H_{Gt} = \rho_g(H_B + H_D)R_G \qquad (2.62)$$

where ρ_g is the ground albedo and R_G is the ground reflection radiation tilt factor.

Therefore, assuming isotropic sky conditions, ground reflected solar radiation component (H_{Gt}) can be obtained by the isotropic solar radiation model of Liu and Jordan (1960) which is given in the Equation 2.63.

$$\rho_g(H_B + H_D) = 2\int_0^{\frac{\pi}{2}} H_r \cos\emptyset d\emptyset = 2H_r \qquad (2.63)$$

Where,

H_r : Isotropic ground reflection radiance (W/m^{2}rad)

Therefore ground reflected radiation on a tilted surface is expressed by Equation 2.64.

$$H_{Gt} = \int_{\frac{\pi}{2}-\beta}^{\frac{\pi}{2}} H_r \cos \emptyset d\emptyset \qquad (2.64)$$

By combining Equations 2.63 and 2.64, Equation 2.65 is obtained.

$$H_{Gt} = \rho_g (H_B + H_D) \left[\frac{1 - \cos \beta}{2}\right] \qquad (2.65)$$

Therefore the ground reflection solar radiation tilt factor is expressed by Equation 2.66.

$$R_G = \left[\frac{1 - \cos \beta}{2}\right] \qquad (2.66)$$

Summary of the solar radiation models so far discussed can be tabulate in Table 2.6

Table 2.6: Summary of several solar radiations models

Model	Year	Type	Formulae
Liue and Jordan	1960	Iso	$H_t = H_B R_B + H_D \left[\frac{1+\cos\beta}{2}\right] + \rho_g (H_B + H_D) \left[\frac{1-\cos\beta}{2}\right]$
Koronakis	1986	Iso	$H_t = H_B R_B + H_D \left[\frac{(2+\cos\beta)}{3}\right] + \rho_g (H_B + H_D) \left[\frac{1-\cos\beta}{2}\right]$
Tian et al.	2001	Iso	$H_t = H_B R_B + H_D \left[1 - \frac{\beta}{180}\right] + \rho_g (H_B + H_D) \left[\frac{1-\cos\beta}{2}\right]$
Badescu et al.	2002	Iso	$H_t = H_B R_B + H_D \left[\frac{3+\cos 3\beta}{4}\right] + \rho_g (H_B + H_D) \left[\frac{1-\cos\beta}{2}\right]$
Klucher	1979	Ani	$H_t = H_B R_B + H_D \left[\frac{1+\cos\beta}{2}\right] \left[1 + \acute{F}\sin^3\left(\frac{\beta}{2}\right)\right] \left[1 + \acute{F}\cos^2\beta\sin^3\emptyset\right] + \rho_g (H_B + H_D) \left[\frac{1-\cos\beta}{2}\right]$
Hay and Davis	1980	Ani	$H_t = (H_B + AH_D)R_B + H_D(1-A) \left[\frac{1+\cos\beta}{2}\right] + \rho_g (H_B + H_D) \left[\frac{1-\cos\beta}{2}\right]$
Reindl Model	1990	Ani	$H_t = (H_B + AH_D)R_B + I_D(1-A) \left[\frac{1+\cos\beta}{2}\right] \left[1 + \sqrt{\frac{H_B}{H_B+H_D}}\sin^3\left(\frac{\beta}{2}\right)\right] + \rho_g (H_B + H_D) \left[\frac{1-\cos\beta}{2}\right]$
HKRD Model	2006	Ani	$H_t = (H_B + AH_D)R_B + H_D(1-A) \left[\frac{1+\cos\beta}{2}\right] \left[1 + \sin^3\left(\frac{\beta}{2}\right)\right] + \rho_g (H_B + H_D) \left[\frac{1-\cos\beta}{2}\right]$

$$R_B = \frac{\cos(\emptyset-\beta)\cos\delta\sin\omega'_s + \omega'_s\sin(\emptyset-\beta)\sin\delta}{\cos\emptyset\cos\delta\sin\omega'_s + \omega_s\sin\emptyset\sin\delta} \text{ and } A = \frac{H_{Bn}}{H_{On}}$$

Solar energy receiving devices such as solar PV panels and solar collectors which are installed on rooftops have the surface tilt angles shown in the table 2.7. Those roof tilt angles are the common roof angles recommended for Sri Lanka.

Table 2.7: Recommended tilt angles for roofs in Sri Lanka

Material	**Slope in degrees**
Plain tile	40
Double clay interlocking tile (Pan tile)	22.5
Concrete single lap tile (interlocking) clip fixing	17.5
Fiber reinforced cement slates	17.5
Profile materials	15
Wood shingles	30

Source: www.buildsrilanka.com

When it is to install solar energy receiving devices on roof slabs, in some cases the particular devices are tilted towards due south by an angle equals to the local latitude to maximize the solar energy utilization.

CHAPTER 3. RESEARCH METHODOLOGY

3.1. Assessment of the Global, Direct and Diffuse Solar Radiation on Horizontal Surface at Colombo

The measured global solar radiation data from the year 2009 to 2014 were used for estimating the monthly average global solar radiation on horizontal surface at Colombo. The global solar radiation resource potential on horizontal surface is derived by averaging the measured global solar radiation data of each month separately within the particular time period. An Angstrom type solar radiation model was developed and the correlation coefficients *a* and *b* were derived to estimate the missing data of the existing global solar radiation data set. For this purpose, readily available data on monthly average global solar insolation on horizontal surface and monthly average daily possible sunshine hours on horizontal surface were obtained from the Meteorological Department of Sri Lanka for Colombo (6.9° N, 79.8° E)

Present model was compared with earlier solar radiation estimation models described in Equation 2.24 and 2.33. Present model was also compared with the NASSA-SSE model which is given in the Table 1.1. The model comparison was carried out by using statistical parameters called Mean Bias Error (MBE) and Root Mean Square Error (RMSE).

$$MBE = \frac{\sum(C_i - M_i)}{n} \tag{3.1}$$

$$RMSE = \sqrt{\frac{\sum(C_i - M_i)^2}{n}} \tag{3.2}$$

Where C_i and M_i are the i^{th} calculated and measured values of global solar radiation respectively

Monthly average clearness index $(\overline{K}_T)$ values which are required to estimate the sky diffuse solar radiation fraction was derived for each month of the year using existing global solar radiation data set. The solar radiation model given by Equation 2.35 was used to estimate the sky diffuse solar radiation resource potential on a horizontal surface at Colombo. According to the relationship given in Equation 2.37, the direct solar radiation resource potential on a horizontal surface at Colombo was also estimated.

3.2. Assessment of the Global, Direct and Diffuse Solar Radiation on Tilted Surface at Colombo

The global solar radiation resource potential on due south faced tilted surface at Colombo was estimated by incorporating the derived direct and diffuse solar radiation values on horizontal surface at Colombo. Tilt angles for solar resource assessment was selected as same as the typical roof angles of Sri Lanka, i.e. 15°, 17.5°, 22.5°, 30°, and 40°. Also the tilt angle equals to the local latitude value of 6.9° was incorporated to the solar resource assessment. Those tilt angles are the typical surface tilt angles of the solar energy receiving devices.

The beam radiation tilt factor (R_B), diffuse solar radiation tilt factor (R_D), and ground reflect solar radiation tilt factor (R_G), were calculated for each month of the year and each surface tilt angle and substituted to the Equation 2.39 to estimate the monthly average global solar radiation resource potential on each tilted surface. Although beam radiation component on tilted surface requires a quite simple analysis, the diffuse solar radiation component requires a detailed analysis. Therefore the diffuse solar radiation tilt factor (R_D) was analyzed under two approaches called isotropic and anisotropic sky models. All the solar radiation models given in the Table 2.6 were taken into consideration for this analysis and a suitable sky model to estimate the diffuse solar radiation component was identified. With the knowledge of surface Albedo value (ρ_g) for Colombo as 0.05 which was adopted from NASA-SSE model, monthly average ground reflected solar radiation component on each tilted surface was also estimated.

The solar insolation on tilted surface was analyzed by varying the surface tilt angle. Since the declination angle varies throughout the year, the average declination angle for a month was selected from the Table 2.4. The optimum surface tilt angle and the relevant insolation values were found by plotting the solar insolation against the tilt angle. Finally the annual average maximum solar energy potential on tilted surface was also found.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Solar Radiation Analysis on Horizontal Surface at Colombo

4.1.1. Correlation of global solar radiation with sunshine hours

New coefficients were proposed for the Angstrom type solar radiation model from existing monthly average daily global solar radiation on horizontal surface. Equation 4.1 indicates these new coefficients.

$$\frac{\bar{H}}{H_o} = \left(0.29 + 0.38\frac{\bar{S}}{S_o}\right) \quad (4.1)$$

The Pearson's correlation coefficient, "r" for the proposed relationship is 0.57. Hence it can be concluded that a moderate linear relationship exists between $\frac{\bar{S}}{S_o}$ and $\frac{\bar{H}}{H_o}$.

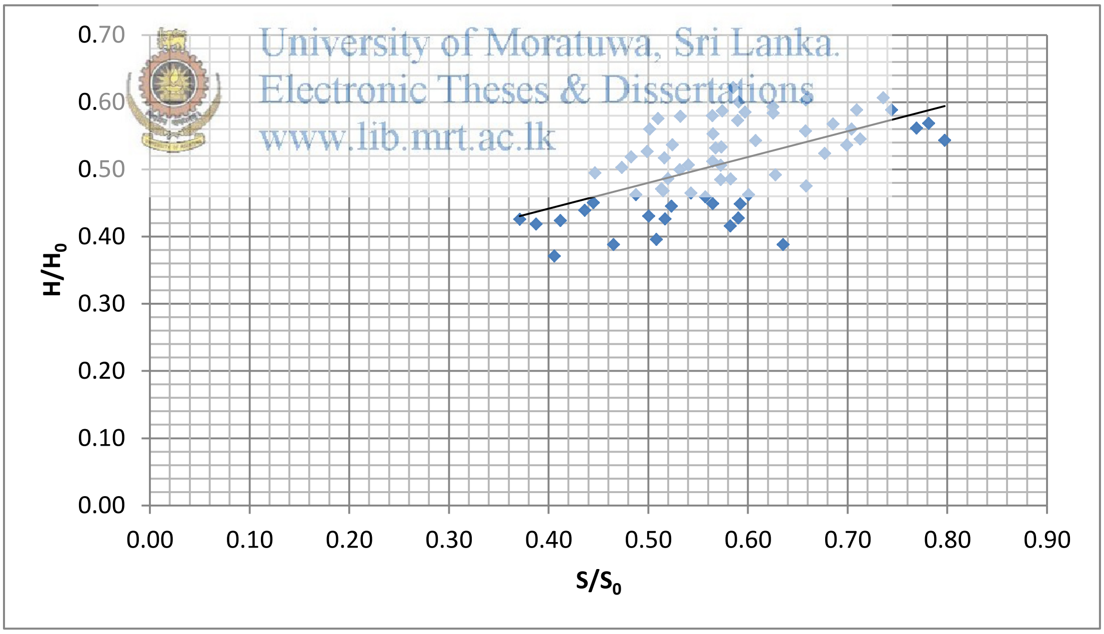

Figure 4.1: Relationship between $\frac{\bar{S}}{S_o}$ and $\frac{\bar{H}}{H_o}$ for the data from year 2009 to 2014

The model developed for the current study was compared with previously developed models which are expressed in Equation 2.24, Equation 2.33 and Table 1.1. Statistical parameters MBE and RMSE were used for this comparison.

Table 4.1: Comparison of solar radiation models using statistical parameters

Model	MBE	RMSE
Present Model	0.01	0.55
Model developed for Visakhapatnam	0.47	0.72
Model developed by Akinogolu and Ecevit	0.31	0.64
NASA-SSE Model	0.53	0.77

Table 4.1 indicates that among all four solar radiation models compared, the solar radiation model developed in the present work shows the minimum values for MBE and RSME. Hence it can be concluded that the present model can predict the global solar radiation on horizontal surface at Colombo more accurately than other solar radiation models.

The solar energy estimation according to all four models for each year from 2010 to 2014 along with the actual measured data is illustrated in the Figure 4.2, 4.3, 4.4, 4.5 and 4.6.

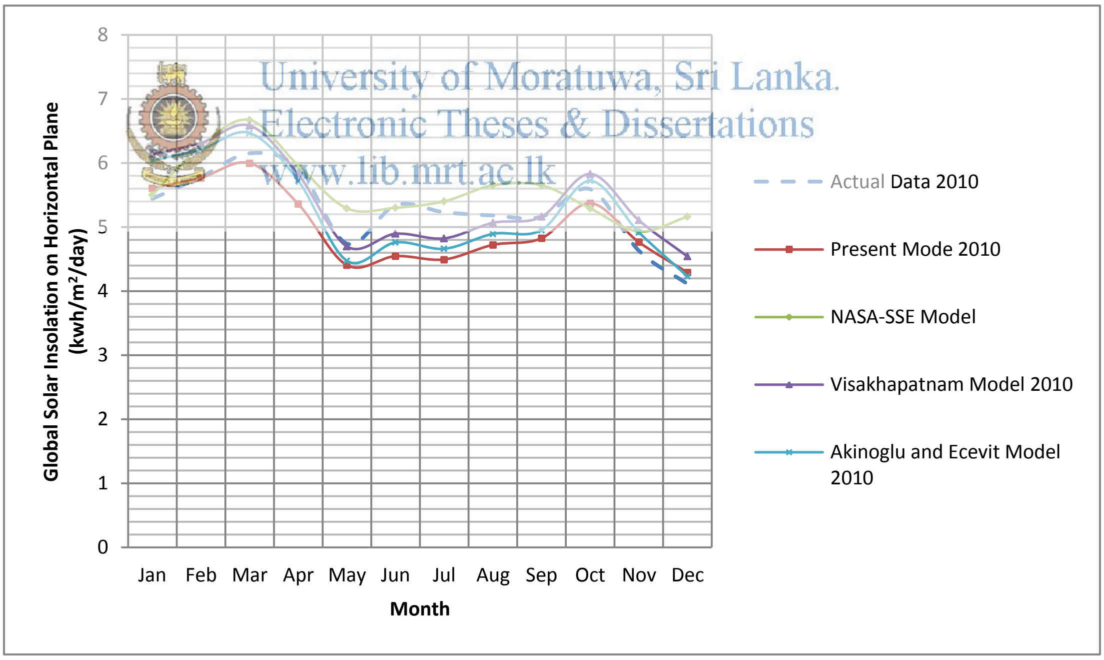

Figure 4.2: Global solar insolation on horizontal surface at Colombo – 2010

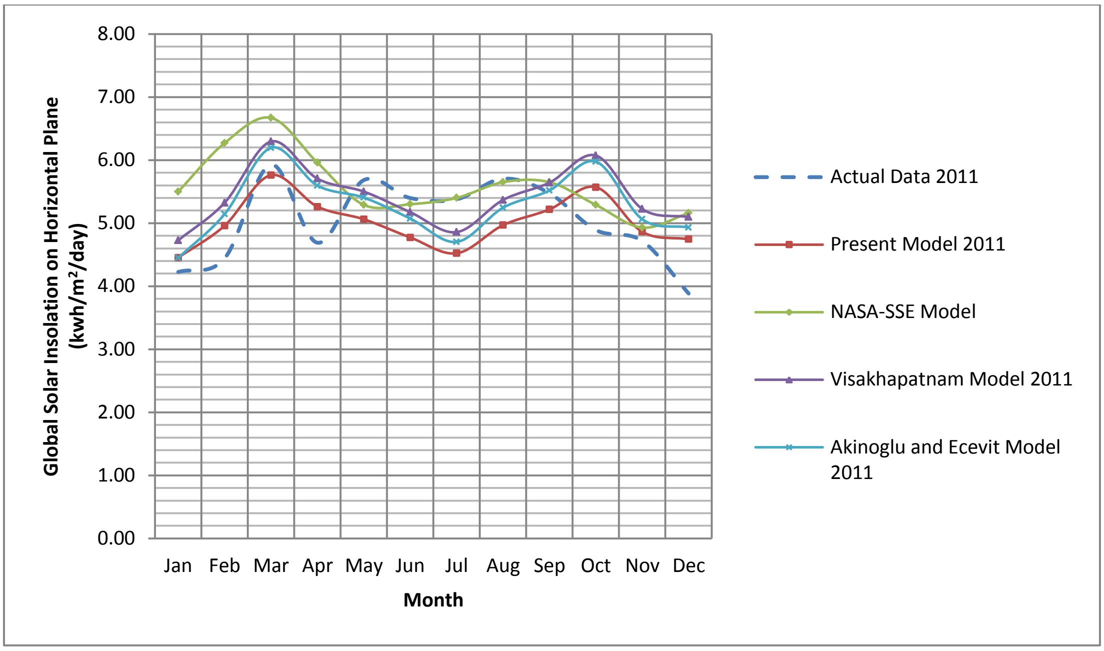

Figure 4.3: Global solar insolation on horizontal surface at Colombo – 2011

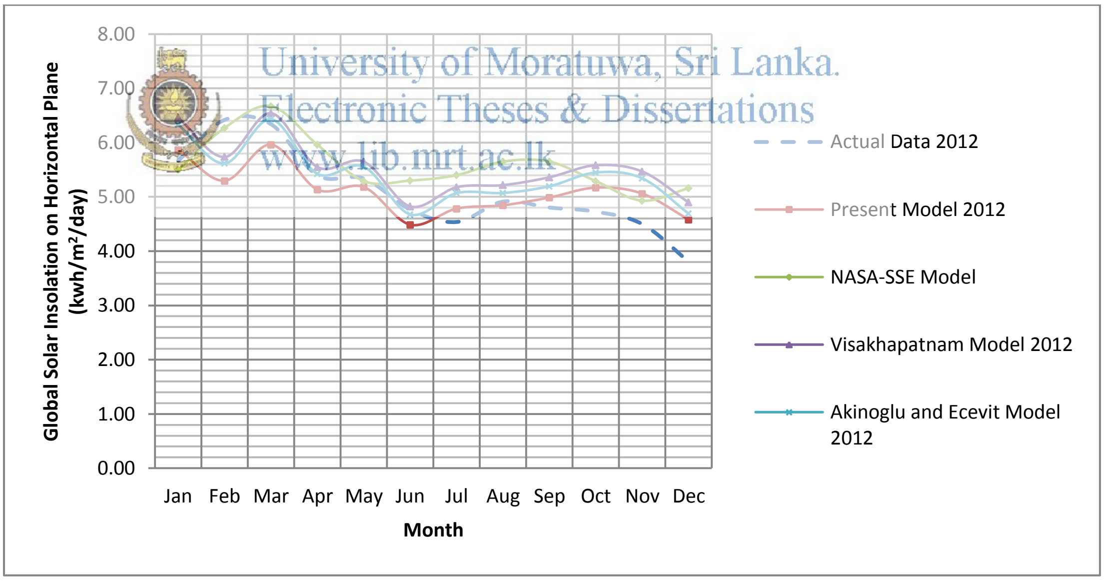

Figure 4.4: Global solar insolation on horizontal surface at Colombo – 2012

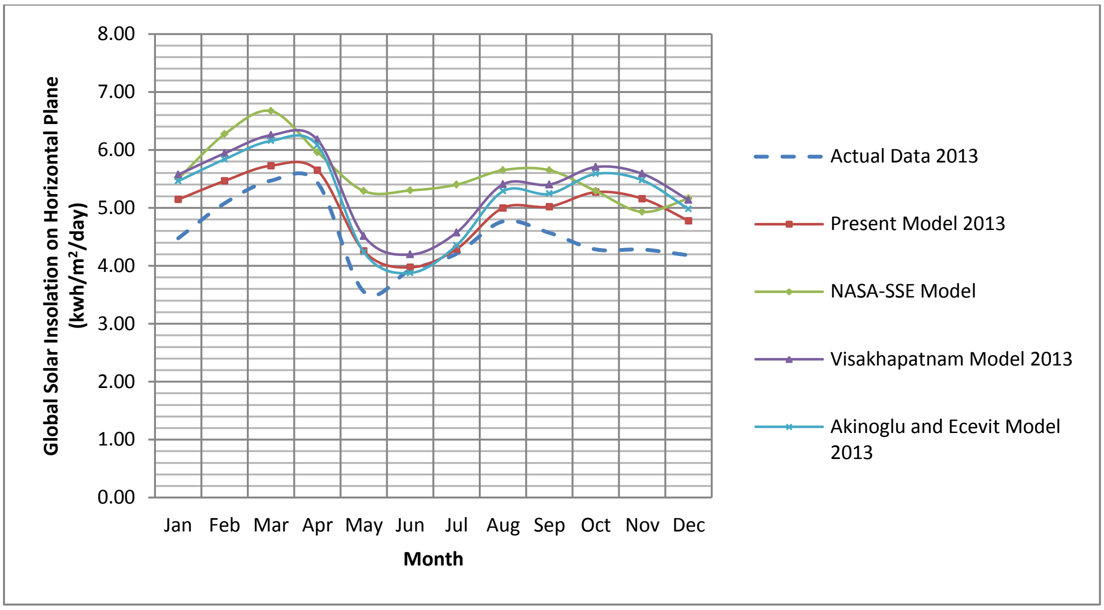

Figure 4.5: Global solar insolation on horizontal surface at Colombo – 2013

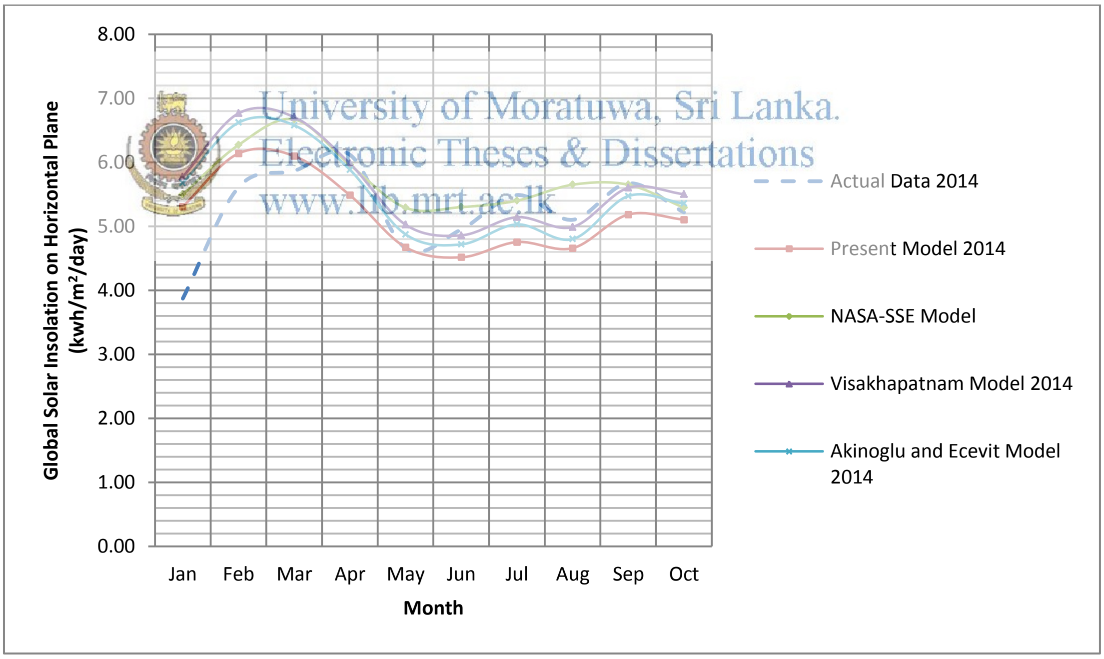

Figure 4.6: Global solar insolation on horizontal surface at Colombo – 2014

4.1.2. Estimation of global horizontal solar resource potential for Colombo

Calculated global solar energy resource potential by averaging monthly average global horizontal insolation from 2009 to 2014 is tabulated in Table 4.2.

Table 4.2: Global solar energy resource potential on horizontal surface at Colombo

Month	Solar insolation on horizontal surface (kWh/m^2/day)
January	4.74
February	5.47
March	5.95
April	5.51
May	4.79
June	4.88
July	4.97
August	5.13
September	5.14
October	4.94
November	4.53
December	4.00
Annual Average	5.00

According to the Table 4.2, global horizontal solar resource potential at Colombo occurs in December which is 4.00 kWh/m^2/day whereas a maximum of 5.95 kWh/m^2/day occurs in March. The annual average global horizontal solar resource potential in Colombo was found to be 5.00 kWh/m^2/day. It can be concluded that favorable global horizontal resource potential exists at Colombo for solar energy applications such as solar PV power and solar thermal power. Solar energy can be expected to receive consistently throughout the year due to the low seasonal variation of global horizontal solar insolation observed.

4.1.3. Estimation of monthly average clearness index ($\bar{K}_T$) for Colombo

Monthly average clearness index ($\bar{K}_T$) for each month of the year at Colombo was calculated by averaging the existing data (from year 2009 to 2014) and compared with the monthly average clearness index values obtained from the NASA-SSE model.

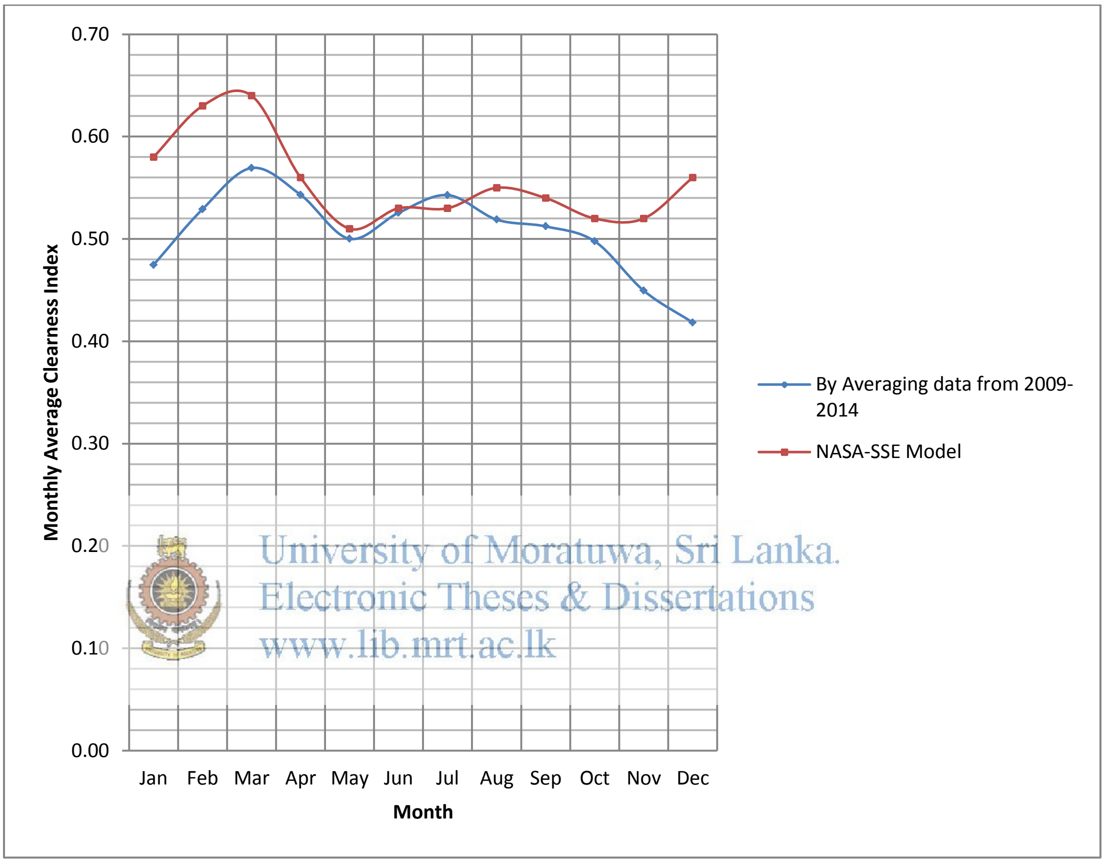

Figure 4.7: Monthly Average Clearness Index for Colombo

It can be observed that except in July, the monthly average clearness index values obtained from NASA-SSE model exceed the values obtained by averaging the actual data set from year 2009 to 2014. It can be concluded that due to this overestimation of monthly average clearness index, NASA-SSE model overestimates the monthly average daily solar radiation as shown in Figure 4.2, 4.3, 4.4, 4.5 and 4.6.

4.1.4. Estimation of the monthly average diffuse horizontal solar radiation at Colombo

Monthly average diffuse solar radiation data obtained from the NASA-SSE model was also used to make comparison with the estimated data. It was observed that the NASA-SSE model slightly overestimates the diffuse solar radiation when compared with the estimated values.

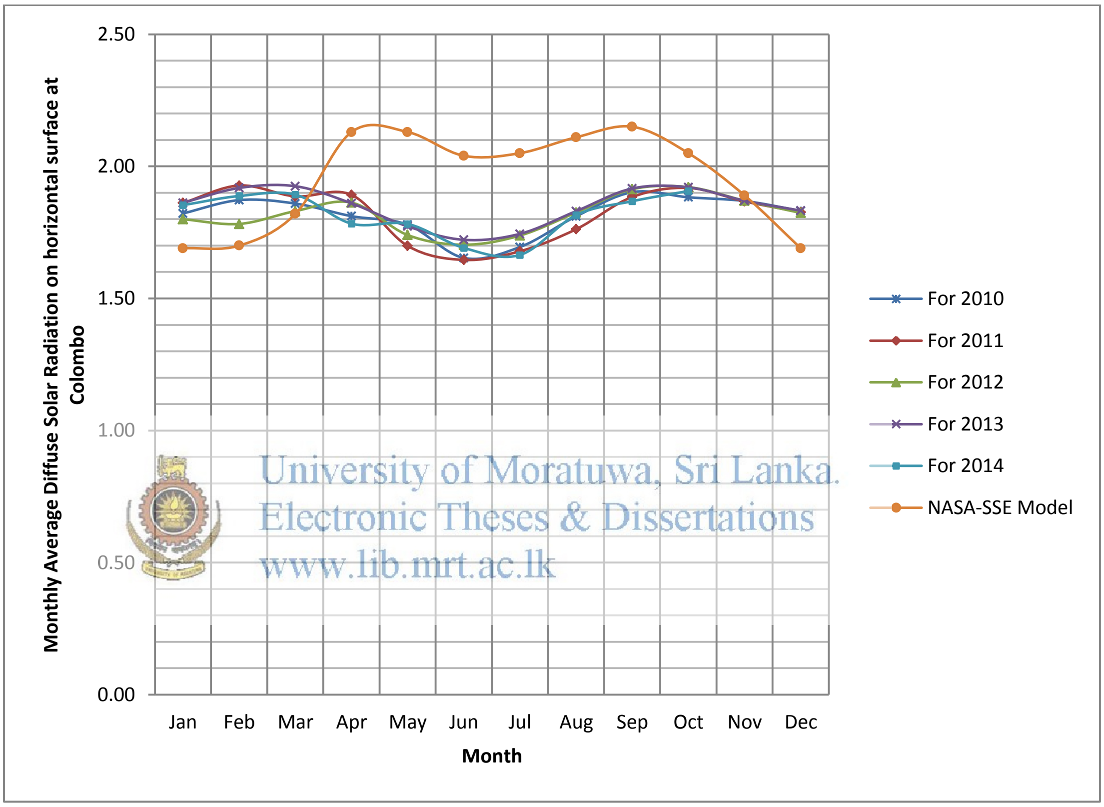

Figure 4.8: Monthly average diffuse solar radiation on horizontal surface at Colombo

4.1.5. Estimation of the monthly average direct solar radiation on horizontal surface at Colombo

Monthly average direct solar radiation data obtained from NASA-SSE model was also used to make comparison with the estimated direct solar radiation data. The present work does not show a satisfactory level of agreement with the NASA-SSE model. Also the estimated values of direct solar radiation data of year 2013 completely lie below the solar radiation data estimated by the NASA-SSE model.

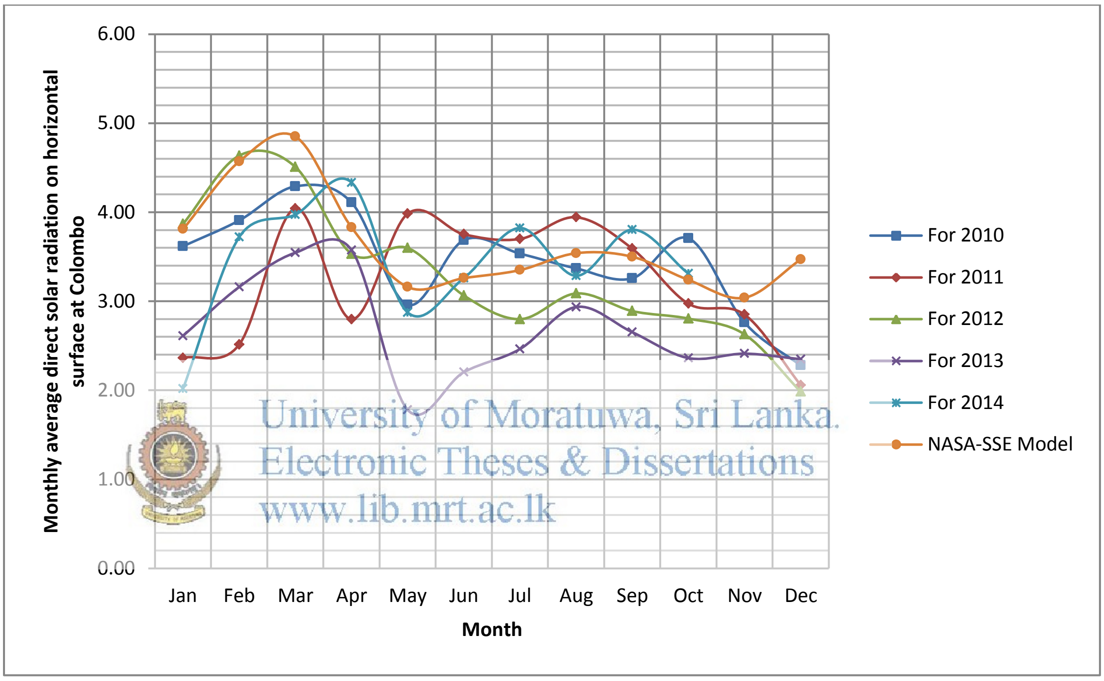

Figure 4.9: Monthly average direct solar radiation estimation on horizontal surface at Colombo

4.1.6. Summary of monthly average solar radiation on horizontal surface at Colombo

Monthly average global, diffuse and direct solar radiation was calculated by averaging the measured and estimated solar radiation data for the period of year 2009 to 2014. Annual average solar radiation values for the location were obtained by averaging the monthly average data set of afore mentioned time period.

Table 4.3: Monthly average solar insolation data (2009-2014)

Month	Average Global Solar Insolation ($kWh/m^2/day$)	Average Diffuse Solar Insolation ($kWh/m^2/day$)	Average Direct Solar Insolation ($kWh/m^2/day$)	Direct solar radiation as a percentage of global solar radiation
Jan	4.74	1.84	2.90	61.2%
Feb	5.47	1.88	3.59	65.6%
Mar	5.95	1.88	4.07	68.4%
Apr	5.51	1.84	3.67	66.6%
May	4.79	1.75	3.04	63.4%
Jun	4.88	1.69	3.19	65.4%
Jul	4.97	1.69	3.27	65.9%
Aug	5.13	1.81	3.32	64.7%
Sep	5.14	1.89	3.25	63.2%
Oct	4.94	1.90	3.04	61.6%
Nov	4.53	1.87	2.66	58.7%
Dec	4.00	1.83	2.17	54.2%
Annual Average	**5.00**	**1.82**	**3.18**	**63.6%**

The estimated data was compared with the NASA-SSE Model.

Table 4.4: Monthly average solar radiation data obtained from NASA-SSE Model

Month	**Average Global Solar Insolation ($kWh/m^2/day$)**	**Average Diffuse Solar Insolation ($kWh/m^2/day$)**	**Average Direct Solar Insolation ($kWh/m^2/day$)**
Jan	5.50	1.69	3.81
Feb	6.27	1.70	4.57
Mar	6.67	1.82	4.85
Apr	5.96	2.13	3.83
May	5.29	2.13	3.16
Jun	5.30	2.04	3.26
Jul	5.40	2.05	3.35
Aug	5.65	2.11	3.54
Sep	5.65	2.15	3.50
Oct	5.29	2.05	3.24
Nov	4.93	1.89	3.04
Dec	5.16	1.69	3.47
Annual Average	**5.58**	**1.96**	**3.62**

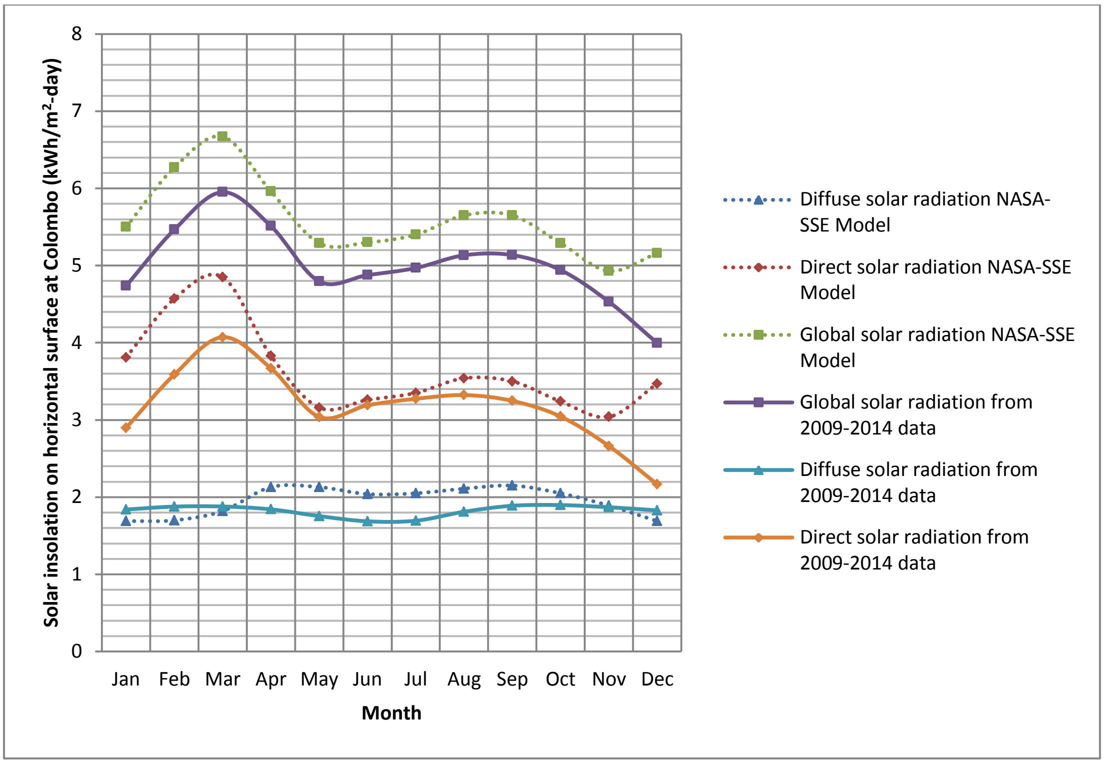

Figure 4.10: Comparison with 2009-2014 estimated values of values obtained from NASA-SSE Model

From the Figure 4.10, it can be observed that the NASA-SSE model overestimates the solar insolation values when compared with the estimated values based on the present work.

4.2. Solar Radiation Analysis on Tilted Surface at Colombo

4.2.1. Monthly average direct solar radiation estimation on tilted surface

Direct radiation tilt factor or beam radiation tilt factor (R_B) was estimated for different tilt angles for a tilted surface oriented to the due south.

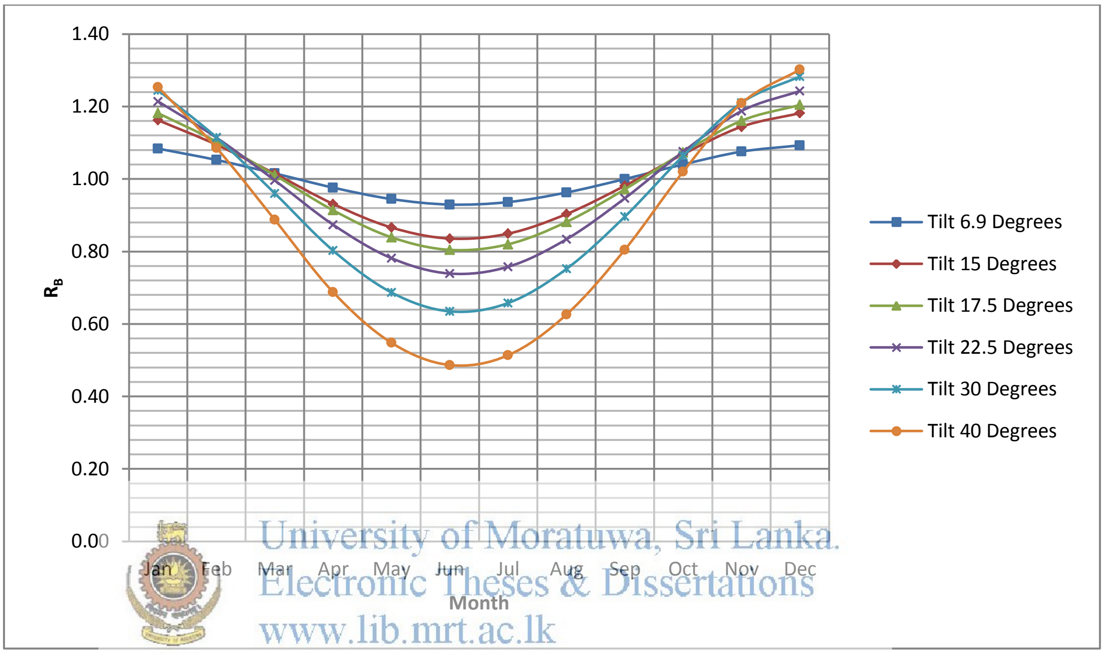

Figure 4.11: Variation of R_B against the tilt angle

It was observed that when the surface tilt angle is increased, the beam radiation tilt factor gets reduced in mid-year months drastically. Beam radiation tilt factor is greater than unity for any of the tilt angles from January to February and October to December. Larger tilt angles results in greater beam radiation tilt factors for those months.

4.2.2. Monthly average diffuse solar radiation estimation on tilted surface

Diffuse radiation tilt factor (R_D) was estimated for different surface tilt angles. Also R_D was estimated under isotropic and anisotropic sky conditions separately.

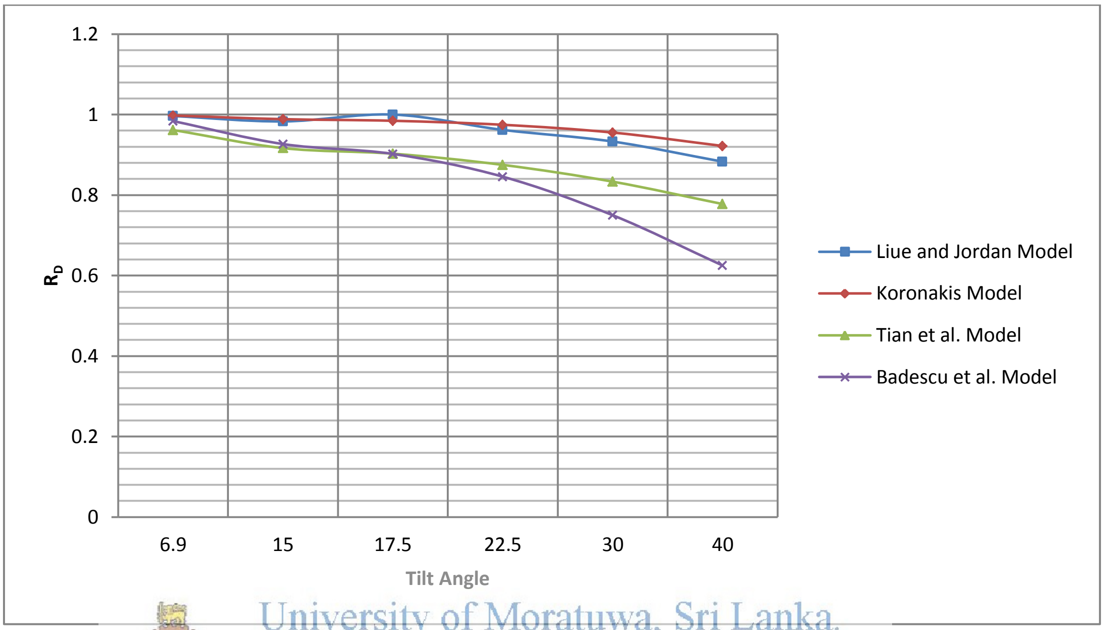

Figure 4.12: Variation of R_D against tilt angle for different isotropic solar radiation models

Monthly variations of diffuse radiation tilt factor was not observed with regards to isotropic solar radiation models. It was observed that when the surface tilt angle is increased, the diffuse radiation tilt factor gets reduced. The isotropic solar radiation model proposed by Badescu et al. (2002) is the most sensitive solar radiation model to the tilt angle. It shows the highest variation with the surface tilt angle.

Diffuse radiation tilt factor (R_D) was estimated for different anisotropic solar radiation models. It was observed that R_D has monthly variations for a given surface tilt angle. R_D was calculated for different surface tilt angles of 6.9°, 15°, 17.5°, 22.5°, 30° and 40° and the results are shown in Figure 4.13 through 4.18.

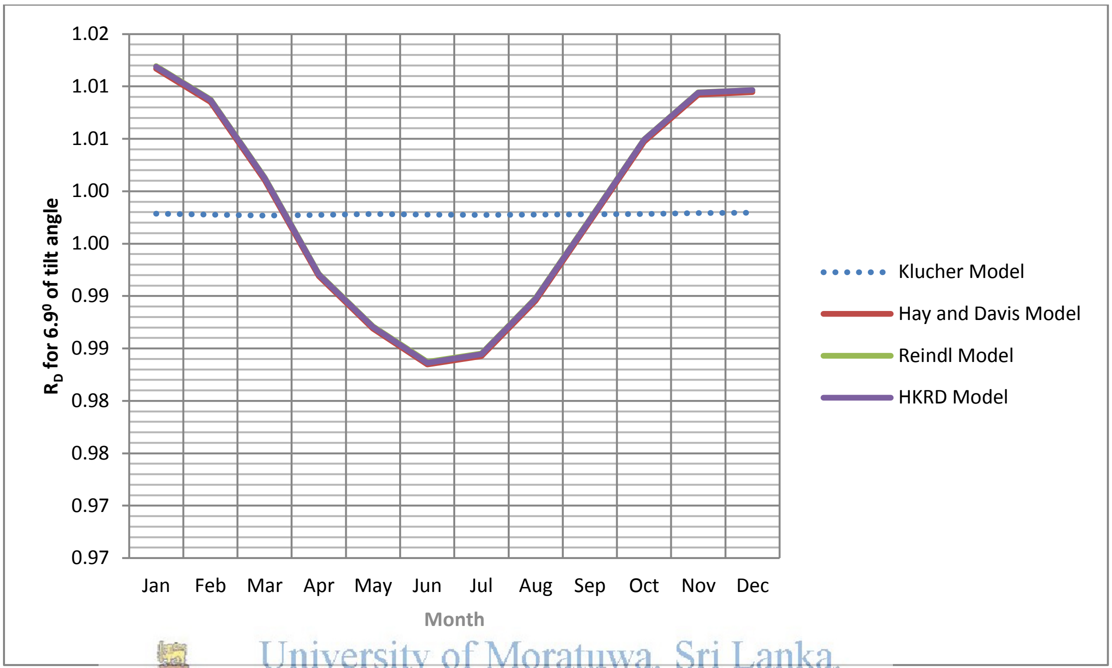

Figure 4.13: R_D for different solar radiation models for 6.9^0 of surface tilt angle

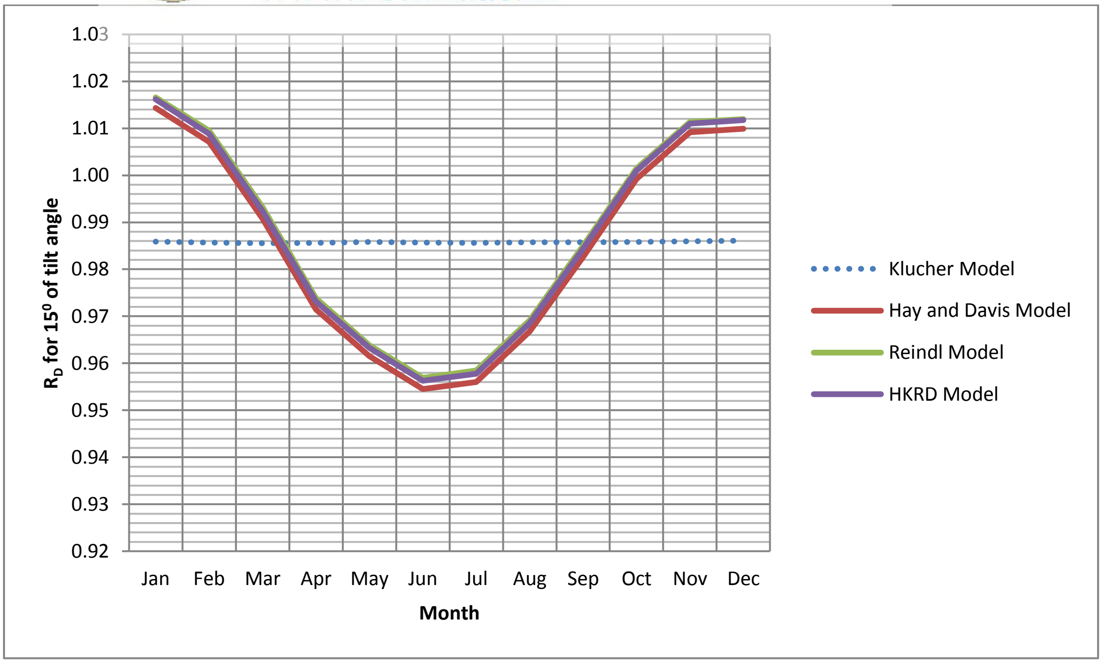

Figure 4.14: R_D for different solar radiation models for 15^0 of surface tilt angle

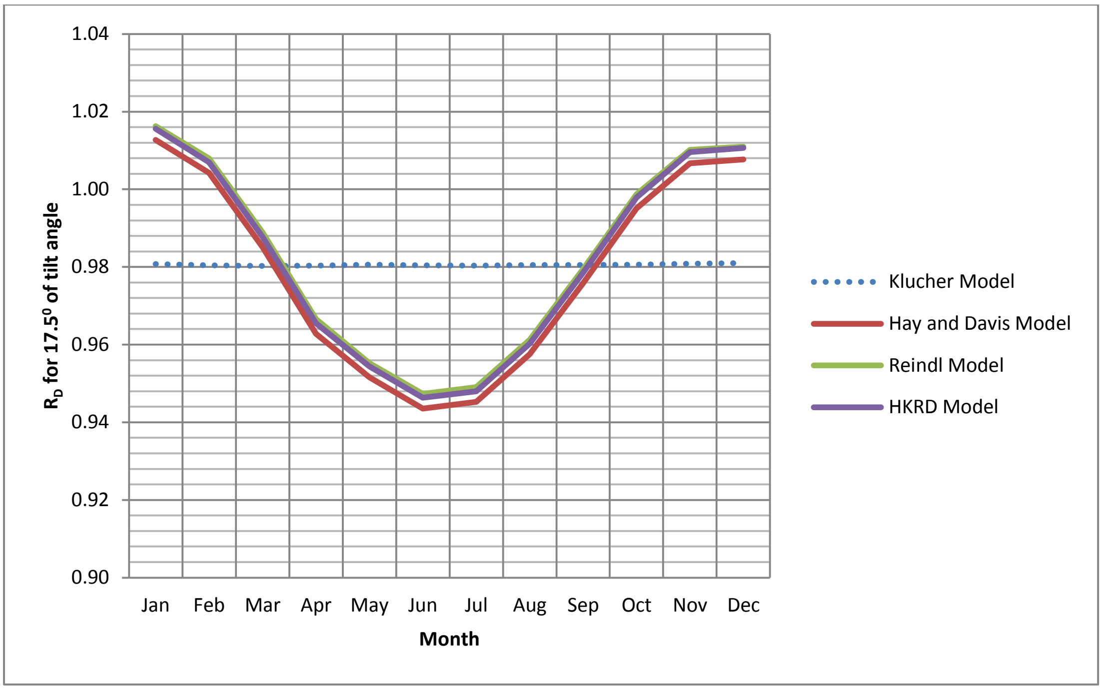

Figure 4.15: R_D for different solar radiation models for 17.5^0 of surface tilt angle

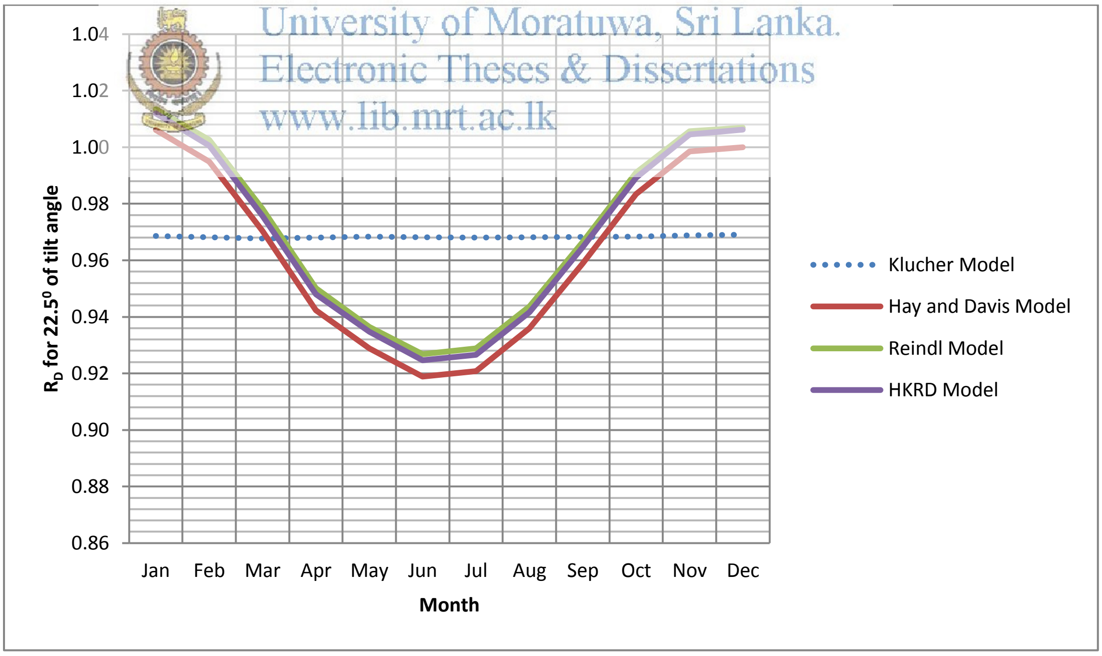

Figure 4.16: R_D for different solar radiation models for 22.5^0 of surface tilt angle

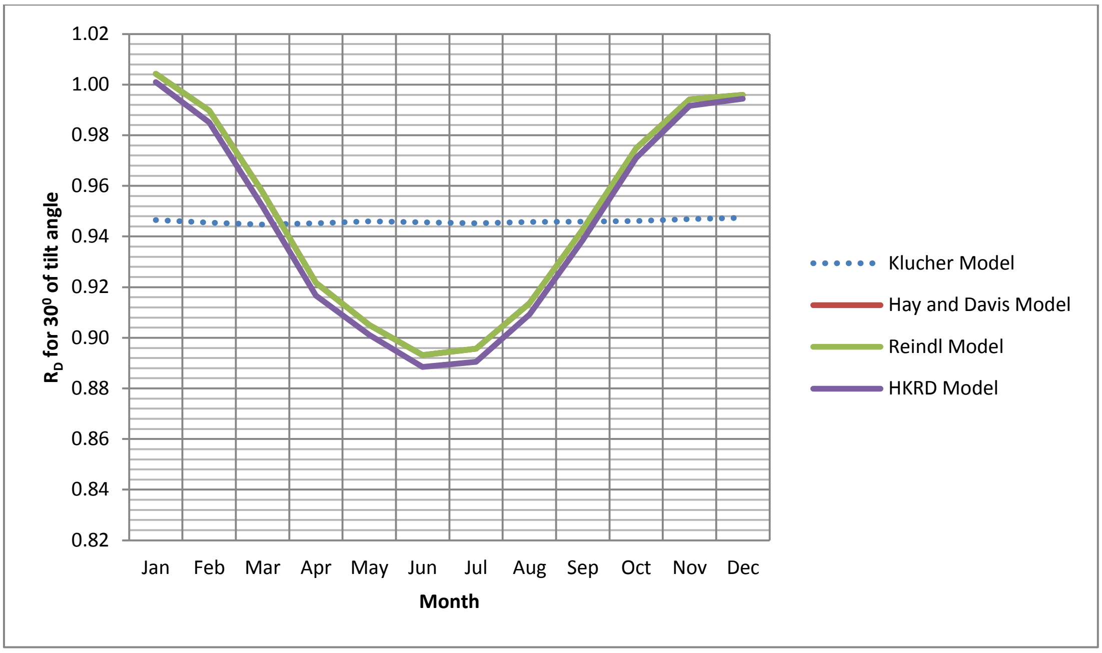

Figure 4.17: R_D for different solar radiation models for 30^0 of surface tilt angle

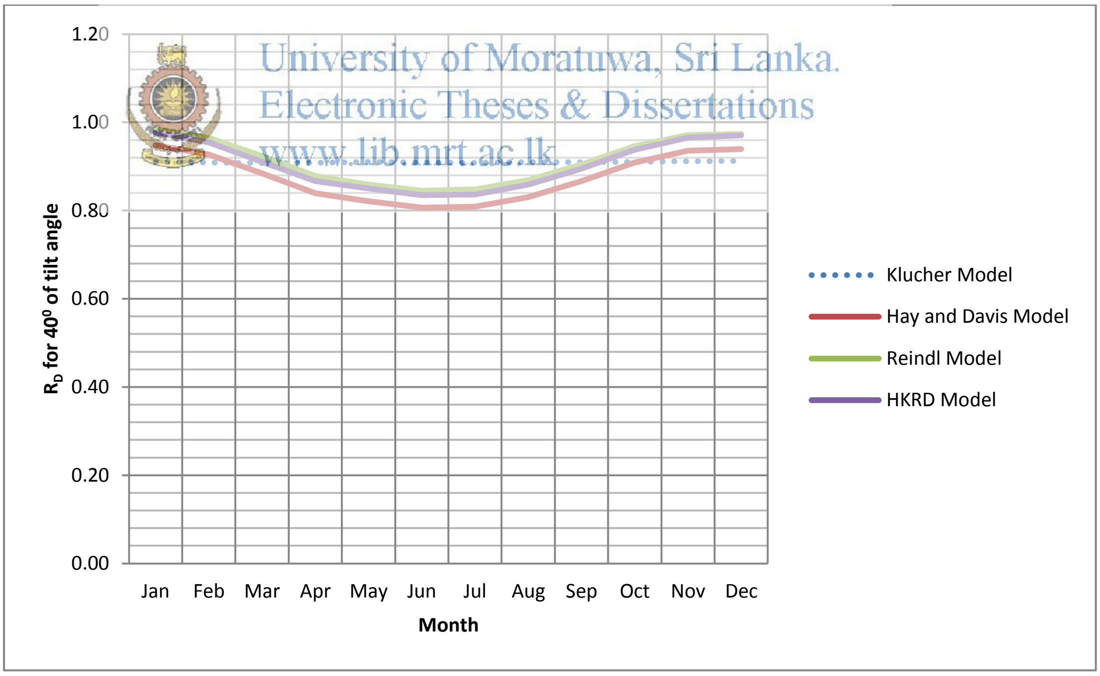

Figure 4.18: R_D for different solar radiation models for 40^0 of surface tilt angle

4.2.1. Monthly average ground reflected solar radiation estimation on tilted surface

Ground reflected solar radiation tilt factor (R_G) varies only with the surface tilt angle since the ground reflected solar radiation is assumed to have isotropic diffusion.

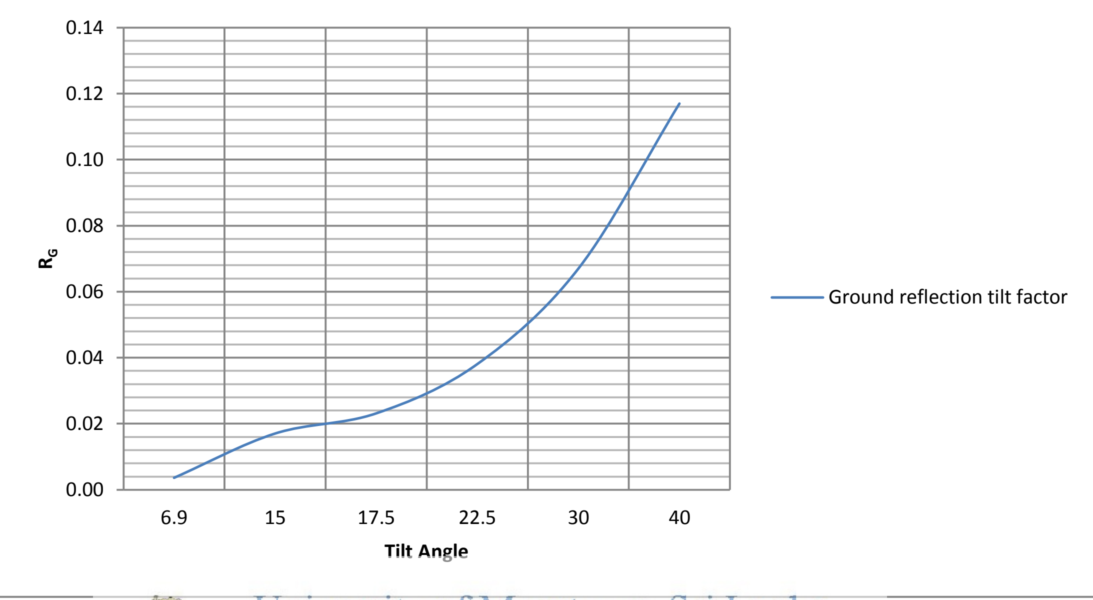

Figure 4.19: Variation of R_G against the surface tilt angle

It was observed that the ground reflected solar radiation tilt factor (R_G) is increased when the surface tilt angle is increased.

Monthly average global solar radiation resource potential on tilted surface at Colombo was estimated by using both Liu and Jordan isotropic model and HDKR anisotropic model. It was found that both models estimate very similar monthly average global solar radiation values. The results are shown in Figure 4.20 and 4.21 and Table 4.5 through Table 4.10.

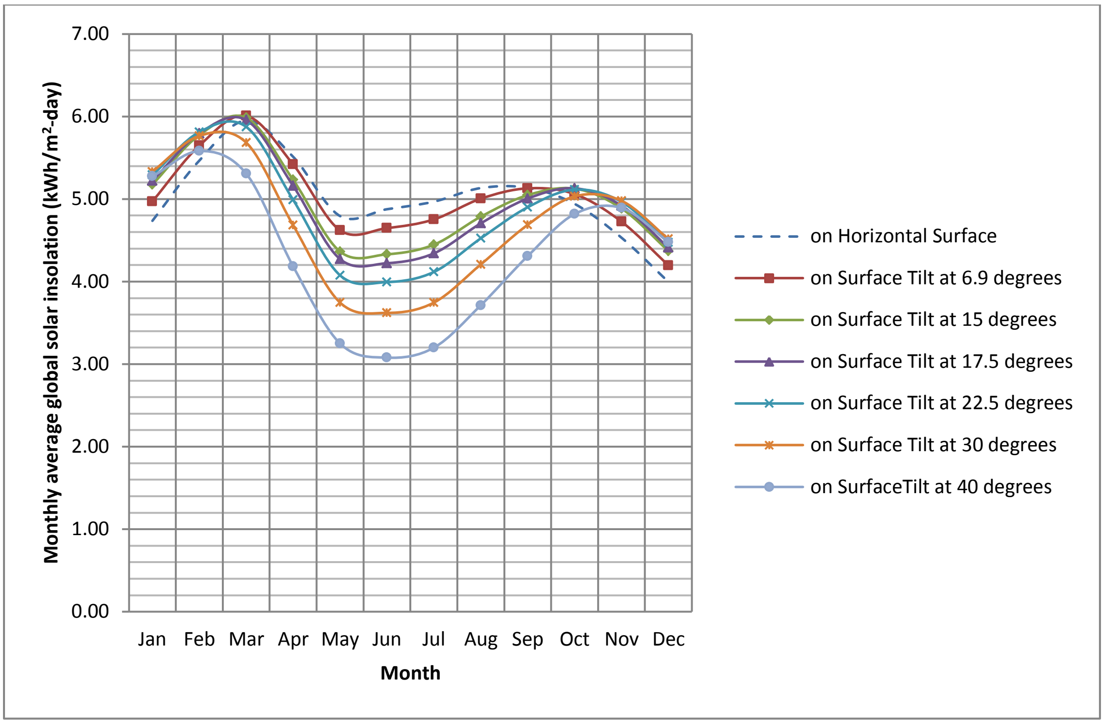

Figure 4.20: Estimation of monthly average global solar radiation by using Liu and Jordan isotropic model

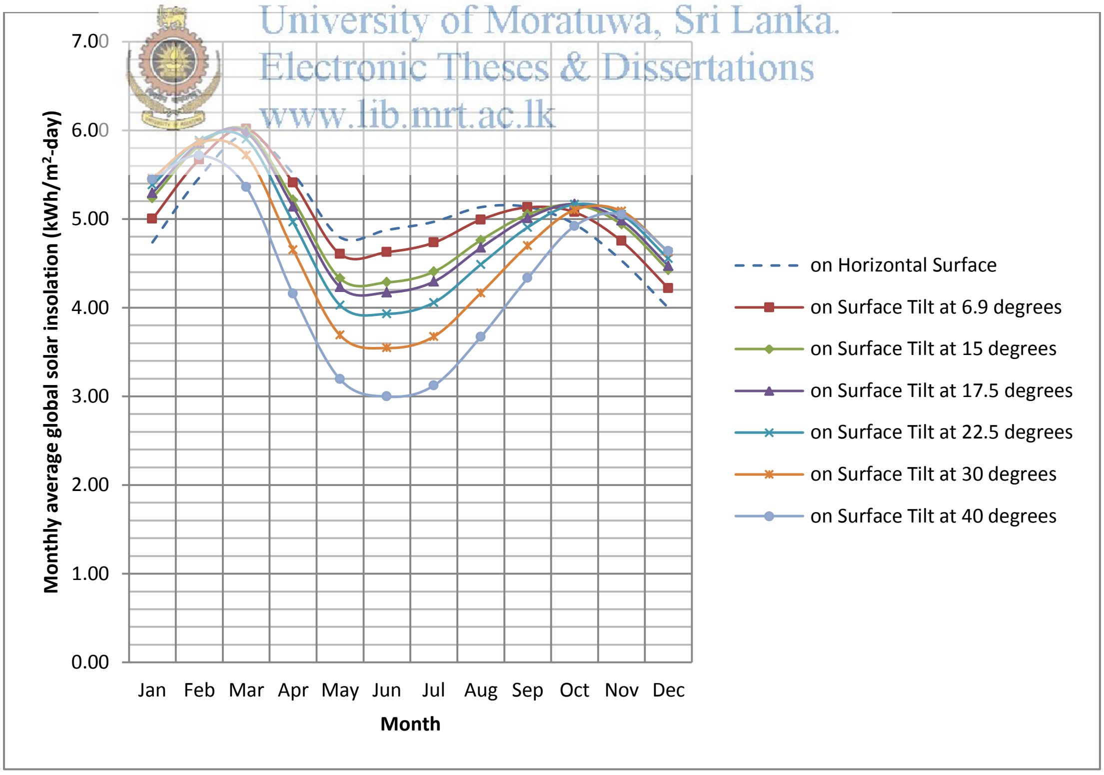

Figure 4.21: Estimation of monthly average global solar radiation by using HDKR anisotropic model

Table 4.5: Monthly average global solar radiation on tilted surface ($\beta = 6.9°$) at Colombo

$\boldsymbol{\beta = 6.9°}$			
Month	**Liu and Jordan Model (kWh/m²/day)**	**HDKR Model (kWh/m²/day)**	**Percentage difference**
Jan	4.97	5.00	0.58
Feb	5.65	5.67	0.41
Mar	6.01	6.02	0.15
Apr	5.42	5.41	-0.15
May	4.62	4.60	-0.36
Jun	4.65	4.63	-0.47
Jul	4.75	4.73	-0.42
Aug	5.00	4.99	-0.24
Sep	5.13	5.13	0.03
Oct	5.06	5.08	0.31
Nov	4.73	4.75	0.52
Dec	4.20	4.22	0.56
Annual Potential (kWh/m²/year)	**1828.84**	**1830.27**	**0.08**

Table 4.6: Monthly average global solar radiation on tilted surface ($\beta = 15°$) at Colombo

$\boldsymbol{\beta = 15°}$			
Month	**Liu and Jordan Model (kWh/m²/day)**	**HDKR Model (kWh/m²/day)**	**Percentage difference**
Jan	5.18	5.24	1.19
Feb	5.78	5.82	0.85
Mar	5.98	6.00	0.30
Apr	5.23	5.21	-0.35
May	4.36	4.33	-0.80
Jun	4.33	4.29	-1.05
Jul	4.45	4.41	-0.95
Aug	4.79	4.76	-0.55
Sep	5.05	5.05	0.05
Oct	5.13	5.16	0.65
Nov	4.89	4.94	1.08
Dec	4.37	4.42	1.17
Annual Potential (kWh/m²/year)	**1808.50**	**1811.50**	**0.17**

Table 4.7: Monthly average global solar radiation on tilted surface ($\beta = 17.5°$) at Colombo

$\boldsymbol{\beta = 17.5°}$			
Month	**Liu and Jordan Model (kWh/m^2/day)**	**HDKR Model (kWh/m^2/day)**	**Percentage difference**
Jan	5.22	5.29	1.38
Feb	5.80	5.85	0.98
Mar	5.96	5.98	0.34
Apr	5.16	5.14	-0.41
May	4.27	4.23	-0.93
Jun	4.22	4.17	-1.23
Jul	4.34	4.29	-1.11
Aug	4.71	4.67	-0.64
Sep	5.01	5.01	0.06
Oct	5.13	5.17	0.75
Nov	4.92	4.98	1.25
Dec	4.41	4.47	1.36
Annual Potential (kWh/m^2/year)	**1796.78**	**1800.38**	**0.20**

Table 4.8: Monthly average global solar radiation on tilted surface ($\beta = 22.5°$) at Colombo

$\boldsymbol{\beta = 22.5°}$			
Month	**Liu and Jordan Model (kWh/m^2/day)**	**HDKR Model (kWh/m^2/day)**	**Percentage difference**
Jan	5.29	5.38	1.76
Feb	5.81	5.88	1.26
Mar	5.87	5.90	0.44
Apr	4.99	4.96	-0.52
May	4.08	4.03	-1.19
Jun	3.99	3.93	-1.59
Jul	4.12	4.06	-1.44
Aug	4.52	4.49	-0.82
Sep	4.90	4.91	0.10
Oct	5.11	5.16	0.98
Nov	4.97	5.05	1.61
Dec	4.47	4.55	1.76
Annual Potential (kWh/m^2/year)	**1765.76**	**1770.88**	**0.29**

Table 4.9: Monthly average global solar radiation on tilted surface ($\beta = 30°$) at Colombo

$\beta = 30°$			
Month	**Liu and Jordan Model (kWh/m²/day)**	**HDKR Model (kWh/m²/day)**	**Percentage difference**
Jan	5.33	5.46	2.37
Feb	5.77	5.86	1.71
Mar	5.68	5.72	0.63
Apr	4.68	4.65	-0.65
May	3.75	3.69	-1.52
Jun	3.62	3.54	-2.10
Jul	3.75	3.67	-1.90
Aug	4.21	4.16	-1.03
Sep	4.69	4.70	0.22
Oct	5.03	5.10	1.39
Nov	4.98	5.09	2.21
Dec	4.52	4.63	2.42
Annual Potential (kWh/m²/year)	**1700.76**	**1709.21**	**0.50**

Table 4.10: Monthly average global solar radiation on tilted surface ($\beta = 40°$) at Colombo

$\beta = 40°$			
Month	**Liu and Jordan Model (kWh/m²/day)**	**HDKR Model (kWh/m²/day)**	**Percentage difference**
Jan	5.28	5.45	3.31
Feb	5.58	5.72	2.43
Mar	5.31	5.36	0.98
Apr	4.18	4.16	-0.70
May	3.25	3.19	-1.78
Jun	3.08	3.00	-2.66
Jul	3.20	3.12	-2.41
Aug	3.71	3.67	-1.18
Sep	4.31	4.33	0.54
Oct	4.82	4.92	2.09
Nov	4.89	5.05	3.17
Dec	4.48	4.63	3.47
Annual Potential (kWh/m²/year)	**1581.52**	**1596.76**	**0.96**

Annual average solar insolation for tilted surfaces was also estimated by using Liu and Jordan isotropic solar radiation model and HDKR anisotropic solar radiation model. The results are shown in the figure 4.22.

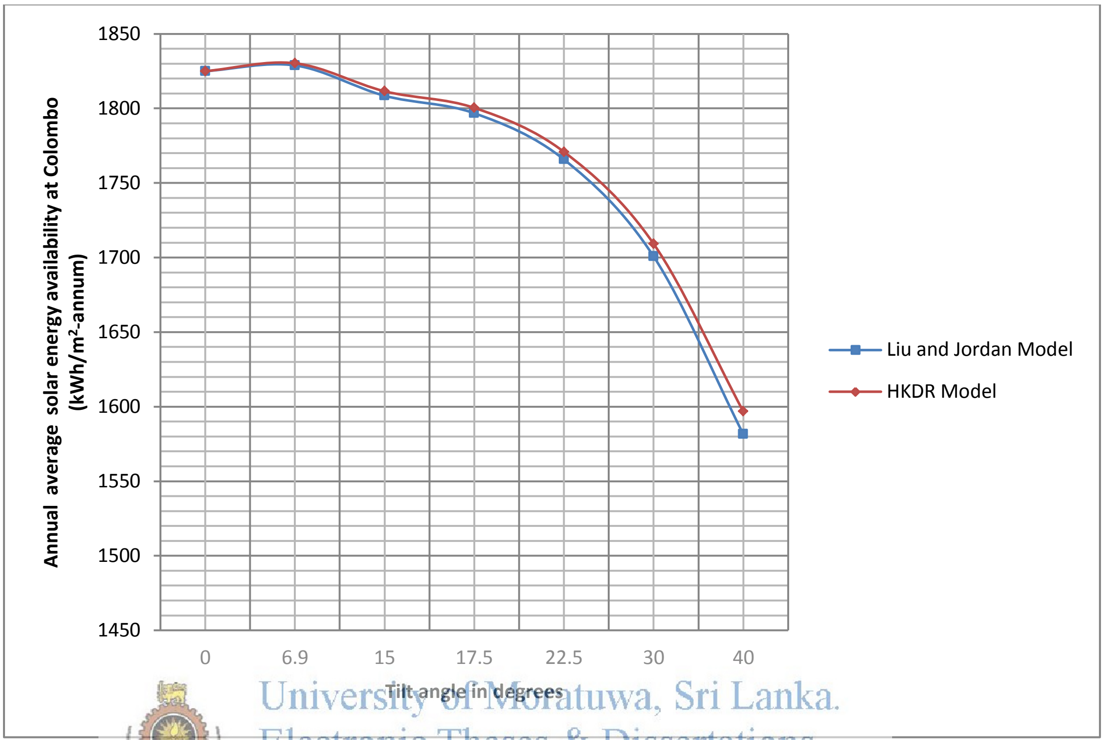

Figure 4.22: Annual average solar energy availability at Colombo

Surface tilt angle should be kept at 6.9° which is equal to the latitude of Colombo for maximum solar resource potential according to the results obtained.

Monthly average optimum surface tilt angles for each month of the year was also estimated by using Liu and Jordan isotropic solar radiation model and HDKR anisotropic solar radiation model. The results are shown in Figure 4.23 through Figure 4.34.

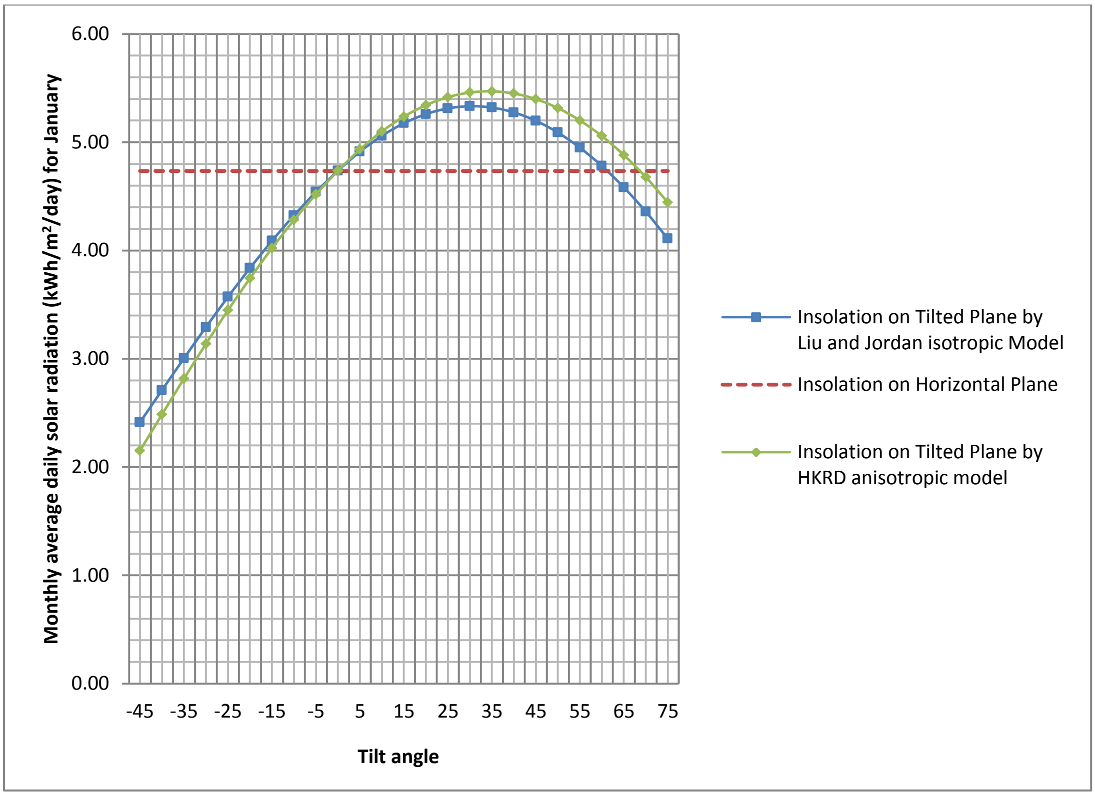

Figure 4.23: Monthly average daily solar radiation for January at Colombo

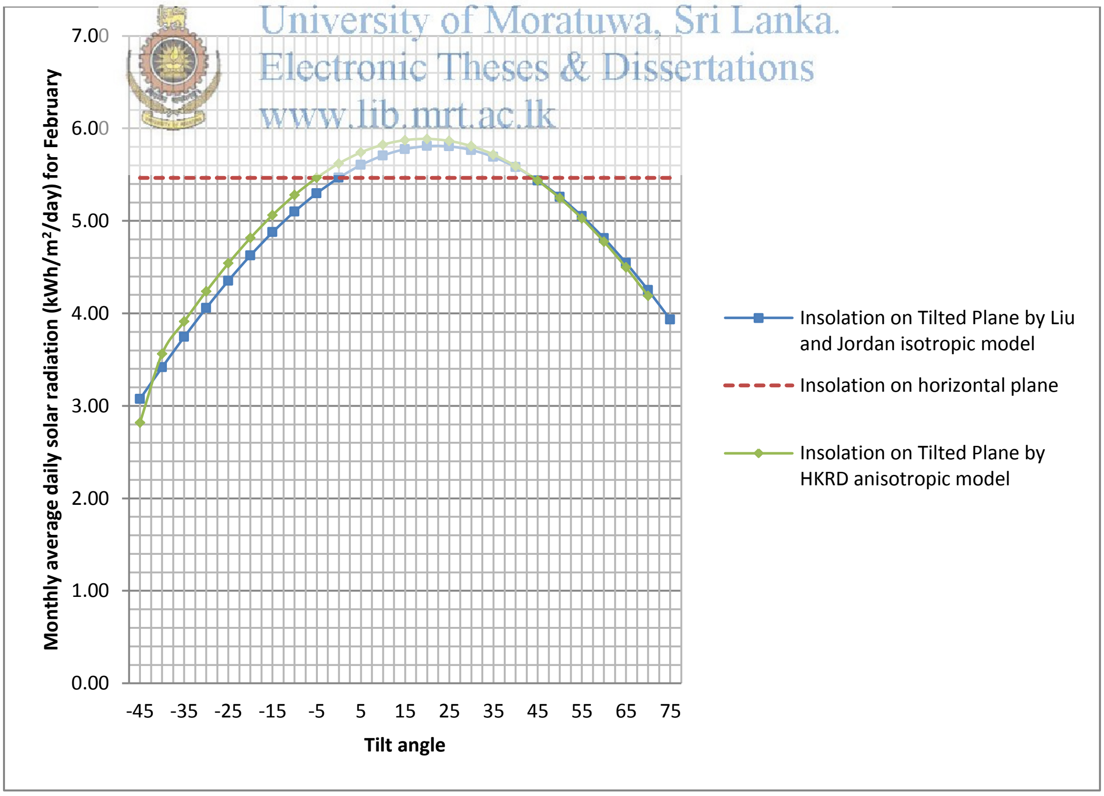

Figure 4.24: Monthly average daily solar radiation for February at Colombo

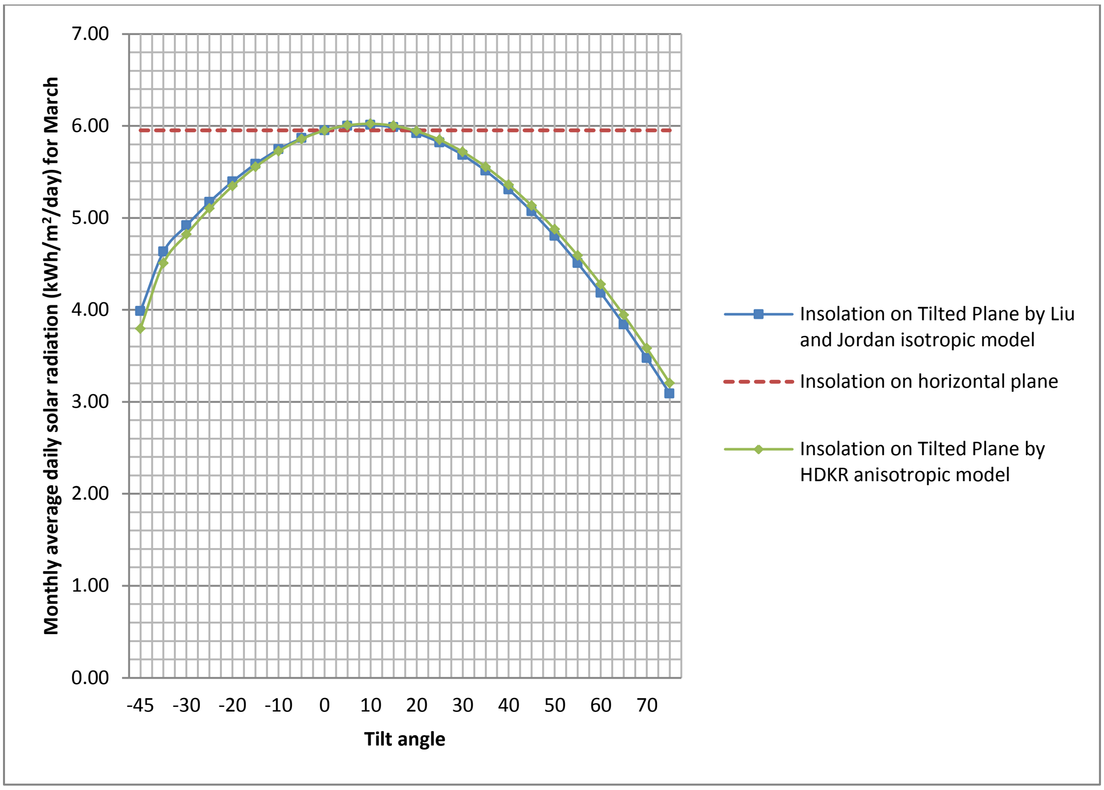

Figure 4.25: Monthly average daily solar radiation for March at Colombo

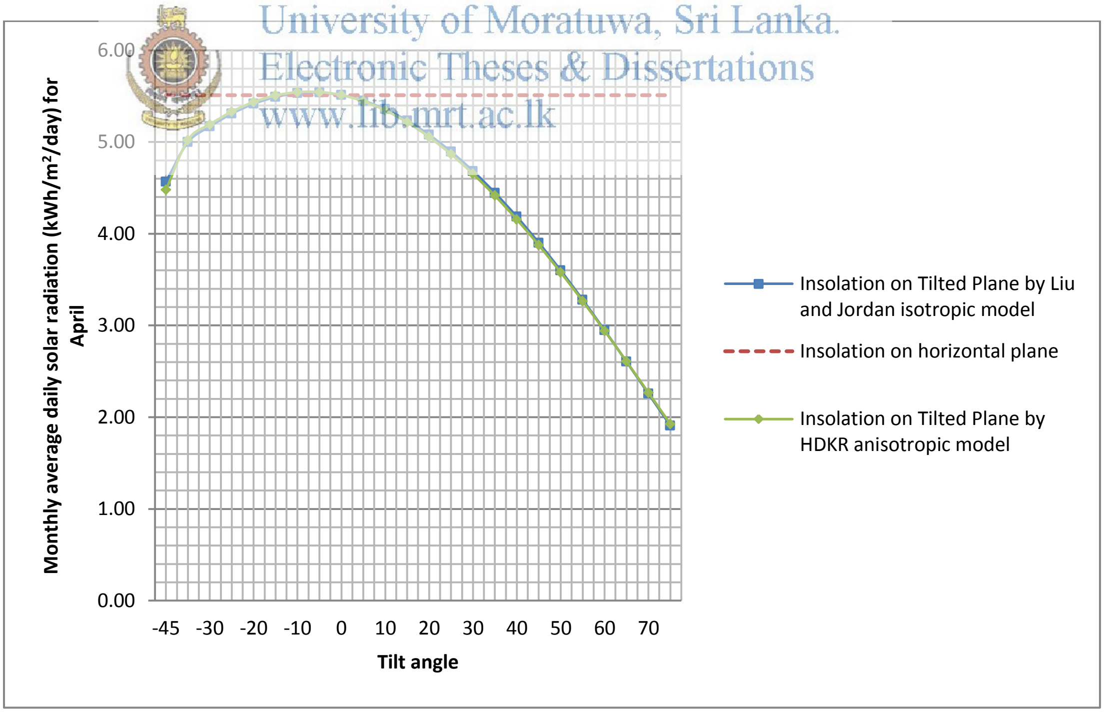

Figure 4.26: Monthly average daily solar radiation for April at Colombo

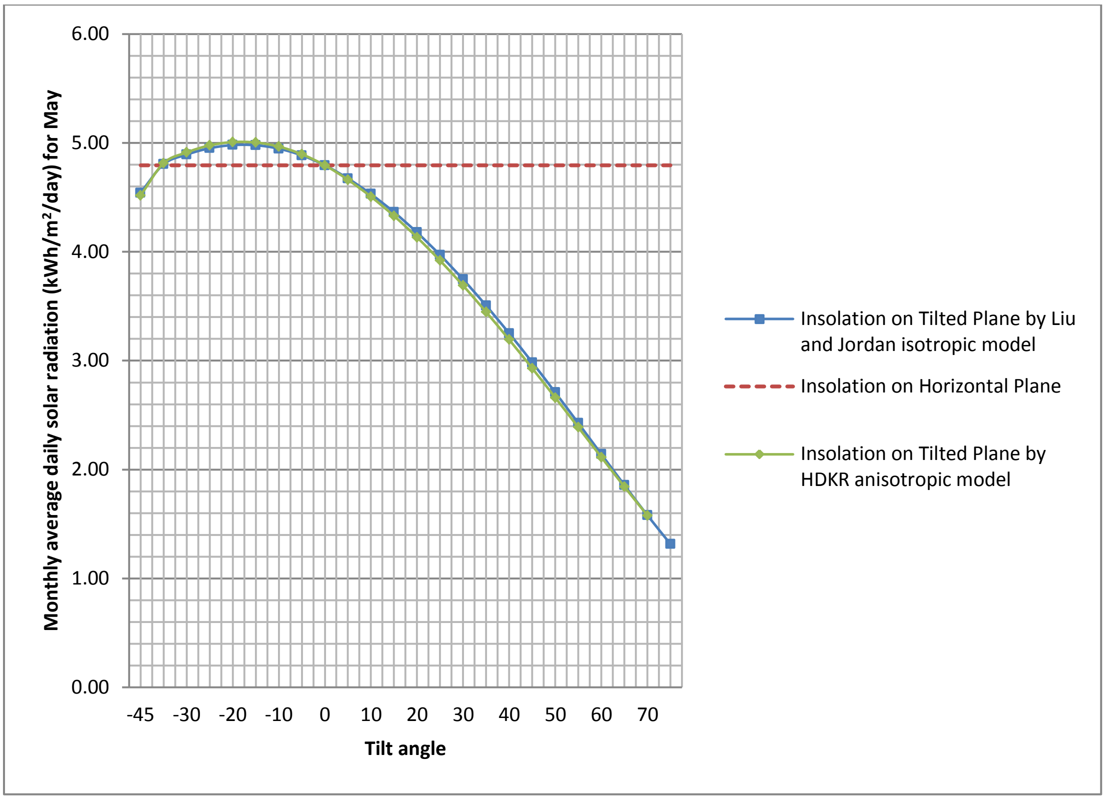

Figure 4.27: Monthly average daily solar radiation for May at Colombo

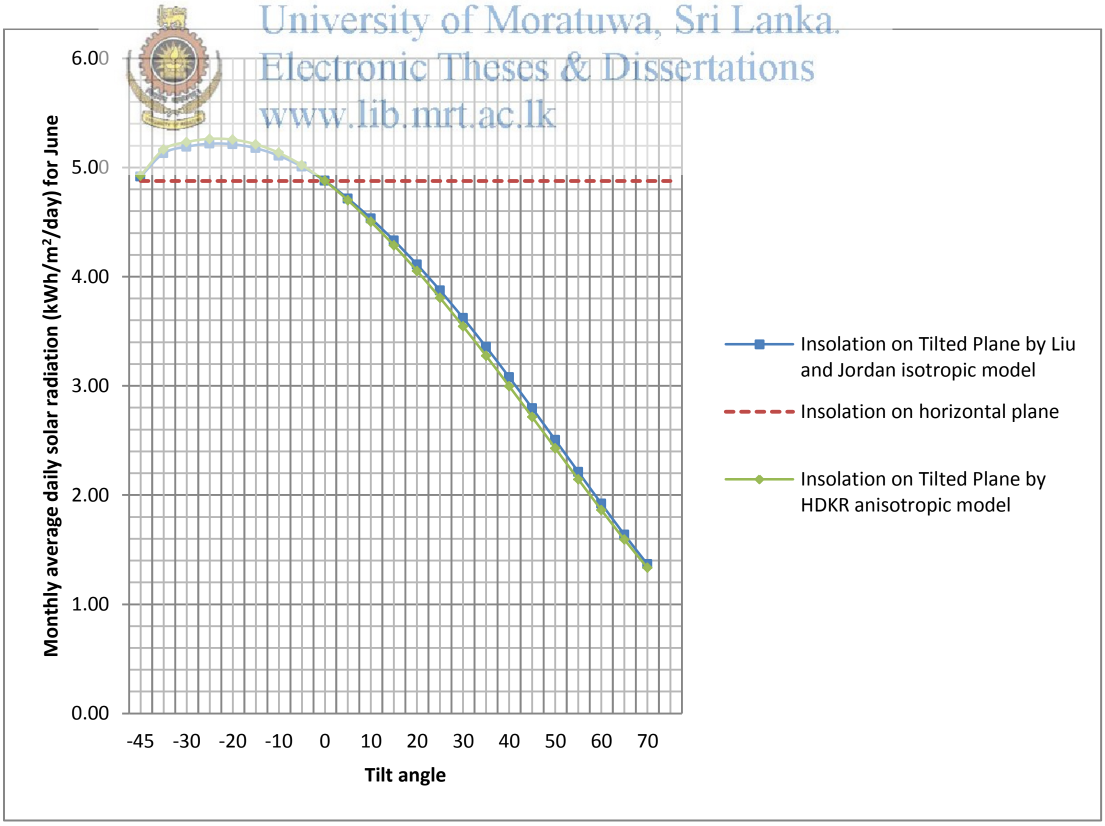

Figure 4.28: Monthly average daily solar radiation for June at Colombo

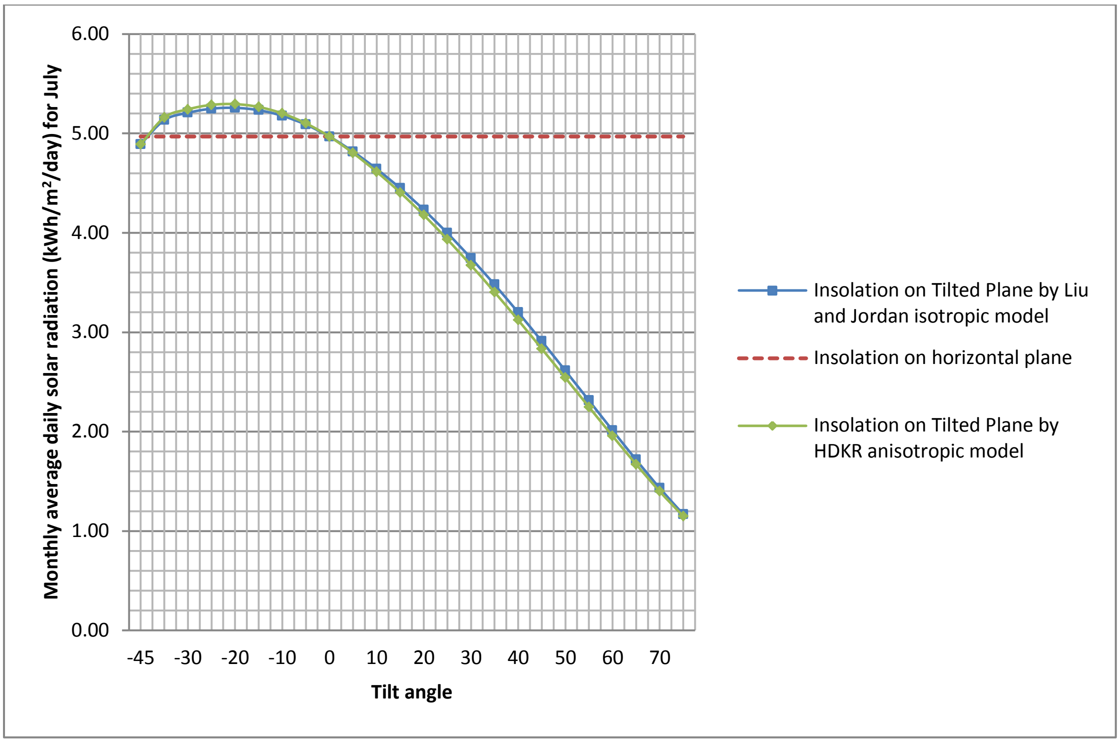

Figure 4.29: Monthly average daily solar radiation for July at Colombo

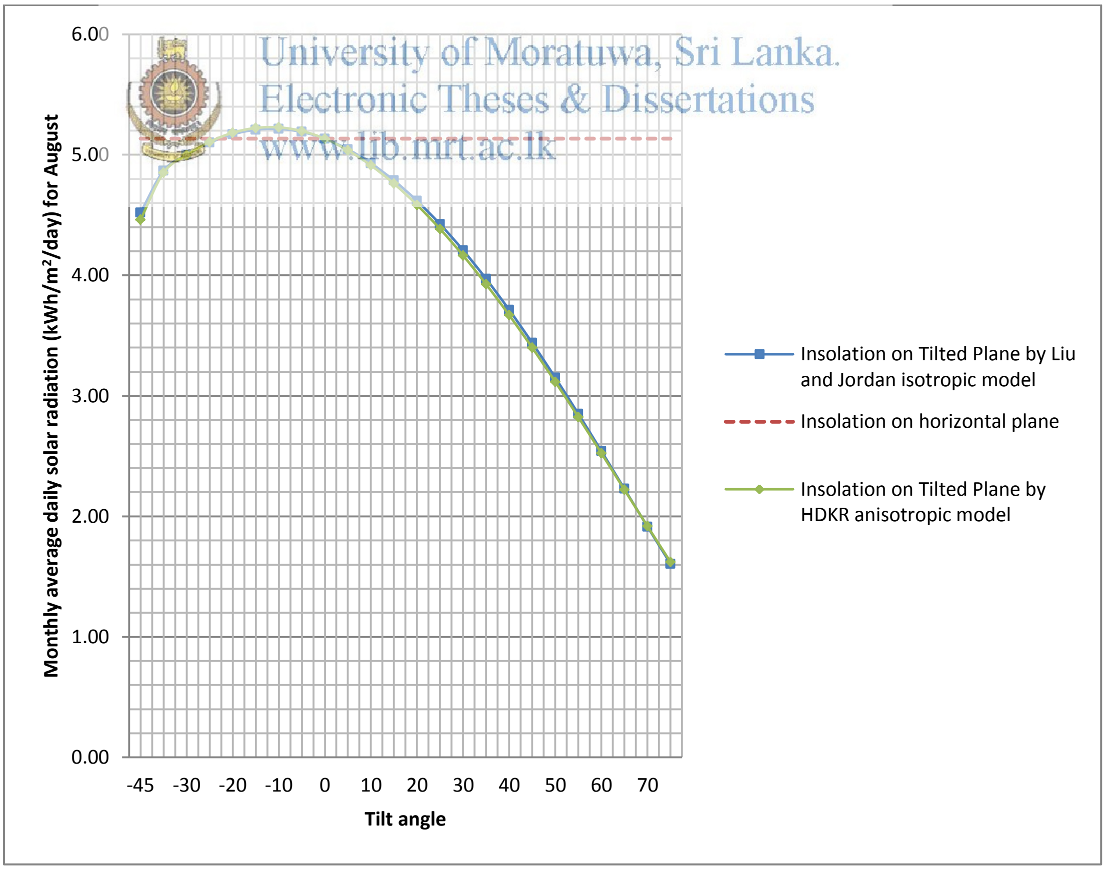

Figure 4.30: Monthly average daily solar radiation for August at Colombo

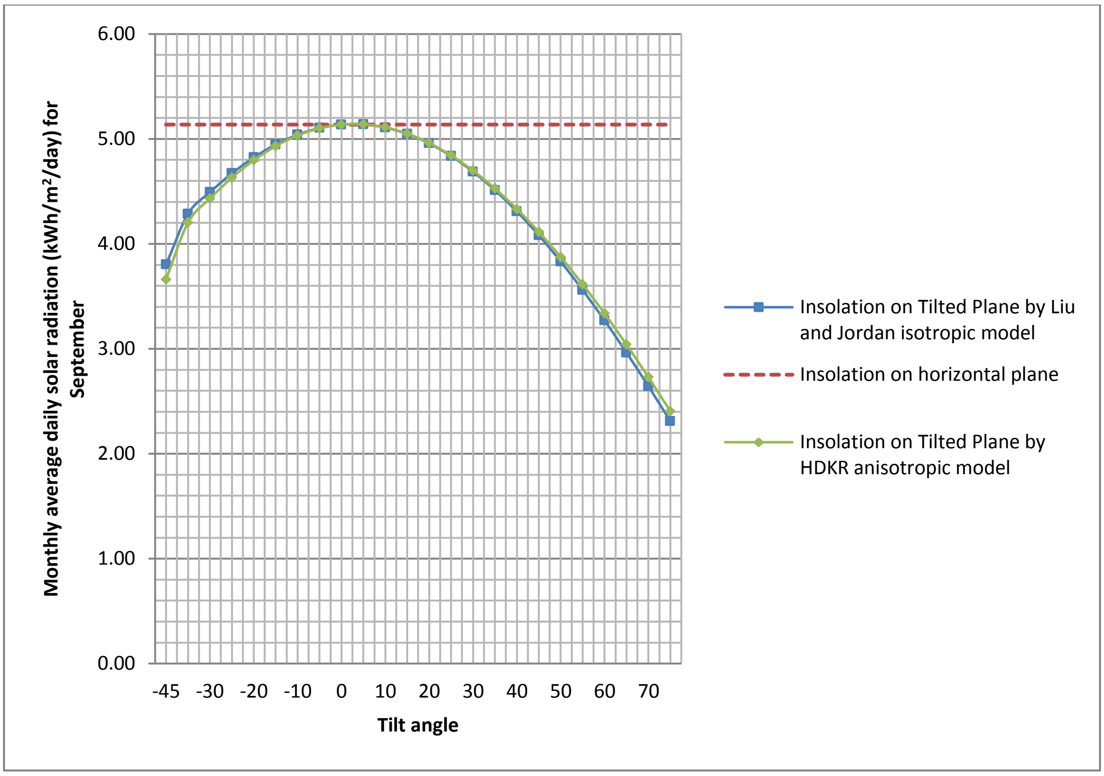

Figure 4.31: Monthly average daily solar radiation for September at Colombo

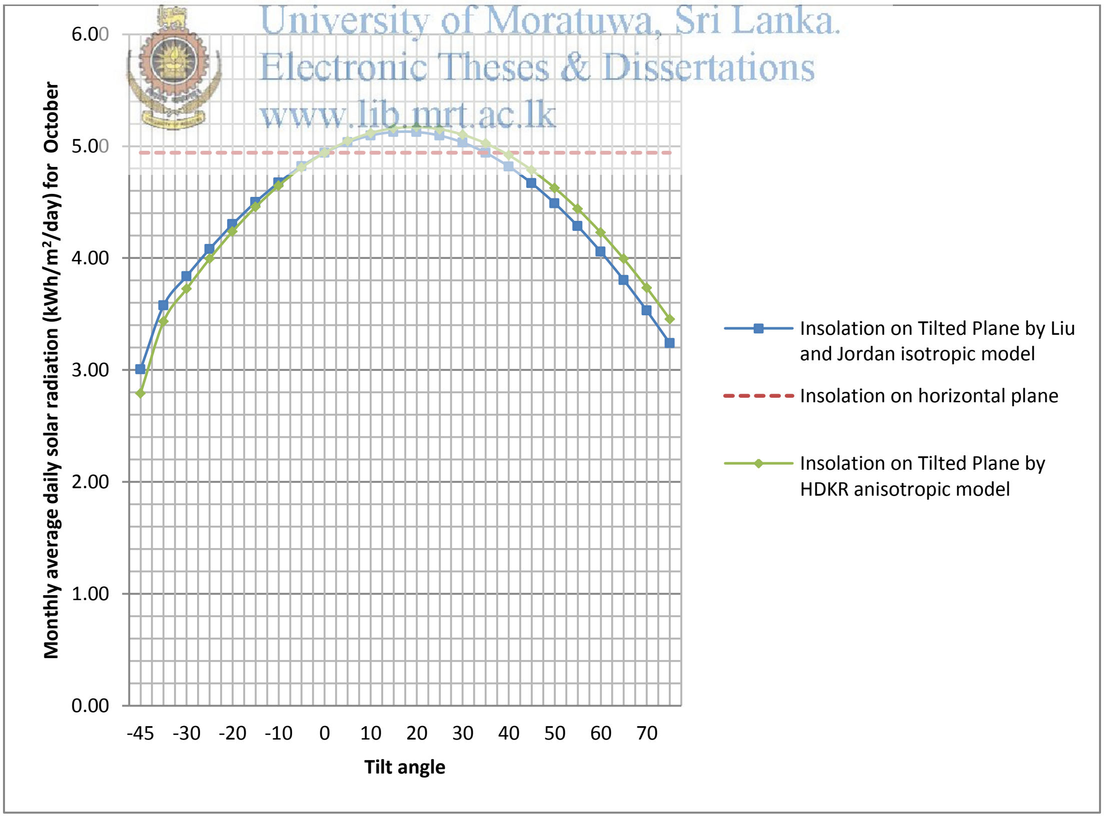

Figure 4.32: Monthly average daily solar radiation for October at Colombo

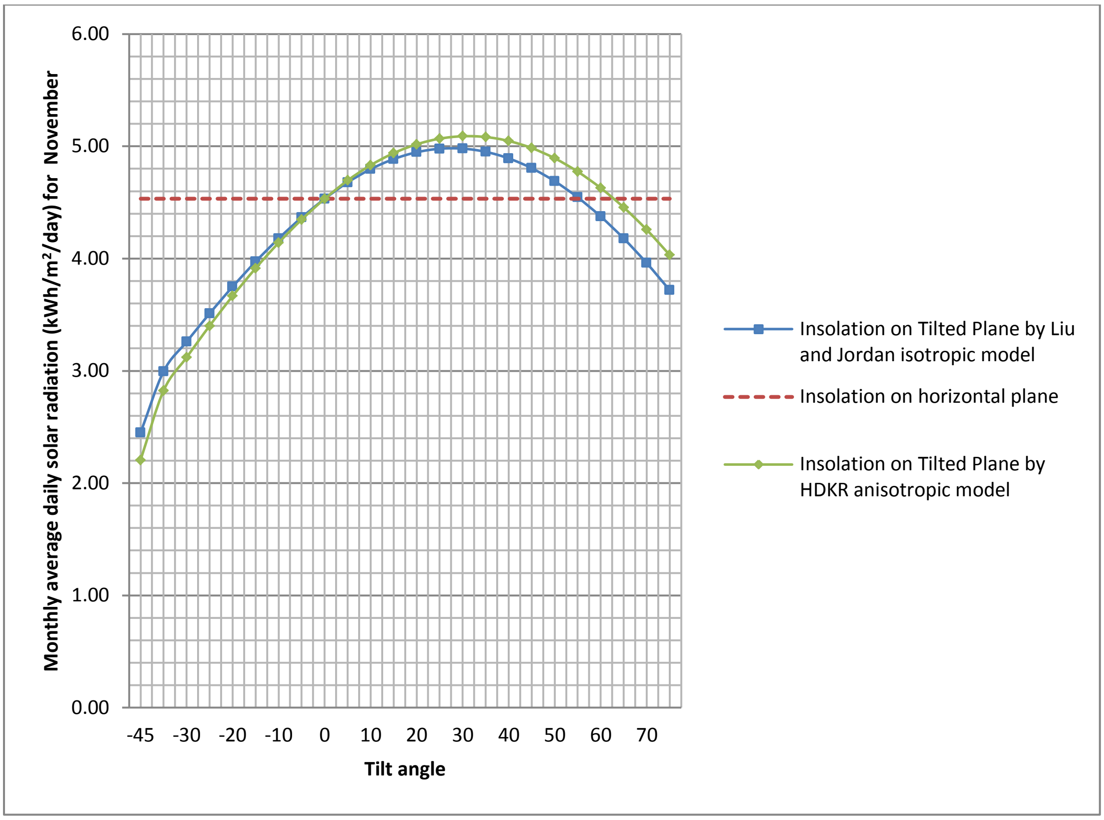

Figure 4.33: Monthly average daily solar radiation for November at Colombo

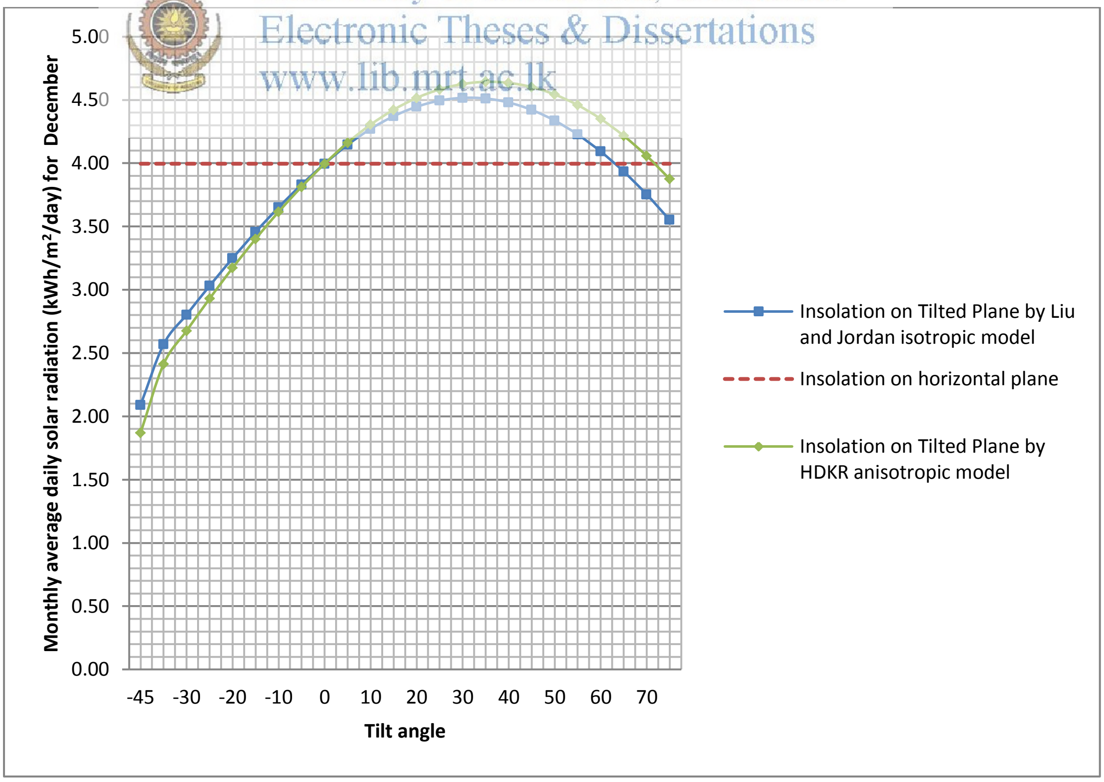

Figure 4.34: Monthly average daily solar radiation for December at Colombo

It was observed that the monthly average optimum tilt angle varies between -25° and +30° and maximum solar insolation on a horizontal surface at Colombo varies between 4.5 and 6.0 kWh/m^2/day.

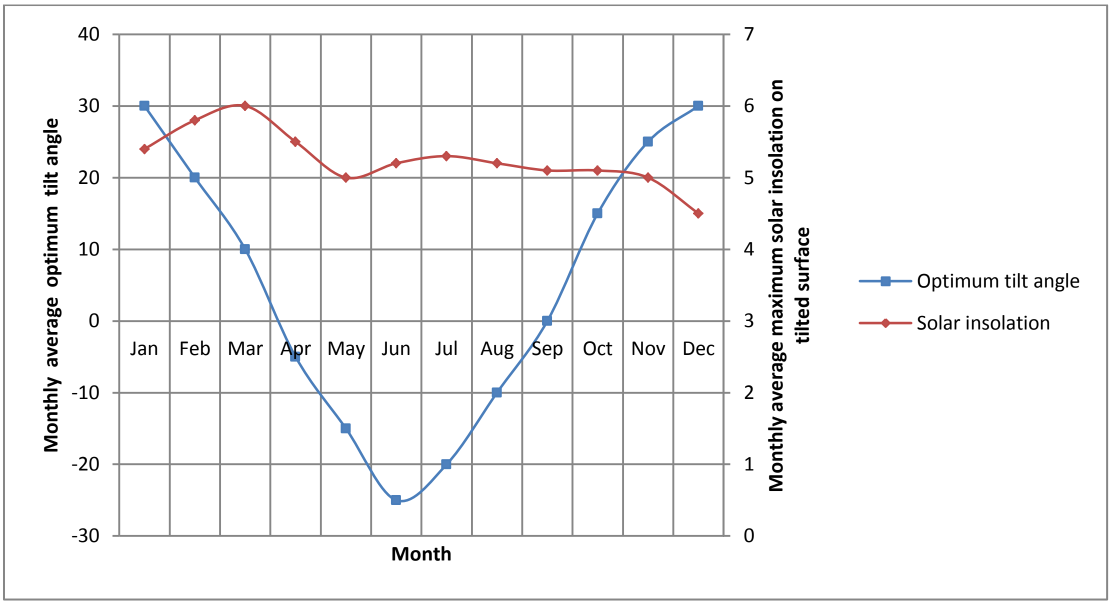

Figure 4.35: Monthly average optimum tilt angle and maximum solar insolation on tilted surface

It is required to tilt the surface towards south for the period from October to March and tilt the surface towards north for the period from April to August and set the surface tilt angle to zero in September to maximize the solar resource potential on tilted surface at Colombo according to the results obtained.

Table 4.11: Monthly average optimum tilt angle and maximum energy availability on tilted surface at Colombo

Month	**Monthly average optimum tilt angle (β) in degrees***	**Monthly average daily solar radiation($\bar{H}$) kWh/m²/day**
January	30	5.4
February	20	5.8
March	10	6.0
April	-5	5.5
May	-15	5.0
June	-25	5.2
July	-20	5.3
August	-10	5.2
September	0	5.1
October	15	5.1
November	25	5.0
December	30	4.5
Annual average maximum solar energy availability at Colombo (kWh/m²)		**1917.9**

(*: +Ve means south faced and –Ve means north faced)

Annual average daily global solar radiation on horizontal surface at Colombo

= 5.0 kWh/m^2/day

Annual average global solar radiation on tilted surface at Colombo

$= 5 \times 365 = 1825$ kWh/m^2

Annual average global solar radiation on tilted surface (set to monthly average optimum tilt angle) at Colombo = 1917.9 kWh/m^2

Percentage of extra solar radiation on tilted surface at Colombo whose tilt angle is set to monthly average optimum tilt angle $= \frac{(1917.9-1825)\times 100\%}{1825} = 5.1\%$

According to the above calculation, it is possible to harness 5.1% extra solar energy on a tilted surface compared to that of a horizontal surface at Colombo if the tilt angle is set to the monthly average optimum value.

CHAPTER 5. CONCLUSION AND FUTURE WORK

An analysis of global, direct and diffuse solar radiation on horizontal and tilted surfaces at Colombo was carried out in this study. A new solar resource potential on a horizontal surface at Colombo was derived by using measured global solar radiation data for the period from 2009 to 2014, obtained from Meteorological Department of Sri Lanka. An Angstrom type empirical linear correlation was developed to estimate the missing solar radiation values of the data set. The derived correlation shows a moderate linear relationship between $\left(\frac{\bar{S}}{\bar{S}_0}\right)$ and $\left(\frac{\bar{H}}{\bar{H}_0}\right)$ with the Pearson's correlation coefficient of 0.57. For the Angstrom type liner relationship 0.29 and 0.38 were proposed as new coefficients for the two variables "a" and "b" respectively. Statistical tests show that the present model exhibits better approximations for the global solar radiation than the previously used solar radiation models.

The estimated monthly average global horizontal solar resource potential varies between 4.00 to 5.95 kWh/m^2/day while the annual average global horizontal solar resource potential is 5.00 kWh/m^2/day. Solar energy can be expected to receive on terrestrial horizontal surface at Colombo consistently throughout the year with a favorable quantity due to the low seasonal variation observed. Calculated monthly average clearness index also varying between 0.42 and 0.57 with its maximum value occurring in March and the minimum value occurring in December. Estimated annual average diffuse solar radiation component on a horizontal surface is 1.82 kWh/m^2/day and the direct solar radiation component is 3.18 kWh/m^2/day which is about 63.6% of the global horizontal insolation at Colombo.

Solar resource assessment was carried out for tilt angles 15°, 17.5°, 22.5°, 30°, and 40° which are the typical roof angles in the Sri Lankan context. Also, the tilt angle equal to the local latitude value which is 6.9° was incorporated to the solar resource assessment. Maximum solar resource potential was derived for the surface tilt angle of 6.9° and it was approximately 1830 kWh/m^2 per annum.

However it is almost equal to the global horizontal resource potential which is approximately 1825 kWh/m^2 per annum. With regarding to other surface tilt angles, it was observed that the solar resource potential has decreased with the increased surface tilt angle. The percentage decrements compared to the global horizontal solar radiation are 0.7%, 1.4%, 3.0%, 6.8% and 14.3% for surface tilt angles of 15°, 17.5°, 22.5°, 30°, and 40° respectively.

To maximize the solar resource potential on a tilted surface with the zero surface azimuth angle and which is free to rotate about its east-west axis, it is required to tilt the surface towards south from October to March and towards north from April to August and set the surface tilt angle to zero in September. It is required to tilt the surface to a maximum of 30° towards the south and a maximum of 25° towards the north within a year. 1918 kWh/m^2 per annum is the maximum solar resource potential on a tilted surface which is 5.1% greater than that of a horizontal surface.

It is required to validate the proposed Angstrom type empirical correlation with actual solar radiation measurements in future. It is not possible to validate the estimated direct and diffuse horizontal solar radiation components due to the unavailability of actual data from 2009 to 2014 at the Meteorological department of Sri Lanka. Assessment of the solar resource potential on tilted surfaces was limited to the tilted surfaces with zero surface azimuth angles. The parameter affected when varying the surface azimuth angle of an irradiated tilted surface is the beam or direct radiation tilt factor. Therefore, it is required to propose a modified procedure to estimate the solar resource potential on tilted surfaces with different surface azimuth angles in future.

REFERENCES

Agarwel, A., Mishra, S. N., & Vashishtha, V. K. (2012). Solar tilt measurement of array for building application & error analysis. *International journal of renewable energy research*, *2*, 781-789.

Ahmad, F., & Ulfat, I. (2004). Empirical models for the correlation of monthly average daily global solar radiation with hours of sunshine on a horizontal surface at Karachi, Pakistan. *Turk J Phys*, 301-307.

Ahmad, M. J., & Tiwari, G. N. (2008). Estimation of hourly solar radiation for composite climate. *Open environmental sciences*, 34-38.

Akinagolu, A., & Ecevit, L. (1993). Modeling of solar radiation. *Journal of Physics*, 269.

Alam, S. B., Das, U. K., Datta, D., & Islam, M. D. (2013). Modeling monthly average daily diffuse radiation for Dhaka, Bangladesh. *International Journal of reaearch in engineering and technology*, 540-544.

Al-Ghamdi, A. A., Al-Hazmi, F. S., El-Sebaii, A. A., & Yaghmour, S. J. (2010). Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia. *Applied Energy*, 568-576.

American Society of HeatingRefrigeration & Air conditioning Engineers, A. (2007). *ASHRAE Hand Book-HVAC Applications.*

Badescu, V. (2008). *Modeling Solar Radiation at the Earth's Surface, Recent Advances.* Springer.

Beckman, W., & Duffie, J. A. (1991). *Solar Engineering of Thermal Processes, Second Edition.* New York: John Wiley & Sons.

Calabro, E. (2013). An algorithm to determine the optimum tilt angle of a solar panel from global horizontal solar radiation. *Journal of renewable energy*, 1-11.

CEB. (2012). *Power Generation Plan 2013-2022.* Ceylon Electricity Board.

Ceylon Electricity Board. (2012). *Power Generation Plan 2013-2022.* Retrieved 10 15, 2014, from http://www.ceb.lk

Choudhury, M. G., Rahman, M. M., Rahuman, R., & Shareef, S. (2000). Computation of Solar radiation tilt factor and optimum tilt angle for Bangladesh. *Indian journal of radio and space physics, Vol 29*, 37-40.

Chow, W. K., & Wong, L. T. (2001). Solar radiation model. *Applied energy*, 191-224.

Collares-Pereira, M., & Rabel, A. (1979). The average distribution of solar radiation-correlations between diffuse and hemispherical and between daily and hourly insolation values. *Solar Energy*, 155-164.

Dissanayake, K., & Vithanage, I. (2011). Solar Energy Development in Sri Lanka, Solar Conference 2011.

Escobedo, J. F., & Souza, A. P. (2013). Estimates of hourly diffuse radiation on tilted surfaces in southeast of Brazil. *International journal of renewable energy research*, 207-221.

Falayi, E. O., Rabiu, A. B., & Teliat, R. O. (2011). Correlations to estimate monthly mean of daily diffuse solar radiation in some selected cities in Nigeria. *Advances in applied science research*, 480-490.

George, R., Gueymard, C., Heimiller, D., Marion, B., & Renne, D. (2003). *Solar Resource Assesment for Sri Lanka and Maldives.* National Renewable Energy Laboratory.

Gowsami, D. Y., Kreider, J. F., & Krieth, F. (1999). *Principles of Solar Engineering.* (2, Ed.) London: Taylor & Francis.

Gracia, A. M., & Huld, T. (2013). *Performance comparison of different models for the estimation of global irradiance on inclined surfaces.* Luxembourq: Joint reseach center of the Europian Comission.

Hay, J. E. (1979). Calculation of Monthly Mean Solar Radiation for Horizontal and Inclined Surfaces. *Solar Energy, Volume 23*, 301-307.

Iqbal, M. (1978). Estimation of the monthly average of the diffuse component of total insolation on horizontal surface. *Solar energy*, 101-106.

Jakharini, A. Q., Kamboh, S. A., Rigit, A. R., & Samo, S. R. (2013). Selection of models for calculation of incident solar radiation on tilted surfaces. *World applied sciences journal*, 1334-1343.

Jayasinghe, M. T., & Sendanayake, S. (n.d.). Estimating incident solar radiation in tropical islands with short term weather data. 108-116.

Jordan, R. C., & Liu, B. Y. (1979). The interrelationship and catechistic distribution of direct, diffuse and total solar radiation. *Solar energy*, 87-90.

Kalogirou, S. A. (2014). *Solar Energy Engineering Processes and Systems* (2 ed.). Kidlington: Acedemic Press.

Kamali, G. A., Moradi, I., & Noorian, A. M. (2008). Evaluation of 12 Models to estimate hourly diffuse Irradiation on Inclined Surfaces. *Renewable Energy*, 1406-1412.

Khatib, T., Mahmoud, M., Mohamed, A., & Sopian, K. (2011). Modeling of daily solar energy on a horizontal surface for five main sites in Malaysia. *Int J Green Energy*, 795-819.

Pandey, C. K., & Katiyar, A. K. (2013). Solar radiation: Models and measurement techniques. *Journal of Energy*, 1-8.

Renewable Energy For Rural Economic Development Project. (2003). *Statistics and reports*. Retrieved 12 02, 2014, from Renewable Energy For Rural Economic Development Project, Sri Lanka: http://www.energyservices.lk/index.htm

Samy, A. K., & Shaffie, A. M. (2013). Performance of Statistical Comparison Models of Solar Energy on Horizontal and Inclined Surface. *International Journal of Energy and Powe, 2*(1), 8-25.

Siyambalapitiya, T. (2009, 01 14). *Net Metering of Electricity has Arrived!* Retrieved 12 02, 2014, from The island oline: http://www.island.lk/2009/01/14/features1.html

SLSEA. (2012). *Sri Lanka Energy Balance.* Sri Lanka Sustainable Energy Authority.

Sri Lanka Sustainable Energy Authority. (2012). *Sri Lanka Energy Balance 2012.* Retrieved 10 12, 2014, from Sri Lanka Sustainable Energy Authority: http://www.energy.gov.lk

Sri Lanka Sustainable EnergyAuthority. (2010). *Sri Lanka Energy Balance 2010.* Retrieved 10 15, 2014, from Sri Lanka Sustainable Energy Authority: http://www.energy.gov.lk

Surface meteorology and Solar Energy. (2005). Retrieved 12 02, 2014, from NASA: https://eosweb.larc.nasa.gov/sse/

Tiwari, G. N. (2013). *Solar Energy: Fundamentals, Design, Modelling and Applications.* Alpha Science International Limited.