



Faculty of Engineering

**Solar Potential and Photovoltaic System Capacity Estimation for Sarawak
based on Empirical Model and *r.sun* Module in GRASS**

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Solar Potential and Photovoltaic System Capacity Estimation for Sarawak based
on Empirical Model and *r.sun* Module in GRASS

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DECLARATION

I certify that except where due acknowledgements have been made the work is that of the author alone. Contents of this thesis are result of work which is carried out during the official commencement date of this master program. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Date :

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ABSTRACT

The study of solar radiation potential is crucial part in the solar energy technology development. In Sarawak, standalone solar PV system is widely used for rural area electrification. Long term and reliable data of solar radiation would be useful in the system energy capacity's estimation. However, the accessibility to the long term and reliable data is still limited in this developing country (i.e. Malaysia). Furthermore, the availability of meteorological stations in Sarawak is very sparse as the country has very wide area. The existing stations are insufficient to provide measured solar radiation of Sarawak thoroughly. Thus, this study focuses on estimating solar radiation potential and system capacity in Sarawak. The estimation of solar radiation potential is estimated locally for Bintulu, Kapit, Kuching, Miri, Limbang, Sibul, and Sri Aman and also for large areas where there are no meteorological stations. For the areas with meteorological stations, the solar radiation prediction is done by using empirical estimation models. Measured air temperature, relative humidity, cloud factor and solar radiation are obtained from Malaysian Meteorological Department (MMD) collected within a period of 2010-2015. Linear regression and multiple linear regressions method are developed based on the measured data and were compared with Hargreaves-Samani and Bristow-Campbell models. The performances of the empirical models are tested with statistical validation of mean bias error (MBE), root mean squared error (RMSE), t-test and correlation coefficient (R). Multiple linear regressions performed the best among the models. Meanwhile, solar radiation study for areas without meteorological station is done by using *r.sun* module of Geographical Resources Analysis Support System (GRASS). The maps of monthly solar radiation (global and overcast) and annual system

capacity are developed. During the month of June, the average solar radiation is the highest for both global solar radiation (6675.92W/m^2) and overcast solar radiation (5391W/m^2).

Keywords: Solar radiation, solar photovoltaic capacity, empirical model, *r.sun* module

**Anggaran Potensi Radiasi Solar dan Kapasiti Sistem Fotovoltaik di Sarawak berdasarkan
Kaedah Empirikal dan Modul r.sun GRASS**

ABSTRAK

Kajian potensi radiasi solar adalah bahagian penting dalam penerapan teknologi tenaga solar. Sistem fotovoltaik digunakan untuk elektrifikasi di kawasan luar Bandar Sarawak. Data sinaran suria jangka panjang adalah berguna dalam anggaran kapasiti tenaga sistem. Namun, akses data tersebut adalah terhad di negara membangun seperti Malaysia disebabkan kerosakan dan kehilangan sebahagian data. Malah, ketersediaan stesen meteorologi di Sarawak amat jarang kerana kawasan yang luas. Stesen-stesen sedia ada di Sarawak tidak cukup untuk menyediakan data radiasi solar dengan teliti. Fokus kajian ini tertumpu kepada anggaran potensi radiasi solar dan kapasiti sistem di Sarawak. Anggaran potensi radiasi solar dilakukan secara tempatan di Bintulu, Kapit, Kuching, Limbang, Miri, Sibu dan Sri Aman dengan menggunakan model anggaran empirikal. Malahan, anggaran meliputi kawasan luas dan tiada stesen meteorologi turut dilakukan. Data yang diukur seperti suhu udara, kelembapan relatif, faktor awan dan radiasi solar bagi tempoh 2010-2015 telah diperolehi dari Jabatan Meteorologi Malaysia (MMD). Kaedah regresi linear dan kaedah regresi berganda linear dibangunkan berdasarkan data diperolehi dan dibandingkan dengan model Hargreaves-Samani dan Bristow-Campbell. Model empirikal tersebut diuji dengan pengesahan statistik seperti ralat min keliru (MBE), ralat kuadrat kuantiti akar (RMSE), ujian t dan koefisien korelasi (R). Hasil perbandingan model mendapati kaedah regresi berganda linear adalah terbaik. Manakala, kajian radiasi solar meliputi kawasan luas dan tiada stesen meteorologi dilakukan dengan menggunakan modul r.sun di Geographical Resources Analysis Support System (GRASS). Peta radiasi bulanan (global dan mendung)

dan kapasitas sistem tahunan telah dibangun. Hasil kajian mendapati radiasi solar pada bulan Jun adalah yang paling tinggi untuk global (6675.92W/m^2) dan mendung (5391W/m^2).

Kata kunci: Radiasi solar, kapasitas sistem fotovoltaik, model empirikal, modul r.sun

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LIST OF ABBREVIATION

E_O	Eccentricity coefficient
CF	Cloud factor
DEM	Digital Elevation Model
GRASS	Geographical Resources Support System
H	Terrestrial radiation
H_B	Beam radiation
H_D	Diffuse radiation
H_O	Extraterrestrial radiation during a day
I_O	Extraterrestrial radiation during a given hour
$I_{O,H}$	Solar radiation on Earth horizontal plane
I_{SC}	Solar Constant
K_C	Clearness Index (computed from cloud factor)
K_{COMP}	Computed Clearness Index
K_{MEAS}	Measured Clearness Index
K_T	Clearness Index
MAD	Monthly Average Daily
MBE	Mean Bias Error
MMD	Malaysian Meteorological Department
MPE	Mean Percentage Error
MRM	Multiple Regression Method
N	Number of day
NTE	Nominal Terrestrial Environment

RH	Relative Humidity
RMSE	Root Mean Square Error
SoDA	European Solar Radiation Data2
SRTM	Shuttle Radar Topographic Mission
T_{LK}	Linke Turbidity Index
δ	Earth Declination
ΔT	Air temperature difference
Θ_z	Solar zenith
ϕ	Latitude
ω_s	Sunrise hour

CHAPTER 1

INTRODUCTION

1.1 Research Background

In the urban-industrial areas of developing nations, the availability of fossil fuels has increased for expansion of economic production and personal consumption. However, the fossil fuel distribution is unevenly distributed throughout the world. Currently, the world uses a lot of energy. It is accounted that average energy usage is 17 terawatt (2.5 kW per person) with world energy market of \$3 trillion/year [1] which commonly generated from non-renewable resources. Malaysia is one of developing country that relies on fossil fuel where the electricity supply made up of 74% of natural gas and 88% of coal [1–3]. To meet the growing demand, the environment and sustainability of energy sources are at tolls [4].

Global energy demand will increase at the rate of 1.6% and 65% increases will be due to developing countries by 2030 [1, 5, 6]. As a consequence, global warming which gives negatives impact (i.e. glacier receding, biodiversity loss) occurs [7]. In addition, fossil fuel is non-renewable energy which will deplete in future. These two factors, threat of global warming and fossil fuels depletion, have become the driving forces towards renewable energy development.

Development of renewable energy is important to reduce the greenhouse gases (GHG) while accommodating electrification to urban areas and remote areas. Every country's economic and environmental well-being is highly dependent on the shift of sustainable, reliable, abundant and relatively clean energy resources. Solar energy technology, for instance,

has high potential to substitute conventional energy sources as it is able to generate electricity without emitting global warming pollutants and have no risk of fuel price spikes.

1.2 Statement of Problem

The solar technology field uses detailed information concerning meteorology and solar radiation to optimize the technology selection (e.g. solar photovoltaic system, concentrated solar power and solar heating system) and performance, hence, secure financing. Sarawak is a tropical country that has significant solar resources but curtailed radiation monitoring network and analyses of the meteorological data [8–10]. Furthermore, availability of long term and reliable solar radiation data (e.g. sunshine duration and daily global solar radiation) is very scarce and often limited due to the absence of measurement or maintenance issues. The missing data may occur for some parameters in meteorological data set while other parameters are complete. Therefore, estimation using suitable solar radiation estimation models, which have been developed using historical data from the weather station, is needed to fill the missing data.

The amount of the solar radiation energy depends on the location, time of the year and atmospheric conditions. Several solar radiation models have been developed based on the meteorological data obtained from weather station or satellite measurements. However, the solar radiation estimation is too local since they rely on the weather stations and unable to estimate the radiation over a wide area [11–13]. The estimation of solar radiation over wide area enables the study of solar radiation at locations where the solar monitoring networks is unavailable.

The implication of estimating the solar radiation over a wide region allows to a better assessment of PV system development. Planning of optimal exploitation of solar energy is

required before sitting of solar panel units. The potential obstacle that prevents optimal exploitation of solar energy is intermittency. Solar power at any location is intermittent: it varies over times that are imperfectly predictable [14]. Geographical mismatches (e.g. terrains, elevation, land cover) between sunlight are creating trade-offs in solar panel system sitting decisions. Estimation of solar irradiation potential with its capacity in a geographical area can be mapped out via Geographical Information System (GIS) for better assessments of the renewable energy. Hence, prediction of solar irradiation to exploit the source should be done.

1.3 Research Question

A study on sun-earth relation is required to understand solar potential estimation. A variety of studies on global solar radiation (or known as solar radiation received on earth surface) has been carried out over the time. However, long-term solar radiation measurements on specific areas are relatively scarce due to equipment maintenance cost or malfunction. The earliest study is done in Kuala Lumpur [15] yet no specific study has been conducted in Sarawak. The issues that become questions in this research are:

- i. How does the existing meteorological data incorporated with the solar radiation estimated?
- ii. What is the best empirical model used to estimate the solar radiation at each meteorological stations? How will the estimation model performs?
- iii. What is the intensity of incoming solar radiation at the locations without weather monitoring network?
- iv. How the local environment does affect the incoming solar radiation?

- v. What is solar photovoltaic system capacity generated within a year based on the solar radiation received?

1.4 Research Objectives

The challenges faced as discussed in the statements of problems become focus of this research work. Therefore, this work will present the solar radiation map which, later, allows the assessments of the solar PV system. The research area of this project will be focus mainly in Sarawak, Malaysia. The objectives of this research project are:

- i. To investigate the current solar radiation estimation model.
- ii. To estimate solar radiation potential and solar system capacity using mathematical model approach.
- iii. To develop GIS mapping for solar radiation potential map and PV system capacity assessment for Sarawak.

1.5 Research Significance and Expected Outcomes

The primary motivation of this research work is to estimate solar radiation and solar PV assessments using GIS approach. The estimation of solar potential is based on existing knowledge of sun-earth relation and meteorological data from selected region. The significance of this research work is presented as following:

- i. Estimation of missing solar radiation data using existing meteorological data in solar radiation model.
- ii. Calibration and evaluation of empirical coefficient of solar radiation model.
- iii. Estimation of solar radiation at areas that are not covered by meteorological stations.

- iv. Development of GIS to estimate solar potential and its capacity in Sarawak using open software, Geographical Resources Analysis Support System (GRASS) GIS software.

At the end of this project, the expected outcomes are:

- i. Mathematical approaches for solar irradiation estimation.
- ii. GIS maps of solar radiation potential and its capacity maps.

1.6 Thesis Outlines and Research Scope

This research focuses on investigating solar radiation potential and its capacity in Sarawak. The outlines of this work are provided as following:

- i. Chapter 1 Introduction provides the introduction of this study background, research statements of problem, objectives and expected outcomes of this research.
- ii. Chapter 2 Literature Review focuses on the works that has been done by other researchers besides brief theoretical background concerning the solar radiation characteristics and solar radiation attenuation factors. In this topic, prospectus of solar energy technology and its potential are discussed based on the current findings and views of researchers.
- iii. Chapter 3 Methodology covers the methods, based on information in Chapter 2, employed in this research work, data collection, missing solar radiation data estimation at the local meteorological stations and development of monthly solar radiation potential and annual solar capacity maps.
- iv. Chapter 4 Result and Discussion gives the result obtained from the analysis and presented in tabular and graphical forms. The solar radiation potential of the study area was determined by analyzing availability and characteristics of the solar

energy throughout the year and location, in addition of the most probable solar radiation received for electricity generation annually. Monthly maps of solar radiation potential and annual solar capacity are also provided in this chapter.

- v. Chapter 5 Conclusion covers overall achievements and conclusion of this research work along with the future work recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

The purpose of this topic is to review current energy statuses and solar technology prospect in Malaysia. Further reviews on the methods in solar radiation forecasting such as empirical estimation models, machine learning tools, satellite analysis model and geographical information system (GIS) application are included in this chapter. The study of solar capacity and atlas maps developed are reviewed for the purpose of this research.

2.2 Malaysia Energy Status

Before implementation of Five Fuel Diversification Policy in 1999, Malaysia has been greatly depended on oil as primary energy resources but subsequently, oil contribution in energy mix (source of energy mix are oil, natural gas, hydro, coal and renewable energy) dropped drastically from 87.9% in 1980 to 4.2% in 2000 [16]. In 2010, it was projected down to 0.2% [17]. Natural gas and coal have become main contributors in energy mix in Malaysia. However, usages of the fossil fuels and natural gas have taking tolls to the environments. According to the World Bank, the carbon dioxide emissions from the burning of fossil in 2011 were 7.9 metric tons per capita [1]. British Petroleum (BP) reported that the GHG emitted in 2011 is 221.14 metric ton and increased to 230.28 the next year [2].

Figure 2.1 shows the power mix evolution in Malaysia. Oil was a major contributor in power mix till 1990. Driven by the change in energy policy due to oil crisis in 1970s, electricity generation companies quickly turned to natural gas and coal. The share of natural

gas in power generation rose exponentially and reached a maximum of 74% of the total power generation in 2000 compared to 20% in 1990 [18]. Coal market share was in a range of 5-12% of the total power generation from 1990 to 2000.

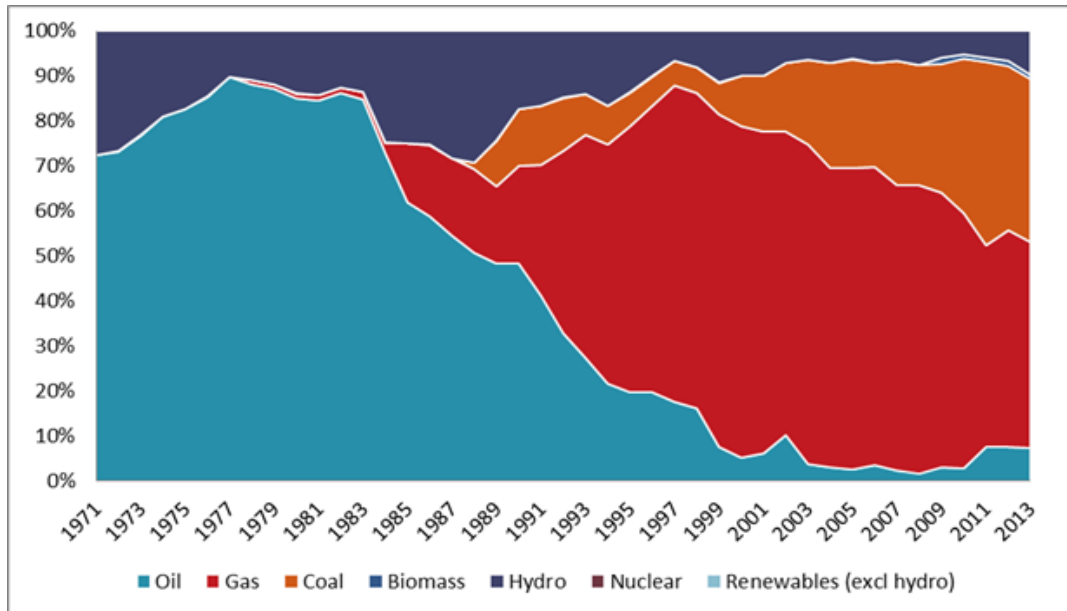


Figure 2.1: Power Projection by Sources [1]

Energy flows development in Malaysia is mainly influenced by four factors which are described as follows [19]:

- i. **Energy Demand:** The energy supply will be affected by energy demand due to its variation in consumption. In end-use sector, the energy is consumed to provide energy services such as in areas of manufacturing sector, transportation sector and domestic sectors (e.g. residential, agricultural and commercial) [20, 21]. Each main end-use sector accounted approximately one third of energy consumption. Electricity (49%), oil product (41%), natural gas (7%) and coal (3%) were the main energy supply forms for end-use [19].
- ii. **Resources Availability:** The structure of energy demand is greatly dependent on energy resources availability. The lack of the resources may cause restriction in energy

demand. In 2011, natural gas share received a big blow due to supply shortages. The generation from natural gas in 2011 was only 58 TWh [22]. The supply shortages left power generation companies with multi-million losses as the gas fired plants had to switch to expensive distillates to maintain the electricity supply. Natural gas shortages led to an increase in the generation from both coal (36%) and oil (7%) in 2013 [23–25]. Malaysia is still greatly depends on natural fuels to generate power and vast amount of coal primary supply were imported [19, 26–30].

- iii. Choice of Technology: Few factors (e.g. environmental impact, social acceptance and optimal energy production) are required to comply before the adoption of different technologies in energy supply sector. Chosen technology to generate energy also depends on the availability of resources. In Fifth Fuel Diversification Policy (5th FDP), energy mix is implemented to sustain future energy supply. Furthermore, [31] concluded that the amount of carbon emissions generated from this energy mix is lower than the 100 million tons limit set for the total system of energy supply.
- iv. Policy Adjustment: The main purpose of energy policy is to ensure the sustainability of energy security. Thus, policy makers need to implement policies and enact acts to regulate the energy supply and consumption. Previous energy policy has been adjusted in order to reduce dependencies on conventional energy resources.

2.3 Solar Energy Development and Advancement

Every country's economic and environmental well-being is highly dependent on the shift of sustainable, reliable, abundant and has relatively clean energy resources. Solar energy technology is one of the technologies that have high potential to substitute conventional energy

sources as it able to generate electricity without emitting global warming pollutants and have no risk of fuel price spikes.

There are several applications for solar energy, for instance: electricity generation, photochemical, solar propulsion, solar desalination, and room temperate control. The collection of solar energy and its transfer to electricity energy will have wide application and deep impact on society, so it has attracted the attention of the researchers. According to energy expert, solar energy growth is forecasted to project by 30% in 2050 which 10% of it will be contributed by solar thermal technology [32].

Nowadays, solar energy technology grows rapidly in worldwide. Developed countries (i.e. America, Europe, Australia, China and Japan) have applied the photovoltaic technology for development of the countries. Meanwhile developing countries (i.e. Malaysia, Thailand, and Vietnam) are starting the use of PV technology. Photovoltaic technology is growing fast due to the environmental awareness. Rapid growth of photovoltaic technologies has led to the decline of PV module cost from 20% to 22% [14]. The cost of PV has dropped dramatically as the industry has scaled up manufacturing and incrementally improved the technology with new materials [33]. Thin-film module prices fluctuated below USD 1/watt (W), with prices between USD 0.84 and USD 0.93/W available at the beginning of 2012 [34]. The prices of crystalline silicon (c-Si) modules are more varied, but were typically in the range USD 1.02 to USD 1.24/W for the most competitive markets [34].

The renewable energy has increasingly become cost-competitive but still expensive compared to its conventional counterparts [21]. Driven to decrease the cost of solar photovoltaic, an international team has simplified steps to create highly efficient silicon solar cells by applying a new mix of materials to standard design. The cell design, called dopant free asymmetric heterocontact (DASH), uses combination of moly dioxide and lithium oxide

to achieve high efficiency in converting sunlight energy without process of doping [35]. Unlike old generation of PV cell (ideal thermodynamic efficiency for ideal single-homojunction cell is ~31% according to [36]), the designed cell average efficiency is more than 19% [35, 37]. Taking the advantage of technology advancement, the cost of renewable energy technologies can be diminished through innovation of technology efficiency [21].

2.4 Solar Energy Prospect and Development in Malaysia

In Malaysia, tropical climates make the application of solar photovoltaic to be versatile and possible form for electrification [38]. Utilization of solar PV systems in Malaysia can be extended due to relative high amount of solar radiation received throughout the year based on the world standards [39]. Figure 2.2 shows the distribution of the solar radiation annually throughout the country. Statistical analysis of solar radiation that was performed by [40] found that Kota Bharu experiences a larger variation of total radiation during northeast monsoon while high radiation received during southeast monsoon. Moreover, the high solar radiation conditions usually from 11.00am to 3.00pm [41]. Malaysia's solar radiation amount ranges from 0.61kWh/m²/day in December to 6.8 KW/m² in August and November [42]. There are a few places in east Malaysia receive the highest amount of solar radiation with an average of exceed 3KW/m² throughout the year [39, 43-46].

In the 7th Malaysia Plan, the government has highlighted that a third of the Government's total allocation of RM469 million was for rural electrification programs under the provision of solar powered installations for rural and remote communities [47]. However, [47] highlighted few limitations and barriers in the implementation of the solar system such as public awareness and system prices. A huge allocation had been dedicated for solar PV systems implementation based on the 9th Malaysia Plan (9MP). A Malaysian Building

Integrated Photovoltaic (MBIPV) project had been announced on 25th July 2005 and it was planned to end by 2010 [46]. The project consists of three categories: BIPV demonstration, national “SURIA1000” and BIPV showcase. The BIPV project has been announced to increase the grid-connected PV system installations up to 850MW by 2030 (and more than 8000MW by 2050) [25,48-50].

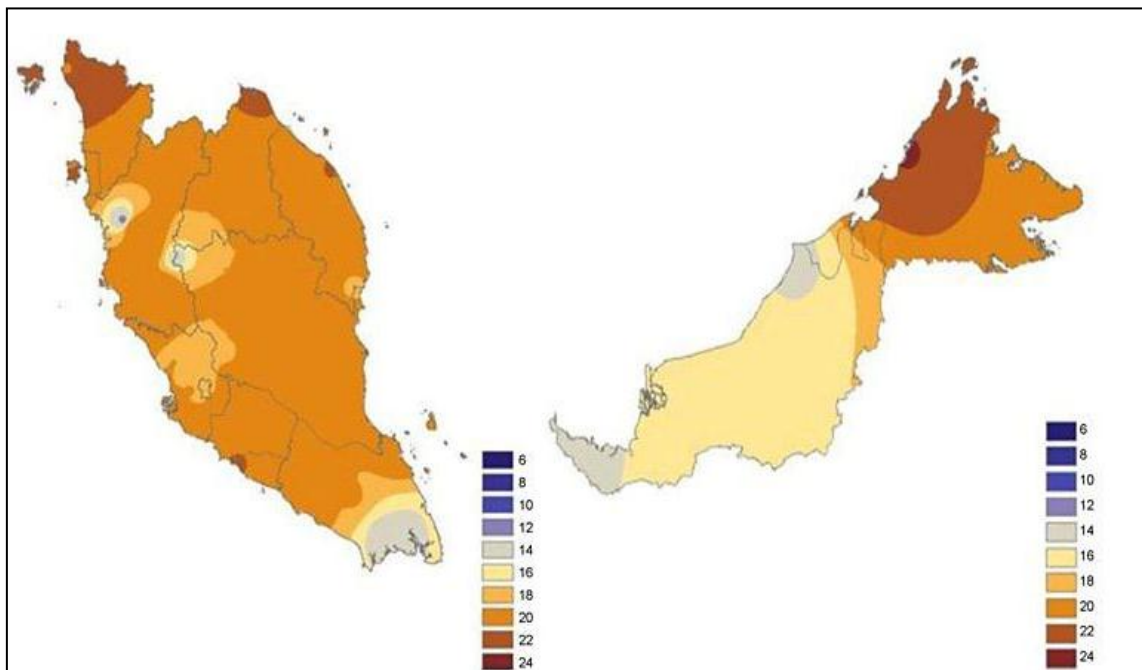


Figure 2.2: Annual Average Solar Radiation MJ/m²/day [46]

The renewable energy programs are implemented to support renewable energy policies, besides introducing financing scheme and tax incentive. The establishment of Green Technology Financing Scheme (GTFS) in 2010 is a program that implemented under the National Green Technology Policy that launched in July 2009. This scheme is a soft loan (approval amount of RM3.5 billions) that offers 60% guarantee of the financing amount and a rate of 2% on the interest and aiming to accelerate the expansion of green investment [52-55]. Malaysian Green Technology Corporation (GreenTech Malaysia) and Credit Guarantee Corporation Malaysia Berhad (CGC) are the agencies tasked with administering the Scheme. GreenTech Malaysia is responsible for the promotion, assessment, certification and

monitoring of producers and users of green technology under the Scheme, while CGC administers the guarantee and rebate payments [53, 55].

Another initiative is introduction Green Technology Tax Allowance (GITA) which was announced in 2014 Budget Announcement by Malaysian Prime Minister. This incentive is one of the ways to strengthen green technology development in Malaysia which enhance local investment. Through the tax incentives, investment up to 100% on qualifying capital expenditure is incurred to the approved green technology project and non-project which has acquisition of qualifying green assets for five years.

Besides, The International GreenTech and Eco Product Exhibition and Conference Malaysia (iGEM) series, a platform for key drivers within the Malaysian Government's Green Technology mandate, was positioned to take the lead and gather industry players and professionals from the public and private sectors (local and international) to explore and grasp the lucrative opportunities in the green market [56]. The iGEM 2015 has recorded that RM 198 billion worth of business leads. To continue the legacy iGEM 2016 is expected to strengthening Malaysia as a Green Technology Hub for ASEAN region and focuses on energy, transport, building, waste technology and management as well as clean water technology and management.

Meanwhile in research and development field, there are five major areas of solar technology development by local universities in Malaysia. The research works are including inverters, PV concentrators, solar cells fabrications and characterization, hybrid systems and energy conversion tracking systems [46]. The research in the fields is majorly funded under the national science and technology funds by the Ministry of Science, Technology and Innovation (MOSTI) which is put in charge of research, telecommunication and information technology.

2.4.1 Obstacles in Solar Energy Development

In a study by Jacobson and Delucchi [57], it is technically feasible to power the world with water power, wind power and solar power (WWS) by 2030. Such powers are biofuels, nuclear power or coal with carbon capture. Nonetheless, converting conventional energy to renewable energy technologies would face difficulties such as cultural barriers, budget estimation difficulties, and lack of proper mentalities [58, 59]. An analytical approach based on bottom-up assessment of national renewable energy plans called REmap predicted that in 2030 the penetration of this technology is relatively low at global level (exceptions for biomass) [21, 60]. The shifting phase from conventional energy resources to the alternative resources would be slow and accompanied by hindrances in term of infrastructure, economy, socio-acceptance, technical and financial [61].

According to Panuily [62], the barriers faced by countries are differs either in technologies or in term of non-technical. In Malaysia, not all region of it are ready in term of infrastructure and economic. Although the potential of renewable energy resources (solar energy, biomass and hydro energy) has been identified in Sabah and Sarawak, method of Feed-in-Tariffs (FiT) implementation and payment has yet to be identified [63]. Unlike Peninsular Malaysia, Sabah and Sarawak has different economic activities, people affordability, geography, and demography. Through the discussion in Fourth National Energy Forum, Sabah faced delay in implementation of FiT due to postponement of 1% FiT levy on electricity tariff [63]. The current harnessing of solar energy is under its actual potential found out that there are two significant barriers (i.e. awareness and economics) [64].

Meanwhile in Sarawak, the system is not applicable as Sarawak is a state with its own legislation and regulations governing their electricity supply. The implementation of FiT in the country is not feasible due to sparse population and large area. The extension of grid wires

through difficult terrains and thick jungle to remote village is unpractical in term of economical in [65]. The average village household in the most rural areas in Sarawak uses 41 kWh/month compared to 205kWh/month for urban Sarawak households [66]. Standalone photovoltaic (SAPV) system is common system used to electrify the rural areas. The technology is able to generate power due to its availability and topological advantages for local power supplies [11].

In Batang Ai, Sarawak, 200 villagers of two long houses are electrified under Sarawak Energy's corporate social responsibility (CSR) initiatives to provide basic lighting and there are 2216 villages in Sarawak yet to be electrified due to difficulties of terrains (as shown in Figure 2.3) [67].

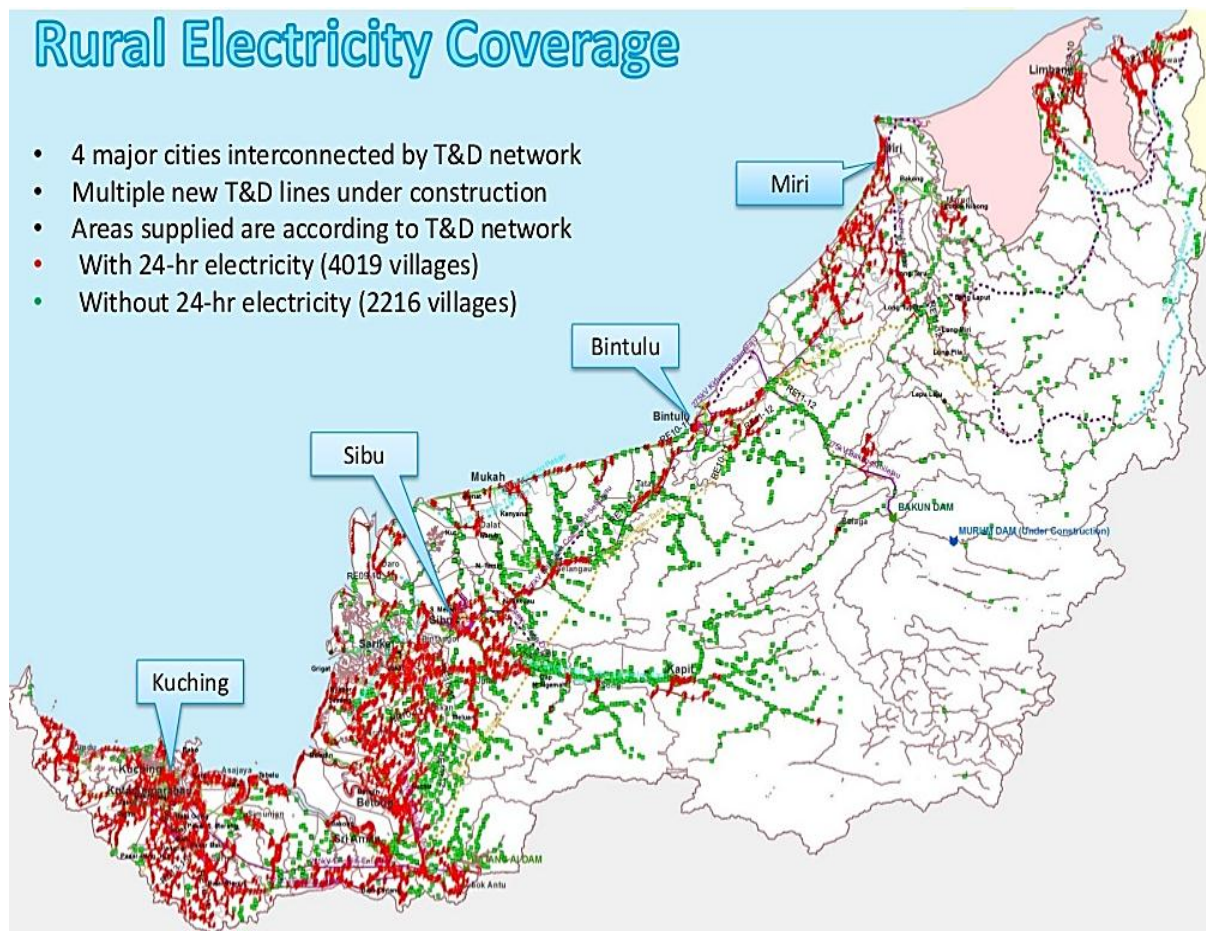


Figure 2.3: Rural Electrification Scheme via Grid Connection [68]

2.5 Solar Energy Resource

Solar energy resource, which originates from the sun, propagates to earth surface in the form of light and heat energy. The majority of light that strikes the earth sustained a thermonuclear fusion reaction that is able to produce energy equivalent to one trillion atomic bombs per second [14]. The reaction, thus, heats the sun's surface and emits radiation which propagates to the earth surface through the vacuum of space.

A solar resource is significantly larger than any other resources in the earth which are approximately 174,000 terawatts (TW) of power and continuously delivered via solar radiation to the upper level of earth's atmosphere [69, 70]. The global average power consumption is roughly 17TW [14]. By comparing the global power usage with the solar resources, the solar energy that strikes the earth in an hour enough to supply all power demand for a year.

Although the solar energy is a large size, it is dispersed. It is distinguished using its intermittency. At a given location on the earth's surface, the solar resource suffers from stochastic unpredictability (fluctuations over time spans of minutes to days resulting from cloud covers and weather systems) and deterministic variability (predictable fluctuations over time spans of days to months resulting from earth's diurnal rotation and seasonal changes). According to United Nation Development Programs in its 2000 World Energy Assessment [71, 72], the annual potential energy of solar energy was 1575-49387 EJ which is larger than the total world energy consumption within a year in 2012. The consumption in 2012 was 559.8 EJ [71].

2.5.1 Extraterrestrial Solar Radiation

The sun is singular resource of renewable energy that emits as large electromagnetic radiation. The intensity of the solar radiation that is leaving the sun at instantaneous is relatively constant with value of 1367 W/m^2 [73]. The amount of solar energy that is received on a unit area of surface (outside the atmosphere) which is perpendicular to the direction of the radiation is known as solar constant, I_{SC} . Throughout the year, the extraterrestrial radiation on the normal plane on N th day of the year is varies in the range of 3.3% which can be calculated as in Equation 2.1, where I_O is extraterrestrial radiation on normal plane, N is the day of the year and I_{SC} is solar constant [74].

$$I_O = I_{SC} \left[1 + 0.033 \cos \left(\frac{360N}{365} \right) \right] \quad \text{Equation 2.1}$$

The total radiation, H_o , incident on the surface that is placed parallel to the ground during a day is shown in Equation 2.2. The equation is obtained from the integration of Equation 2.3. The derivation of this equation can be found in [73].

$$H_o = \frac{24}{\pi} \times I_{SC} E_o \times (\sin \delta \times \sin \phi) \left[\frac{\pi \omega_s}{180} - \tan \omega_s \right] \quad \text{Equation 2.2}$$

Where:

H_o	=	extraterrestrial irradiation on horizontal surface
I_{SC}	=	solar constants
E_o	=	eccentricity coefficient
δ	=	earth declination ($^\circ$)
ϕ	=	latitude ($^\circ$)
ω_s	=	sunrise hour

2.5.2 Solar Energy Reduction Factors

Sunlight takes 8.3 minutes to reach the earth which is separated by 150 million kilometres from the sun [69]. Sunlight strikes upper level of the earth atmosphere with average intensity of 1367 watts per square (W/m^2) at instantaneous which is known as the solar constant. Earth's atmosphere consists of layers that are transparent to visible light. Interaction with the atmosphere has important effects on the intensity, spectrum, and diffusivity of solar radiation. The intensity varies by $\pm 3.3\%$ over a year as the earth's slightly elliptical orbit [14]. There are also minor variations less than $\pm 0.1\%$ over the sun's 11-year sunspot cycle [75].

The maximum radiation can be received by the earth is during the atmosphere is clear. Most of the solar devices perform the best during that time. For the clear sky, the solar radiation that falls on the earth surface at maximum intensity is defined as clear sky global solar radiation.

Figure 2.4 shows the reduction in average solar power density from different factors. Upon reaching the earth surface, the major factors that cause variation in solar intensity are [14]:

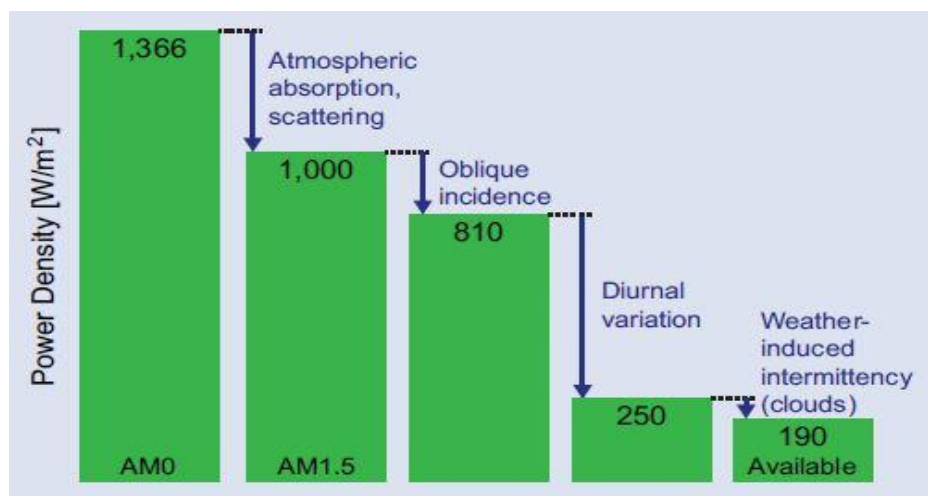


Figure 2.4: Reduction in Average Solar Power Density from Different Factors [14]

i. Atmospheric Attenuation Effects

Sunlight that travels from the top of the atmosphere to earth's surface is scattered and absorbed by air particles and clouds during the transition to the earth surface. The characteristics of sunlight spectrum scattering are dependent on the particle size at the atmosphere where scattering by small particles (e.g. air molecules) is known as Rayleigh scattering while by aerosol (e.g. dust) is known as Mie Scattering [76]. Thus, the spectrum of solar energy and scattering effects by particles in the air gives colours to the sky [76].

ii. Obliquity across Different Latitude

Energy from the sunlight is not spread evenly over the earth. The annual of incoming solar insolation is varies from tropical latitude to polar latitude and one hemisphere is always dark when the other of it is receiving solar insolation. When the Earth is receiving sunlight, the surface of equator receives the most sun rays as it is perpendicular to the incoming light path. The sun rays meet earth at smaller angles, as it spread over the longer surface from the equator to poles, the solar intensity is decreasing. The variation of solar intensity on the earth surface across different latitude is caused by cosine effect which defined in Equation 2.3.

$$I_{O,H} = I_{SC} \times \cos \theta_Z \quad \text{Equation 2.3}$$

Where:

$I_{O,H}$ = Solar insolation on horizontal surface of Earth.

I_{SC} = Solar constant

θ_Z = Solar zenith angle

iii. Diurnal and Seasonal Variation

From Figure 2.4, the intensity of solar radiation at a location is further reduced by the effect of diurnal and seasonal variation. Diurnal variation is known as rotation of the earth on its own axis produces day and night while seasonal variation is positions of the sun around the sun which affects the seasons and changes of day length throughout a year

iv. Weather Changes

The changes of the weather are often related to the existence of clouds. Weather condition is able to stop but a small amount of solar radiation from reaching earth's surface for many consequence days. Nevertheless, researchers focus on the study of the effect of cloud cover on the solar radiation that reaching the earth surface. Primarily low, thick clouds reflect the solar radiation and cool Earth surface while high, thin clouds enable the sun radiation to warm the Earth surfaces [77, 78].

2.5.3 Terrestrial Solar Radiation

As the solar radiation enters through the atmosphere, it is absorbed, reflected, scattered, diffused and some part of it is transmitted directly. Thus, the intensity of the radiation is lower at the ground level. Global solar radiation (consists of beam, diffuse, and reflected radiation components) is the amount of solar radiation being received at the earth surface [73, 74]. Often, beam radiation is perceived as direct solar radiation that comes directly from the sun; whilst diffuse radiation is appear from all direction.

The maximum radiation can be received under cloudless and clear skies, when most of solar devices can operate or at least above threshold level. The degree of sky clearness can be quantified by human observation of cloud cover or sunshine duration measurements.

However, based on [73] the condition of the sky can be defined as the ratio of solar radiation incidents on horizontal surface to the extraterrestrial that falls on horizontal surface. The Equation 2.4 shows the definition of the clear-sky index, K_T .

$$K_T = \frac{H}{H_0} \quad \text{Equation 2.4}$$

The terrestrial solar radiation or global solar radiation is a function of solar altitude, site altitude, albedo, atmospheric transparency and cloudiness [79]. The value of H can be either estimated or based on weather observation. Routine measurement and observation of the daily radiation is often done by government agency such as meteorological department.

Meanwhile, the estimation method of solar radiation is depending on the variable used and often used when the measurement of radiation is unavailable [80]. Empirical model is widely used and based on correlations derived through regression analysis [74]. It can be range from simple, single variables to complex combination of variables. There are physically induced correlations between the solar radiation values and meteorological variables. The solar radiation prediction requires measured hourly solar radiation to perform the best [45, 81, 82]. However, in most cases the data type is not available for long term. Thus, long-term average daily radiation data can be used [74] for the purpose. The review of different types of solar radiation prediction methods is available in Subtopic 2.7

2.6 Solar System Capacity

The energy is harnessed using solar technology. However, with current technologies, generation of the electricity depends on the technology to harness the sunlight. There are three primary technologies that are used to harness the energy from the sun: (i) Solar Photovoltaic System, (ii) Concentrated Solar Power and (iii) Solar Heating and Cooling. The technology can be deployed either through distributed generation (the equipment is located to where

energy is used) or utility-scale installations (energy is produced as a central power plant.). The technology is always evolving to harness optimal sun energy.

Solar system generator is one of the resources that dependent on the time of day, weather pattern and season. The capacity is defined as the rated output of the plant when operating at maximum output [83]. The power output cannot be control unlike the conventional generators which can be control to meet demands and the interruptions of the plants may leave insufficient power. The element that is important in all renewable energy plant systems is its capacity value. Capacity of the system is potential maximum power output that can be generated or known as net capacity [84].

In designing maximum capacity solar system plant, there are several elements that every system integrators considers. The factors that affect solar PV system capacity are: types of solar PV material, environmental conditions (solar radiation, ambient temperature, and relative humidity), operating temperature of PV cells, orientation of the sun and shading effects, power lost due to wiring and power point, soiling and PV panel contamination. Brief description will be focuses on types of solar photovoltaic, intensity of solar radiation received, operating temperature of PV cells and orientation of the sun and shading effects in following Subsections.

2.6.1 Types of Photovoltaic Material

The PV panel is made to endure harsh (e.g. marine, tropic, artic and desert) environment. Therefore, the choice of PV material, such as material composition and structure, is crucial in system designing and performances. The properties of material used often took consideration of four main categories: electrical, mechanical, chemical and thermal [85]. In term of mechanical aspect, the PV panel is designed to support variety of mechanical

forces, both static and dynamic [86]. Meanwhile, the chemical properties of the panel are related to material degradation and deterioration due to corrosion and ultraviolet radiation exposure. The thermal properties of PV panel are concerned of thermal expansion and contraction due to thermal stresses.

Lastly, the electrical property of PV panel is focuses on the materials used to produce the current. PV cells are made from semi-conductor materials and are treated to produce an electric field with positive on one side (backside) and negative on the other side, when being exposed to the sunlight. As solar energy (photons) hits the PV cell, electrons are hit loose from the atoms in the semiconductor material (include silicon, gallium arsenide, copper indium diselenide, cadmium telluride, and indium phosphide), hence, generating electron–hole pairs. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons are captured in the form of electric current called photocurrent.

All technologies related to harnessing solar energy for a direct electricity generator are described as photovoltaic. But, this technology is subdivided into crystalline, thin film, compound semiconductor and nanotechnology depending on atomic structure of the cell. The atomic structure of a PV cell can be monocrystal, multiycrystalline, or amorphous [87].

i. Crystalline technology

This technology is the first generation of PV technology which employs silicon to produce solar cells. Despite the advancement of PV cell technology, it is not obsolete rather it is constantly being developed to improve its capability and efficiency. The structure of the cell can be mono-crystalline, poly-crystalline, and emitter wrap through (EWT) which are under the umbrella of silicon crystalline structures.

ii. Thin film technology

Thin film technology has potential to reduce the PV array cost by lowering material and manufacturing. In this technology, pieces of semiconductors are sandwiched between glass panels to create the modules. The thin film panels are created by depositing thin layers of certain materials on glass or stainless steel (SS) substrates, using sputtering tools [88, 89]. The thickness of the deposited layers which are barely a few micron (smaller than $10\mu\text{m}$) thick allows the creation of flexible PV modules, thus, lowering the manufacturing and materials cost due. Furthermore, the ability to deposit many different materials and alloys has allowed great improvement in efficiencies. There are four kinds of thin film cells have emerged: amorphous silicon cell (multiple-junction structure), thin polycrystalline silicon on a low cost substrate, copper indium diselenide/cadmium sulphide hetero-junction cell, and the cadmium telluride/cadmium sulphide hetero-junction cell [89].

iii. Compound semiconductor technology

Compound semiconductor is a complicated stack of crystalline layers with different band gaps that are made to absorb most of the solar radiation [88, 89]. Each type of semiconductor has different properties of band gap energy which enables the absorption of light efficiently, at a certain wavelength, hence absorption of electromagnetic radiation over a portion of the spectrum. Initially, light strikes a wide band-gap layer producing a high voltage therefore enabling lower energy photons transfer to narrow band-gap sub devices which absorb the transmitted infrared photons.

iv. Nanotechnology

The application of nanotechnology in PV cells reduces limitation of solar cells efficiencies. Nano scale components have the ability to control energy band-gap which

will provide flexibility and inter-changeability [90, 91]. Semiconductor quantum dots (QD) is a starting point to increase the cells conversion efficiencies. Through the technology, the band gaps is adjustable specifically to convert also longer- wave light and thus increase the efficiency of the solar cells. As material systems for QD solar cells, III/V-semiconductors and other material combinations such as Si/Ge or Si/Be Te/Se are considered [92]. Potential advantages of these Si/Ge QD solar cells are: i) higher light absorption in particular in the infrared spectral region, ii) Compatibility with standard silicon solar cell production (in contrast to III/V semiconductors), iii) Increase of the photo current at higher temperatures, iv) Improved radiation hardness compared with conventional solar cells.

2.6.2 Solar Radiation

Solar energy system, such as photovoltaic (PV) system, concentrates solar power (CSP) and solar heating cooling (SHC) system, is used to extract the solar radiation. The amount of solar radiation that's being extracted can define the performances of solar system. Each of the solar energy system has its own extracting plates which has its own material properties and designs. Typically, PV system uses flat-surfaced panel to collect the radiation before converting it to electrical supply and the cells absorb up to 80% of the incident solar radiation [93], however, only small part of the absorbed incident energy is converted into electricity depending on the conversion efficiency of the PV cell technology used [94]. The power output performance of the solar PV system is depends on the arbsorptance of solar radiation on the solar cell. There are different types of semiconductor that's has different absorption coefficient (rate of particular solar radiation wavelength penetrated and absorbed by semiconductor) are being used as the PV panel.

With a typical maximum solar insolation of 800W/m^2 (based on standard operating condition) a PV module is able to produce a maximum of about 100W/m^2 [95]. The efficiency of a solar PV module depends on the environmental condition (i.e. air temperature) and the dust contamination of the surface of the PV cells. The reduction of a solar PV cell efficiency due to high air temperature is estimated to 8% for Malaysia conditions and the reduction in efficiency due to dust contamination is assumed to be 2% [95].

Photovoltaic semiconductor converts the solar radiation directly to electric power. The solar radiation that falls on the panel can be considered as discrete energy units called a photon. For a semiconductor electron to produce currents, its energy level must be increased from its normal valence level to its higher energy conduction level. The photons with at least the band gap energy have the ability to free electrons to create a current.

In the Figure 2.5, the mustard coloured area is energy wavelengths of photons which can be absorbed by crystalline silicon cell to produce electricity [36, 96]. Absorption of electromagnetic radiation is the process of a photon from the sun is transformed into other form of energy. The photons with excess band gap energy generate a free electron and a hole, thus producing electron-hole pair formation, but their extra energy gets dissipated as heat. The mustard coloured area is basically a theory of the Shockley Quisser (SQ) Limit applied to silicon [97, 98].

The photon energy of light varies according to the different wavelengths of light and covers a range of about 0.5eV to about 2.9eV. The PV semiconductors are not responding to the entire light spectrum. Photons with energy less than silicon's band gap pass through the cell and are not absorbed, which wastes about 18% of incoming energy. The energy content of photons above the bandgap will be wasted surplus re-emitted as heat or light. This accounts

for an additional loss of about 49%. Thus, about 67% of energy from the original sunlight is lost, or only 33% is usable for electricity in an ideal solar cell [100-103].

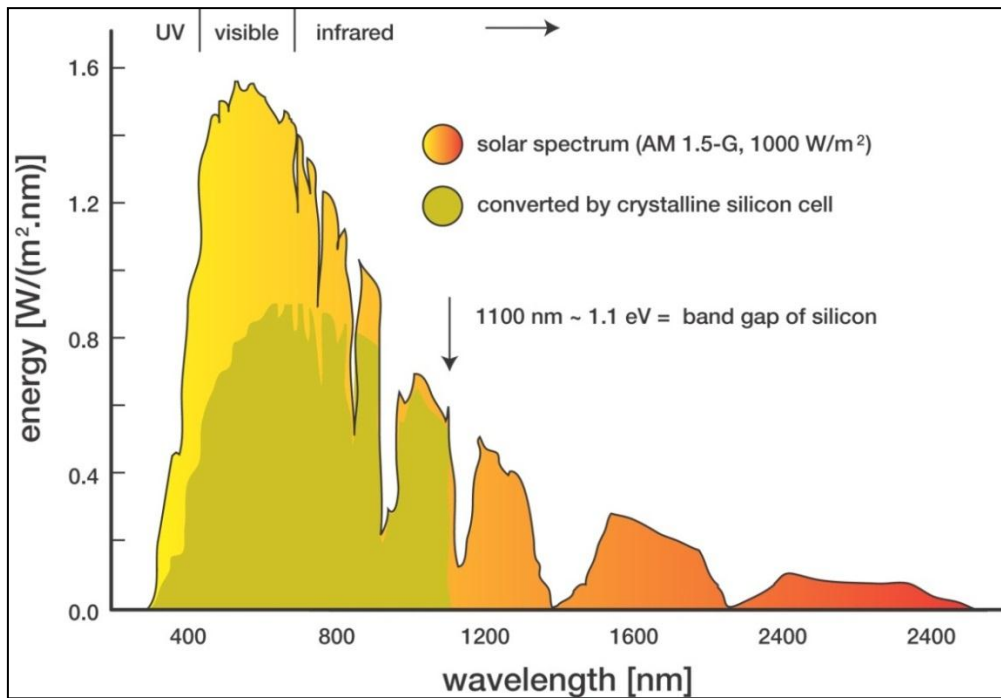


Figure 2.5: Sunlight Energy Distribution Chart [98].

2.6.3 Shading Effect

The shading effect often occurs and affects the capacity of solar system. The shading results power losses in the output. The typical shading problems are:

- i. Shading of harnessing solar collector by nearby surrounding such as trees, buildings or terrains. This problem occurs due to geometries irregularities and systematic calculation of shading becomes difficult. Hence, solar plots (2D representation of sun paths over sky dome) are suggested to be used in determination of solar position at a point in time. The collectors have finite size and the point of receiving surface may not same what another point received. So, the hypotheses of collector point can be made if the distance of collector and obstruction is larger than the size of collector itself.

- ii. Shading of collectors in other than first row of multi-row arrays by the collectors on adjoining row. Therefore, shading calculations are needed when collectors are arranged in rows. Normally, the first row is unobstructed, but the subsequent rows may be partially shaded by the first row.

2.6.4 Operating Temperature

The remainder of 80% solar radiation that has been absorbed by the solar PV is dissipated as heat and the PV module temperature can reach as high as 40°C above ambient temperature [93]. These PV cells convert a certain wavelength of the incoming solar radiation which assists the direct conversion of light into electricity, while the rest is dissipated as heat [104-107]. Solar photovoltaic cells tend to have an impact from high temperature due to radiation from the sun, especially concentrated radiation. It further elevates the temperature of the PV cells junction. The PV cell performance decreases with increasing temperatures, as it has properties of increased intrinsic carrier concentrations which increase the dark saturation current of the p-n junction [94, 104, 106]. Reduction in band-gap due to high doping also increases the intrinsic carrier concentration [94]. The increase in dark saturation current causes the open-circuit voltage to decrease linearly at 300K corresponds to about -2.3mV/1°C for silicon [94, 104].

There are many correlations that express the PV cell temperature, T_C , as the function of weather variables (e.g. ambient temperature, wind speed, and solar radiation) with material and system-dependent properties (e.g. plate absorptance and glazing cover transmittance). The effect of temperature on the electrical efficiency of PV cell or module can be obtained by using fundamental Equation 2.5, where FF is fill factor, I_{sc} is short circuit current, V_{oc} is open circuit voltage and subscript M refers to the maximum power point in the module I-V curve.

Both the open circuit voltage and the fill factor decrease substantially with temperature while short-circuit current increases slightly as explained in [93, 107, 108].

$$P_M = I_M V_M = (FF) \times I_{SC} V_{OC} \quad \text{Equation 2.5}$$

Therefore, the efficiency of the cell, η_c , due to temperature is expressed as in Equation 2.6 where η_{Tref} is electrical efficiency of PV module at reference temperature, T_{ref} and solar radiation of 1000W/m^2 , β_{ref} is temperature coefficient and γ is solar radiation coefficient which depends on material properties of module. The equation then is reduced to

Equation 2.7 as the solar radiation coefficient is usually is taken as zero [109]. The latter equation is representing the traditional linear equation of PV electrical efficiency [111-113].

$$\eta_C = \eta_{Tref} \times [1 - \beta_{ref} (T_C - T_{ref}) + \gamma \text{Log}_{10} H] \quad \text{Equation 2.6}$$

$$\eta_C = \eta_{Tref} \times [1 - \beta_{ref} (T_C - T_{ref})] \quad \text{Equation 2.7}$$

The value of T_{ref} and β_{ref} are provided by PV manufacturer but can be obtained from flash test which the module's output is measured two different temperature at a given solar radiation [34, 106, 113]. Hence, the efficiency of solar cell at nominal operating temperature (NOCT) can be referred to Equation 2.8 where T_{NOCT} is nominal operating cell temperature, T_a is ambient temperature and H_{NOCT} is global solar flux at 800W/m^2 . The quantities that are labeled as NOCT are measured under open-circuit conditions (i.e., with no load attached) while operating in the so-called nominal terrestrial environment (NTE) follows [114, 115]:

$$\eta_{CNOCT} = \eta_{Tref} \times \left[1 - \beta_{ref} \left(T_C - T_{ref} + (T_{NOCT} - T_a) \frac{H}{H_{NOCT}} \right) \right] \quad \text{Equation 2.8}$$

2.7 Review of Solar Radiation Estimation Models

The study of global solar radiation is done throughout the world with different kind of methods. With the rapid rise of renewable energy, especially solar power systems, the estimation model often used to examine the challenges of system integrations. Previously, the benefits of solar radiation prediction are neglected due to low penetration level of the renewable energy technology. Accurate prediction of solar radiation values can effectively reduce the inefficiencies through unit commitment of power plant and economic dispatches decisions [117-120]. Following are reviews of solar radiation estimation models which has been developed and implemented in different countries.

2.7.1 Empirical Estimation Models

The study of solar radiation using empirical estimation models is an attempt made to compute the amount of solar radiation at each and every place based on measured meteorological data all over the world. This type of model has semi-empirical nature and their regression coefficients are dependent on measurement made on the places [87, 120] and often known as statistical time series method.

The simplest form of empirical model for solar radiation estimation is sunshine based model proposed by Angstrom-Prescott [121]. The model has served as a fundamental in solar radiation estimation due to its simplicity. The empirical coefficients is site dependent but according to [122] it is a time dependent and a differential Angstrom model with coefficient of varying time is developed by the author. Some studies are using damping structure to determine solar radiation by taking consideration physical process in details [8, 124-127]. However, the damping spectrums are very irregular and hence numerical integration is indispensable [127]. Therefore, a hybrid model (a model that maintains simplicity of

Angstrom model) is proposed by [128] to tackle the difficulties. The model is tested with data from Japan and found out that it requires greater turbidity when being applied to urban areas due to air pollution. Satellite data also has been applied in derivation of the empirical model [130-136] yet different methodologies have been developed. Further review of empirical solar radiation models are as in following Subsections.

A) Sunshine-based Solar Radiation Estimation Model

Back then, the first existence of average daily irradiation and measured sunshine duration was demonstrated by Kimball in 1919. The relations of the two parameters were presented graphically along with the relation of average daily irradiation and cloudiness. This has concluded that “ the radiation ratio and sunshine data plot very nearly on the straight line connecting 100% sunshine and 0% sunshine radiation intensities” [136].

Optionally, Angstrom proposed a method to define the relation between the solar irradiation and measured sunshine duration. The original form of the equation used by Angstrom to estimate the solar irradiation in Stockholm is as shown in Equation 2.9: where H and H_c are the total irradiation income on horizontal surface and irradiation on clear sky respectively. While, $\frac{S}{S_o}$ is the ratio of calculated sunshine duration and measured sunshine period. The result of the research has led to a conclusion that the value of regression coefficients a and b lie on the diffuse component of energy income [121].

$$H = H_c \left(0.25 + 0.75 \frac{S}{S_o} \right) \quad \text{Equation 2.9}$$

Later in 1940, Prescott used available solar irradiation data in Acton, Canberra to obtain the regression coefficient and deploy it to estimate solar irradiation for the region. The author replaced the clear sky reference value with a general “Angot’s value” which defines radiation

on horizontal surface with transparent atmosphere. The model then is known as Angstrom-Prescott relation and shown in Equation 2.10.

$$\frac{H}{H_o} = a + b \left(\frac{S}{S_o} \right) \quad \text{Equation 2.10}$$

Where H and H_o are measured global solar irradiation and extraterrestrial irradiation respectively while coefficient a and b are regression coefficient (different places have unique value). This type of model uses H and S to estimate solar irradiation. The two parameters are subjected to the variability of meteorological events such as weather changes. It affects the two parameters in such of two ways: (i) the value of S and H is less than S_o and H_o respectively; (ii) shortening effect due to indefinite and random day time. Theoretically, the global solar irradiation estimated by this model is proportional to the sunshine duration. Each of the parameters used in the Angstrom-Prescott sunshine based model contain its own physical properties which allows identifying characters of global solar irradiation estimated. Table 2.1 depicts the physicals properties of the parameters exist in Equation 2.10.

Other meteorological parameters (e.g. air pressure, ambient temperature and cloud cover) are not used when estimation of global solar irradiation using the model is applied; hence, making the estimation less accurate. To cover the estimation accuracy, Şahin and Şen have set the value of the regression coefficient a and b to non-constant value [137]. The Angstrom solar radiation model may have similar linear equation or modified either by relating some meteorological parameters or expressing in term of non-linear models [138]. Researchers from different places have formulated the value of the regression coefficients using collection of reliable long term data of sunshine duration and daily insolation. In facts, the coefficients depend on all physical, spatial and dynamic properties of atmosphere at a study area thus making its have wide range of different value [140-144].

Table 2.1: Angstrom-Prescott Sunshine Based Model Parameters Physical Properties [121].

$\frac{H}{H_0}$	This parameter is known as clearness index which is the ratio of estimated global irradiation and extraterrestrial solar irradiation.
$\frac{S}{S_0}$	The ratio of measured sunshine period over the calculated sunshine period gives information of atmosphere characteristics and study area conditions.
a	The value of regression coefficient a represent diffuse component inside of the global solar irradiation estimated.
b	Regression coefficient b gives information on the variation and relation of $\frac{H}{H_0}$ and $\frac{S}{S_0}$ which has four condition: Condition 1: the case which the total extraterrestrial irradiation reaches horizontal surface of the earth without attenuated by atmosphere layers. The relation of $\frac{H}{H_0}$ and $\frac{S}{S_0}$ form a 45° straight lines. Condition 2: the case which the location is cloudy and the diffuse irradiation is high. This condition could be a good condition for electrical solar application. Condition 3: the case where represent observable conditions of the Earth. In this condition, parameter a indicates low total diffuse irradiation and there are the existences of cloudiness and cloudy separation. Condition 4: the case is not applicable for Angstrom-Prescott model as the relation of $\frac{H}{H_0}$ and $\frac{S}{S_0}$ is inversely proportional.

B) Temperature-based Solar Irradiation Estimation Model

In estimating the amount of solar energy, sunshine duration data is frequently used. However, for the case where such meteorological data is unavailable due to financial, maintenance, institutional limitation and calibration requirement, temperature data would be the alternative way to estimate the solar energy amount.

The application of this method is widely used by Food and Agriculture Organization (FAO) for crop modeling in agriculture and urban planning, irrigation scheduling and regional water balance study [144]. This type of solar irradiation estimation model uses air temperature as a key component. Back then in 1960s and 1970s, a lot of attempts to estimate crop evatranspiration were based on solar radiation of the surface [146-148]. Hargreaves's, in 1974, conclusion of an analysis of climate data from Davis, California and several literature review has led him to develop a model as follow Equation 2.11:

$$H = 0.075 \times H_o \times S^{0.5} \quad \text{Equation 2.11}$$

Through years Equation 2.11 has gone several modification due to inaccessibility of sunshine duration data in some places [137]. Therefore, instead of using the same method as classical Angstrom model, Hagreaves and Samani proposed a predictive model [147-149] as shown in Equation 2.12: where K_{rs} is empirical coefficient, T_{max} and T_{min} are maximum and minimum temperature in degree Celsius ($^{\circ}C$).

The model proposed is simple and able to predict solar radiation at the circumstances where the climatic data is limited and missing. The air temperature-based data is readily available at all meteorological stations.

$$H = K_{rs} H_o \sqrt{T_{max} - T_{min}} \quad \text{Equation 2.12}$$

Hargreaves-Samani Model directly relates the differences of maximum and minimum air temperature with extraterrestrial radiation (H_o) received at ground level. It predicts that the value of estimated global solar radiation (H) is dependent of the range of temperature difference. Despite being dependent on the temperature, the estimation of the model can be affected by other meteorological factors (e.g. humidity, cloudiness, and atmospheric turbulences) and geographical profiles of a point of interest (latitude, storm pattern, advection

and proximity of large water body). The two factors affect the Hargreaves-Samani Model in two distinct ways:

- i. Meteorological factors can influence the temperature range in a given location. Large range of temperature indicates the solar radiation received at the ground is high.
- ii. Geographical profile factors affect the estimation in a way of value given by empirical coefficient, K_{rs} .

The relation of geographical factors to the empirical coefficient K_{rs} has been improvised and studied to increase the accuracy of temperature-based model. The coefficient was set to 0.16 for interior area and 0.19 for coastal area (using climatic data from Senegal River Basin) by Hargreaves in 1983 [145, 148, 149]. While FAO-56 adopted Equation 2.12 to predict H when the data are missing and questionable in term of integrity [145]. Table 2.2 shows modification of K_{rs} by different researchers.

Table 2.2: Empirical Coefficient, K_{rs} studied by Different Researchers

Hargreaves (1982)	The empirical coefficient is set to 0.16 for interior area and 0.19 for coastal area.
Allen (1995)	$K_{rs} = K_{ra} \times \sqrt{\left(\frac{P}{P_o}\right)}$ Equation 2.13 Where, K_{ra} is solar radiation coefficient which equal to 0.17 at inland area and 0.20 at coastal area, P and P_o are air pressure at site and air pressure at sea level respectively. The author relates the coefficient K_{rs} with air pressure of site which accounts the effects of elevation of site.
Samani (2000)	$K_{rs} = 0.00185 \times (T_{\max} - T_{\min})^2 - 0.0433 \times (T_{\max} - T_{\min}) + 0.4023$ Equation 2.14 The author relates the coefficient with average monthly temperature and radiation data for a period of 25 years from 65 weather stations located between 7° to 50° for continental United States [147, 150].

Utilization of the empirical relationships needs to produce a set of equations to forecast solar irradiation from commonly measured climatic parameters. In 1984, Bristow and Campbell have identified the need to obtain reliable solar radiation data. They remodeled solar radiation using an empirical formula for three sites in the United States and highlighted the relationship between temperature range and solar radiation varies over the year, which should be considered [124, 151, 152]. Daily extraterrestrial irradiation is often relates in a number of formulae and methods reported [10, 154-156]. The concept of this method is to express the global radiation, H as the fraction of extraterrestrial radiation, H_0 which is based on the reduction of incoming radiation by the atmosphere. The relation between atmospheric transmittance and some weather variables are described empirically [124].

Bristow and Campbell have constructed a model that relates the fraction of global irradiation and extraterrestrial irradiation, $\frac{H}{H_0}$ with atmosphere transmittivity coefficient, τ_r as shown in Equation 2.15. The atmosphere transmittivity coefficient, τ_r during a day is estimated from the relation of temperature range, ΔT using exponential equation in Equation 2.16 where a , b , and c are empirical coefficient which can be calibrated for particular site from observed solar radiation data. The three empirical coefficients do have their own physical characteristics. Coefficient a represents the maximum clear sky τ_r characteristics (may varies with elevation and pollution contents in air) at site while b and c indicates how soon maximum τ_r is achieved as ΔT increases.

$$\frac{H}{H_0} = \tau_r \quad \text{Equation 2.15}$$

$$\frac{H}{H_0} = a (1 - e^{-b \Delta T^c}) \quad \text{Equation 2.16}$$

ΔT is temperature range within a day of particular site and is calculated as in Equation 2.17: where $T_{\max}$ is maximum temperature in degree Celsius while $T_{\min_J}$ and $T_{\min_J+1}$ are minimum temperature on the day and the next day respectively.

$$\Delta T = T_{\max} - \frac{T_{\min_J} + T_{\min_J+1}}{2} \quad \text{Equation 2.17}$$

In response to the accuracy of the study, [156] has improvised Bristow Campbell Model. The modified model also based on the air temperature relationship and solar irradiation. The Modified Bristow-Campbell Model is expressed as Equation 2.18.

$$\frac{H}{H_o} = a \left(1 - e^{-b \frac{\Delta T^c}{H_o}} \right) \quad \text{Equation 2.18}$$

It is supposed that the global solar irradiation, H at the fixed height and on a horizontal surface during a clear day is largely a function of clear-sky solar radiation. Since daily surface and near surface thermal conditions are largely driven by H , maximum and minimum temperatures are good indicator of cloudiness and resultant incident solar radiation [155].

C) Other Meteorological Based Solar Radiation Estimation Model

Many researchers have been trying to relate other meteorological parameters to the solar radiation estimation model [127, 154, 158-166]. The first highest polynomial model was claimed to be a good fit to solar radiation [166]. The model is expressed as in Equation 2.19 where a , b and c are regression coefficients while X_1 and X_2 are meteorological parameters (e.g. sunshine duration, ambient temperature and relative humidity).

$$\frac{H}{H_o} = a + bX_1 + cX_2^2 \quad \text{Equation 2.19}$$

The linear equation of sunshine based model by [121] is improved by many researchers through the years as the relation shows a significant discontinuity [138]. Hence, sunshine

based model is applied in the higher order polynomials as in [140, 168-172]. Page highlighted that the linear type equation based on meteorology data is unnecessarily be expected to be applicable for a specific day [172]. The fact then was clarified by [173]. In the recent study, Katiyar and Pandey performed sixth order polynomial using sunshine duration to estimate solar radiation in Indian locations [138].

Another statistical method in solar radiation forecast is multiple regressions. This method uses one or more combination of meteorological parameters to predict solar radiation. A prediction model by [169] for solar radiation in Iseyin, Nigeria used mean daily temperature, ratio of maximum and minimum daily temperature, relative humidity and relative sunshine ratio. The same method was used by [174] to determine solar radiation at Baghdad, Mosul and Rutba, Iraq using the combination of maximum temperature, relative sunshine ratio, and relative humidity. A study by [13, 160] also applied the combination of sunshine duration ratio, relative humidity and ambient temperature in modeling the empirical model for Sarawak. The outcome of the model prediction is found to be good fit to daily solar radiation.

2.7.2 Machine Learning Models

Machine learning model is widely used in the study of solar radiation prediction [138, 176-178]. The model is the study of algorithm development that able to learn, adapt and predict values based on data available. It entangles computational of statistics, pattern recognition and mathematical optimization. There are different types of machine learning models (e.g. *k*-nearest-neighbors algorithm, artificial neural network, multi-layer perceptron and genetic algorithm) which are described as follows:

i. *K*-nearest-neighbors (kNN) algorithm

The *k*-nearest-neighbors algorithm is the simplest machine learning model that is widely implement in pattern recognition, classification and prediction. Basically it identifies past pattern and applies the most similar pattern for subsequent solar radiation time series.

ii. Multiple-layer perceptron (MLP) and Radial Basis Function (RBF)

Multiple-layer perceptron (MPL) is based on feed forward flow concept which has three primary layers namely input layer, hidden layer and output layer [178, 179]. Meanwhile Radial Basis Function (RBF) is identified by a transfer function in hidden unit layer processing radial proportion with respect to other center. [180] proposed the application of the two neural network methods to predict solar radiation from a clearness index. The author approach was by using three MLP models with one, two, and three hidden layers together with RBF model to train and validate with ten years data from eight meteorological stations. The input parameters are time, sunshine ratio, altitude, latitude and longitude. The outcomes shows applied models perform similar yet has optimized computational speed using RBF.

iii. Artificial Neural Network (ANN)

The Artificial Neural Network (ANN) model is a type of artificial intelligent the resemblances human action. It is able to model linear and non-linear system without performing mathematical formulation. ANN is classified into two types: feed forward network (FFN) and feedback network. The steps in designing this models involves data assembly, pre-processing, data conversion and normalization, statistical analysis, design

of neural network object, network training, simulation based on new inputs, and lastly is validation and testing [181].

The neural network method is implemented in hourly solar radiation prediction using atmospheric transmittance as input by [182]. The input is divided into two parts: trend and random component. The multiple-layer perceptron (MLP) model with FFN is used in trend component while autocorrelation coefficient and standard deviation on random component. Data with period of eight years from seven stations in Spain are used to validate. Both trend and random component reproduced by the model.

Sfetsos and Coonick proposed an ANN models (combination of recurrent neural network and radial basis neural networks) in estimating hourly solar radiation [183]. The model uses raw data of solar radiation values, temperature, air pressure and wind speed and direction as input parameters. It was found that the model is outperform adaptive neurofuzzy inference scheme and Levenberg-Marquardt algorithm when being compared [184, 185].

2.7.3 Satellite Analysis Models

There are many models proposed to estimate solar radiation at ground level by using satellite image analysis. The models are categorized into two types: statistical and physical models. The statistical model is statistical regression of satellite information and ground observation. Meanwhile the latter is using atmospheric condition as attenuation parameter to obtain precise information. Cano was the pioneer in satellite modeling and proposed the famous HELIOSAT model by using meteorological stationary satellite (METEOSAT) [186].

Generally, information from METEOSAT is used in the solar radiation prediction. It orbits around the earth with height of 36,000 km. Hence, allow it to provide temporal

resolution up to 15 minutes and spation resolution up to 1km. However, the spatial resolution is decrease with increasing latitude since the satellites is located above the equator. The low spatial resolution curtails the application when above 70° South or North [187, 188]. The satellite images which scanned by radiometer is classified into four types: spatial resolution, time resolution, spectral resolution and radiometric resolution [189].

The original HELIOSAT 1 model was a pure empirical model (a linear relation between cloud cover and clearness index) which then further improved by incorporating aerosol and atmospheric absorber parameters known as HELIOSAT 3 [190]. HELIOSAT 3 is enhanced with improved information from multiple channels of second generation METEOSAT.

2.7.4 Solar Radiation Models with Geographical Information System

Solar radiation on the earth surface is the result of complex interaction of energy between atmosphere and surface. When comes to estimate the radiation at different scale, different parameters should be considered. At global scale, solar radiation is reduced by latitudinal gradients due to Earth's geometry, rotation and revolutions. The energy then further reduced by Earth surface factors (e.g. terrain, slope, orientation, shadows cast and elevation) at different regions. Spatial and temporal variety of the incoming radiation determines the dynamics of landscape processes (e.g. humidity, temperature, and evatranspiration) which has relations to human society impacts. Therefore, accurate and spatially distributed solar radiation data are desired for many applications such as climatology, environmental science study, remote sensing, land management and etc.

Spatially continous solar radiation databases often derived directly from METEOSAT. The databases able to cover vast territories but processing of the data provides less accurate values when compared to ground measured values. Therefore, another approach is the

integration of solar radiation model with GIS application. The integration allows the different environmental data to be processed and cooperate with other model.

Table 2.3 depicts the comparison of GIS based model. The first generation of GIS based solar radiation model developed for ARC/INFO GIS was SolarFlux [191]. The similar implementation of algorithm also used in GIS Genasys using AML script [192]. Meanwhile, Solei is a standalone model under MS Windows that linked to GIS IDRISI via data format [193, 194]. The three GIS based model is based on simple empirical formulas and still unsuitable for wide area calculation due to spatially averaged (lumped) value.

The more advanced methods are implemented in Solar Analyst for the purpose of ecological and biological applications. The Solar Analyst is developed as an ArcView GIS extension model [195]. In the preprocessing process of the model, it generates an upward looking hemisphere viewshed based on digital terrain model (DTM), thus providing suitable studies on fine scale analysis (faster calculation of sunmap raster cell). However, Solar Analyst's flaw is it does not have the flexibility to calculate atmospheric transmittivity.

The SRAD model was designed to model short waves and long waves of solar radiation interaction with the earth surface and atmosphere. It able to characterize spatial variability of the landscape processes by considering the main solar radiation factors, though it was designed to model topo and mesoscale processes (the calculation is limited) [196, 197].

The *r.sun* module has been implemented in GRASS GIS open environment which is developed under European Solar Radiation Atlas (ESRA) project. Its features is based on the previous works by Hofierka [198, 199] and has properties which eliminates the existing models discussed. The *r.sun* module is implemented as a part of module in Geographical Resources Analysis Support System (GRASS) GIS environment using C programming. This module is relatively new approach that is used to estimate solar radiation at wide area [199]. It

computes solar radiation (beam, diffuse and reflect components) raster maps at given time, latitude, surface and atmospheric conditions.

Table 2.3: Comparisons of GIS based solar radiation model

GIS based Model	Year	Author	Advantage	Limitation
SolarFlux	1995	Dubayah and Rich [191]	○ Extension of ARC/INFO GIS	Parameters are spatially lumped (averaged), thus limiting the calculation of wide area.
GIS Genasys	1997	Kumar, Skidmore and Knowles [192]	○ Using AML script	
Solei	1998	Miklanek and Meszaros [201-204]	○ Standalone model under MS Windows ○ Linked to GIS IDRISI	
Solar Analyst	1999	Rich [195]	○ Based on DTM ○ Faster calculation of sunmap raster cell	Not flexible enough for atmospheric transmittivity calculation
SRAD Model	2000	Wilson and Gallant [196, 197]	○ Complex short and long wave solar energy interaction modelling for topo- and mesoscale processes ○ Landscape process spatial variability characterizing by considering solar radiation factors	Limited calculation
GRASS GIS r.sun module	2005	Hofierka and Suri [70, 199, 204]	○ Equation of this model is based on European Solar Radiation Atlas (ESRA) project. It is implemented in Geographical Resources Analysis Support System (GRASS) GIS using C programming. ○ Works in two modes where it is able to compute solar radiation at instant time and daily.	Accuracy of model is dependent on finess of DEM inputs

Unlike other GIS based model, the *r.sun* module treats errors exist in computed diffuse component of solar radiation. The component often produces errors when being estimated at inclined surfaces [205]. Another issue which the user of this module should take notes is that the accuracy of map generated is dependent on the coarseness of the elevation, aspect and slope map input. The extent and spatial resolution of modeled area is limited to the memory and data storage as this module can consume significant amount of memory [206].

The program able to operate in two modes where the first mode calculates a solar incidence angle and radiations values for set of local time and second mode is daily sums of solar radiation are computed within a set [205]. The two modes can be used either as a separate mode or in a combination when a scripting is applied. The input parameters that are required to compute the solar radiation value are: latitudes raster layer, elevation raster layer, aspect and slope raster layer, Linke Turbidity raster layer and ground measured solar radiation shapefiles. Table 2.4 shows the module input parameters. The output of this model will be in three radiation components: reflect, diffuse and beam solar radiation. This module will be used in development of solar potential and capacity maps of Sarawak.

Table 2.4: The *r.sun* module input parameters [200, 208-210].

Parameter	Input Type	Description	Mode	Units
elevation	Raster map	Name of input elevation	1,2	Meter
aspect	Raster map	Name of input aspect map (terrain aspect or azimuth of the solar panel)	1,2	Decimal degree
aspect_value	Single value	A single value of the orientation (aspect). Default value is 270 which indicate south.	1,2	Decimal degrees
slope	Raster map	Name of input slope raster map (terrain slope or panel inclination).	1,2	Degree decimal
slope_value	Single value	A single value of inclination (slope) default value is zero	1,2	Degree

Table 2.4 continued

Parameter	Input Type	Description	Mode	Units
linke	Raster map	Name of the Linke atmospheric turbidity coefficient input raster map.	1,2	Dimensionless
linke_value	Single value	A single value of Linle turbidity coefficient. Default value is 3.0.	1,2	Dimensionless
albedo	Raster map	Name of ground albedo coefficient input raster map	1,2	
albedo_value	Single value	A single value of grounfd albedo coefficient. Default value is 0.2.	1,2	
lat	Raster map	Input raster map that containing latitudes.	1,2	Decimal degrees
long	Raster map	Input raster map that containing longitudes.	1,2	Decimal degrees
coeff_bh	Raster map	Name of real-sky beam radiation coefficient (thick cloud) input raster map.	1,2	Dimensionless
coeff_dh	Raster map	Name of real-sky diffuse radiation coefficient (thick cloud) input raster map.	1,2	Dimensionless
horizon_basename	Raster map	The horizon angle information input map basename.	1,2	Dimensionless
horizon_step	Single value	Angle step size for multidirectional horizon.	1,2	Degrees
day	Single value	Number of day in the year (1-365).	2	
time	Single value	Local solar time.	1	

2.8 Review of Solar Potential Atlas Projects

Most of available solar radiation mapping projects are developed and implemented widely in Europe countries. The study of solar potential is ongoing in the developed country which becomes major factor in exploitation of the abundant solar energy resources. The

implementation of the solar atlas provides a general survey of solar energy at different locations. Following are the atlas or map of solar potential projects:

- i. Photovoltaic Geographical Information System (PVGIS) is project of Institute for Energy and Transport of Joint Research Centre (JRC) under European Commissions [210]. It is used to assess the solar energy resources in Europe. The resource maps are calculated based on algorithm which implemented in GRASS *r.sun* module [211].
- ii. Satel-light is the European database of daylight and solar radiation. It provides access to solar radiation database from satellite for all over Europe. The database consist of data that covers from period of 1996 until 2000 with half hourly resolution [212].
- iii. Solar Radiation Data (SoDa) is a web service based that provides solar radiation data access as time series or maps either for purchase or free. The data of the application is obtained from HelioClim1, HelioClim2, HelioClim3 and NASA-SSE [213].
- iv. METEONORM uses an integration of satellite images and ground observation which then deliver resource maps in form of time series. METEONORM database contains data from more than 8300 meteorological stations, where approximately 1200 of these stations contains measurements of solar radiation [214, 215].
- v. SOLEMI delivers hourly time series based on satellite data worldwide up to 66 degrees latitude in form of temporal coverage for Europe [216] and its temporal coverage covers 1991-2005 for Europe. The data has a geographical resolution up to $2.5 \times 2.5 \text{ km}^2$. After 2005, it has data of geographical resolution up to $1 \times 1 \text{ km}^2$. The parameters given from SOLEMI are global horizontal radiation and direct normal radiation.

2.9 Previous Studies and Research Gap

The earliest study of solar radiation in Malaysia was by [40] specifically in Peninsular Malaysia. A few individual studies have been done for different locations in Malaysia [8, 10, 13, 15, 39, 40, 149, 168, 218-222]. The solar radiation estimates for Peninsular Malaysia by Chuah and Lee [40] used the Angstrom type regression equation to determine clear day radiation. Recent studies of meteorological and radiation data in Malaysia together with forecast of solar radiation by neural network was done [8]; it is found that global solar radiation values depended strongly on rainfall. [82] has discussed different models. An investigation of a relationship between solar radiation and temperature and prediction of solar radiation base on robust linear regression by [148, 154] was done and realized that the proposed model is closer to zero when being compared with measured observation. Meanwhile the application of satellite image in forecasting solar radiation was done by [217] as an alternative method [4].

Previous study of solar radiation in Sarawak was done based on ground observed data from Meteorological Station at Kuching [8, 218]. The most recent study of solar potential in Sarawak was done in 2011 by Jakhrani and proposed a solar radiation model based on combination of maximum air temperature, relative humidity and sunshine duration [13]. The outcomes of the research found out that the proposed model performances at four locations in Sarawak (i.e. Sri Aman, Sibu, Bintulu, and Limbang) are closed to unity. The data used by the author is based on monthly solar radiation and sunshine duration. The current ground measurement of solar radiation in Sarawak is curtailed due to missing and defective tools. Sunshine duration measurement data is unavailable for the recent years. Hence, the proposed method by [13] may incorrect if assumption of sunshine duration is used. Existing and readily

available data such as air temperature, relative humidity and cloud factor can be used to model new empirical model.

Hitherto, the study of solar potential in Sarawak is quite limited due to the availability of meteorological stations. The existing meteorological stations are inadequate to provide the measurement of solar radiation throughout Sarawak. Sarawak has wide area which is almost the size of peninsular Malaysia itself. It has area of 124,000km² and stretches over 700km along the northeastern coast of Borneo island is positioned between the latitude of 0° 50' and 5°N and longitude of 109°36' and 115°40' [221]. Building more meteorological stations to cover more areas would become costly. Therefore, the investigation of solar potential in Sarawak can be further extended by determining the potential of solar at different locations and times where locations of unavailable solar radiation monitoring network can be covered. Application of GIS could be as an alternative where in this study *r.sun* module of GRASS will be used. The module is widely used to study the effect of geographical variation and local environment to the incoming solar radiation [200, 224-226].

2.10 Chapter Summary

Malaysia has great dependency on conventional energy sources (i.e. fossil fuels, natural gas, and coal) to meet the energy demands. The energy flows development of Malaysia is mainly affected by the energy demand, resources availability, technology choices, and policy adjustment. Most of energy is used in energy service provisions such as manufacturing sector, transportation sector and domestic sector. Dependency on the conventional energy sources has taking toll to the environments. Therefore, switching to green and clean energy would be the alternative to the energy source.

The developed country (i.e. America, Europe, Australia, China and Japan) has applied solar technology for the country development and alternative of energy demand. Nowadays, the solar energy technology has grown rapidly due to environmental awareness. The PV module cost has decline and become more cost competitive through the advancement and improvement of solar technology.

Meanwhile in developing country such Malaysia is starting to use the solar technology. The tropical climates in Malaysia allow the application of the technology to be versatile and possible form for rural electrification especially in Sarawak. The solar radiation receives in Malaysia is sufficient for utilization of solar PV system. The government has taken action to promote the development of solar technology and instill environmental awareness through renewable projects and introduction of taxes and incentives. Despite of the intensive initiative, shifting from conventional energy technology to the renewable energy would face obstacles in term of cultural barriers, technology barriers and acceptances.

The study of solar potential is important to plan and optimized solar system operations. The earliest study on solar radiation estimation model is developed by Angstrom which defines the relationship of solar radiation and sunshine durations. Throughout the years, different methodologies (GIS, machine learning tools, satellite analysis methods, and empirical models) have been conducted by researchers to estimate solar radiation at different locations. The factors such as geographical surfaces, atmospheric attenuations and meteorological parameters are taken considered in the solar radiation estimation models in order to increase its accuracy. Therefore, solar system capacity can be predicted from the estimated solar radiation as well as by considering other factors such as types of PV material used, shadowing effect and operating temperature.

The study of solar potential in Sarawak is still limited due to availability of meteorological stations. The recent study of solar potential is conducted by Jakhrani in 2011 [13]. The author has developed empirical model which uses sunshine duration, temperature, and relative humidity as parameters. However, the study is limited due to unavailability of recent measured sunshine duration and localized properties of model developed. Therefore, this research will uses readily available meteorological data in solar radiation estimation model development and utilization of *r.sun* module in GRASS to estimates areas that are uncovered by meteorological stations.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this part of chapter, the topic that will be highlighted on is the estimation of solar radiation on horizontal surface in Sarawak. There are seven meteorological stations that are available in Sarawak. The observational data of air temperature, cloud factor, relative humidity and solar radiation can be obtained from Malaysia Meteorological Department (MMD). There are few missing and defectives data of solar radiation in Sarawak. The solar radiation prediction is started by estimating the missing data at each of the local meteorological stations in Sarawak before the estimation in large area being done. Existing air temperature based solar radiation models (Hargreaves-Samani Model [145, 225], and Bristow-Campbell Model [226]) are used in the estimation at each of the local meteorological station. Meanwhile, the estimation of solar radiation in a wider area requires applications of GRASS *r.sun* module. The available observational data is used for regression analysis to develop a general model of solar radiation for local Sarawak meteorological stations. The last part this chapter will be describing the method of solar potential and annual electrical output and generation of its digital atlas.

3.2 Targeted Research Area

Sarawak has an area of 124,000 km² and stretches over 700 km along the northeastern coast of Borneo island and is positioned immediately north of the equator between the latitude of 0° 50' and 5°N and longitude of 109°36' and 115°40' [221]. The country is tropical Borneo Island which has high humidity and year-round temperature of 23°C to 32°C.

The weather is unpredictable where the rainfall can occur any times of the year and often changing quickly. It is localized and complicated throughout the land where one region receives high rainfall but the other region may dry as bone. The inland areas of Sarawak experiences high level rainfalls compared to the coastline. The weather and climate of Sarawak are observed by local weather station of Malaysia Meteorological Department (MMD). There are seven main local weather stations that are available in Sarawak (envisaged in Figure 3.1).

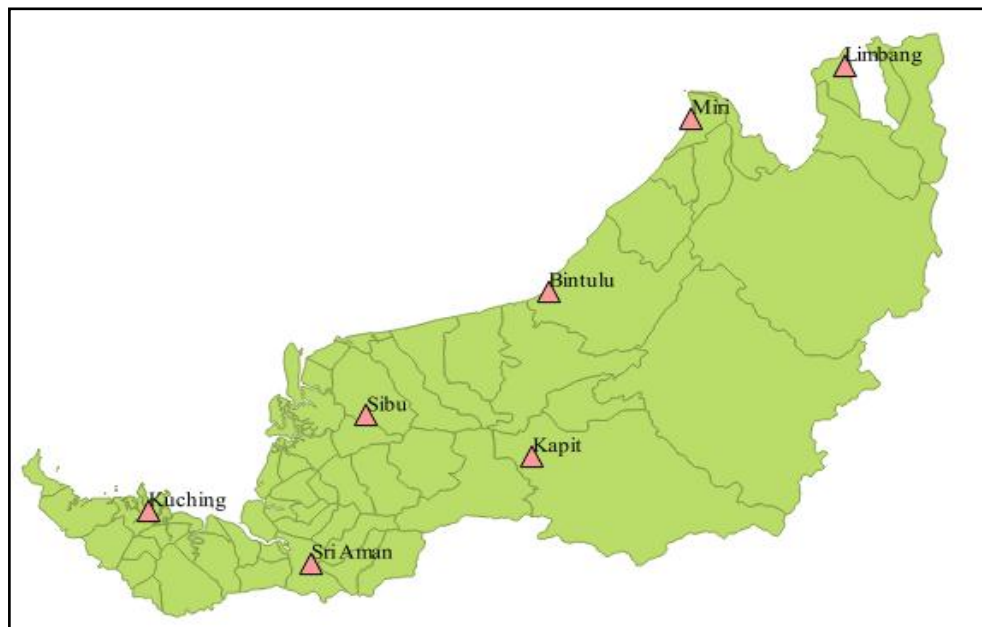


Figure 3.1: Local Weather Station in Sarawak

3.3 Conceptual Framework

The overall concept of this study framework consist of the description of study area with local weather stations availability check, data and topographic acquisition, local weather station solar radiation model estimation, solar radiation estimation over large area using GIS and solar PV assessment over the year according to the radiation yield at different locations. Figure 3.2 shows the flow of this study method which would describe the procedures and stages involved to achieve research objectives.

3.4 Meteorological data and digital map acquisition

This research work requires meteorological data and digital map of Sarawak. Further explanation on the two data is provided in Subsection 3.4.1 and Subsection 3.4.2.

3.4.1 Meteorological data

The first stage of this research study is to acquire the climatic data from the Malaysian Meteorological Department (MMD). This department has the responsibility to monitor, observe and archive the weather information and provide meteorological and geophysical activities.

For this research study, the data utilized is comprised of solar radiation, maximum and minimum temperature, relative humidity, and cloud cover. The data is observed by seven local weather stations within Sarawak. The locations are Kuching, Miri, Sibul, Kapit, Limbang, Sibul and Sri Aman. The data period used is recent five years' worth of data (envisaged in Table 3.1).

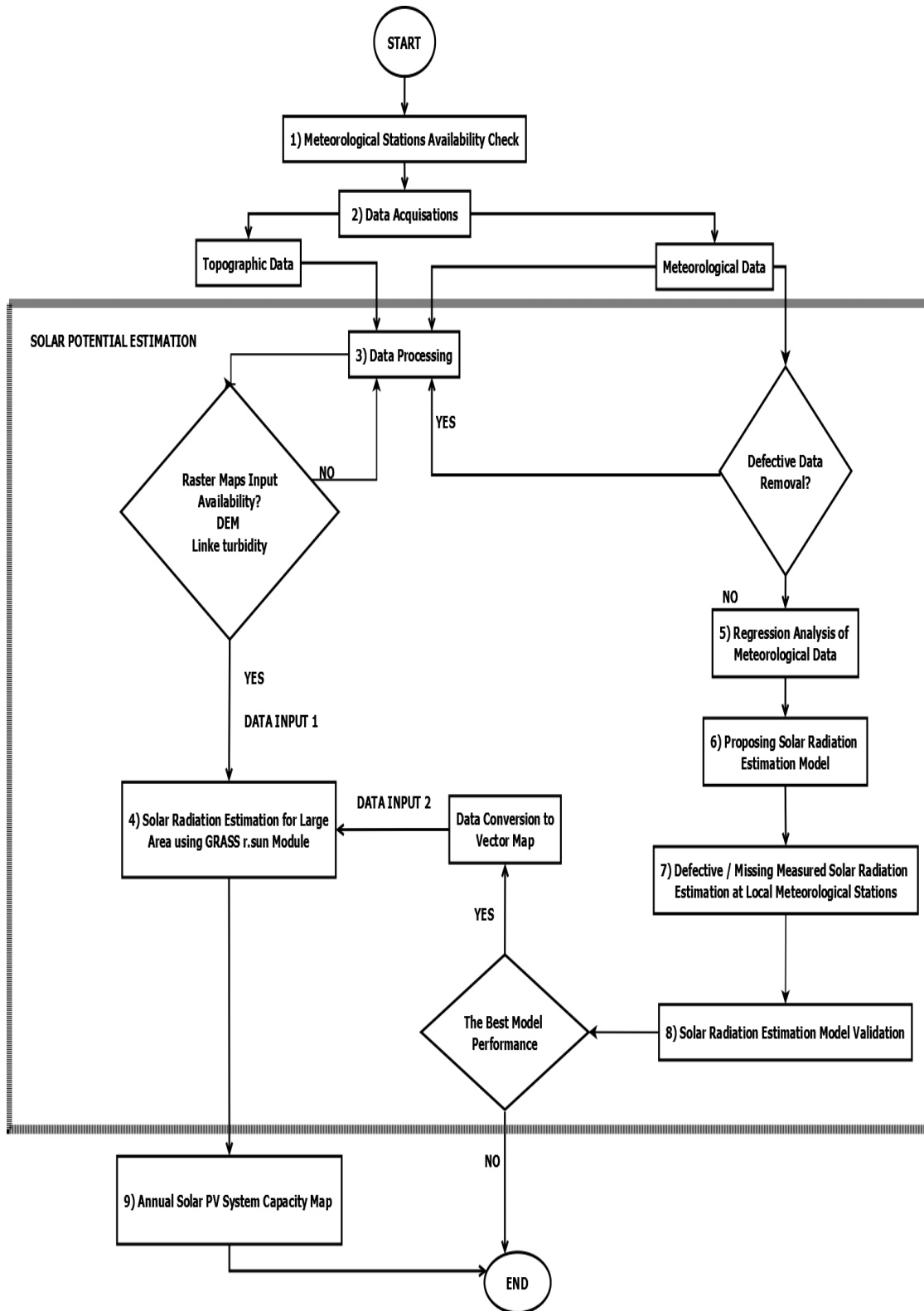


Figure 3.2: Conceptual Framework

Table 3.1: Measured Meteorological Data

Stations	Max and Min Air Temperature (°C)	Relative Humidity (%)	Cloud Factor (Octas)	Solar Radiation (MJ/day)
Bintulu	2010-2015			Nov 2015- 2015
Kapit	2010-2015			Feb 2014 - 2015
Kuching	2010-2015			July 2010 -2014
Limbang	2010-2015			July 2013-Sept 2014
Miri	2010-2015			2011-2015
Sibu	2010-2015			July 2013 -2015
Sri Aman	2010-2015			July 2013 -2015

3.4.2 Topographic Map

The topographic map that is used for the development of GIS is Digital Elevation Model (DEM) map. Usually, the topographic map is obtained from Department of Survey and Mapping Malaysia (JUPEM). However, to simplify the process of scanning and digitizing the map provided, DEM layer is obtained from United States Geological Survey (USGS) website. The agency is a scientific agency which carries out study on natural hazard, health of ecosystem, impact of climate changes and land use changes. The data obtained by this agency is a real-time data from remote sensing and satellites images of Earth.

There are different types of DEM format obtained from USGS and the DEM files are kept on updated and enhanced. Shuttle Radar Topographic Mission (SRTM) and Global 30 Arc-Second Elevation (GTOPO30) are widely used for the application of GIS. GTOPO30 is a global digital elevation model with horizontal grid spacing of 30 arc seconds and was derived from several raster and vector topographic information. While SRTM is DEM on a near scale 56°S to 60°N and the most complete high resolution digital topographic database of Earth [227]. Current SRTM comprises of combination of data from both SRTM and GTOPO30. The development of GIS in this research will use SRTM file to generate raster layers in GRASS application.

3.5 Data Processing

The second stage is to conduct data processing as shown in Figure 3.3. The data is required to be processed to identify any missing or incomplete data. For the climatic data obtained from MMD, necessary unit conversion is needed to be done after checking the missing or defectives data. The defectives or missing data would be removed and will be estimated using solar radiation model. The meteorological data also would be evaluated in terms of monthly average, maximum and minimum values of each parameter. After the meteorological data is being processed regression analysis can be conducted to develop solar radiation estimation model.

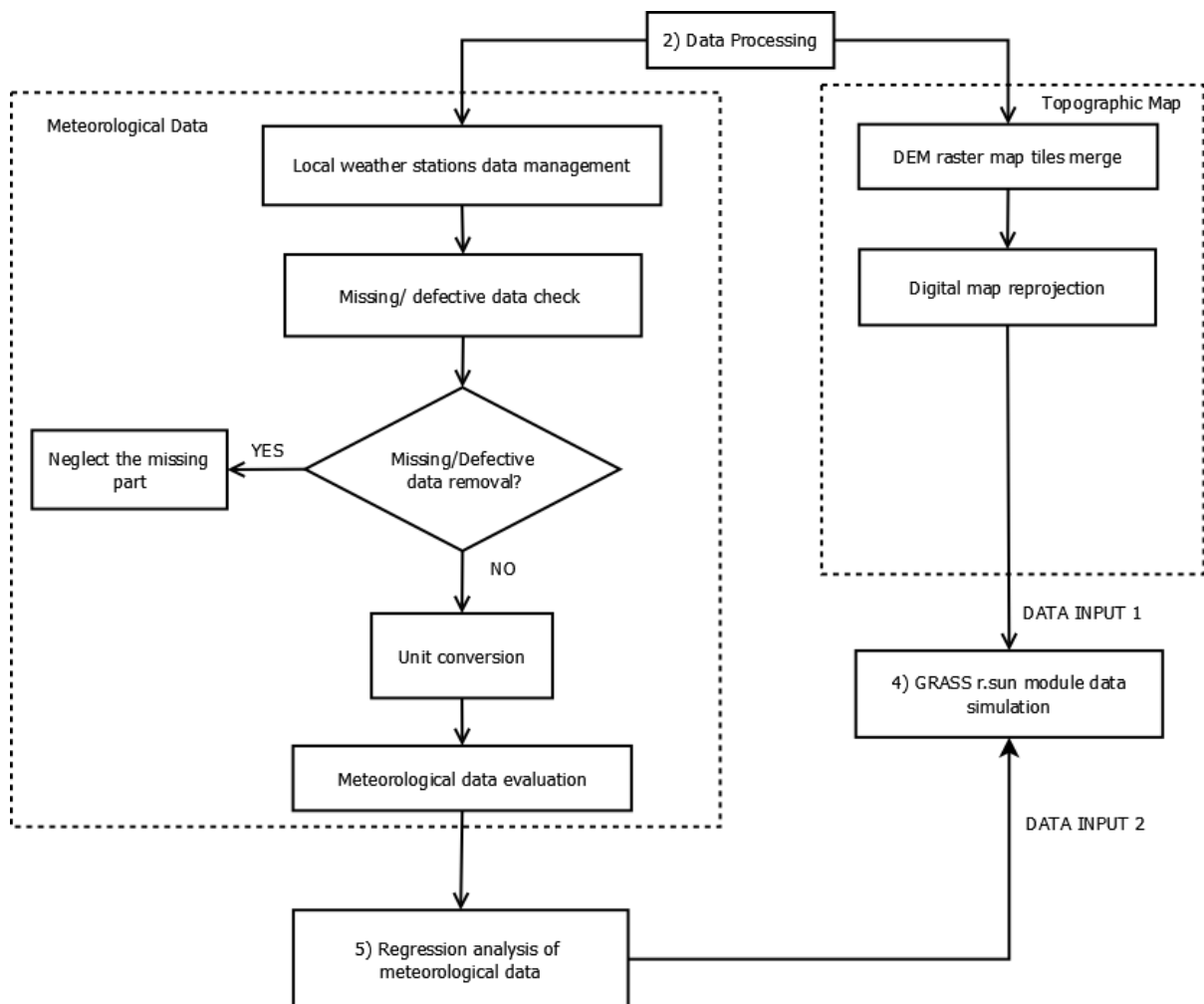


Figure 3.3: Data Processing

The DEM files map obtained from USGS is divided in tiles, therefore the maps are merged together to obtain a complete set of DEM map of Sarawak. To validate accuracy of the map, reprojection of the map is done by overlaid it on the Google maps in Keyhole Markup Language (KML) format.

3.6 Regression Analysis for Model Prediction of Missing Solar Radiation Data

The relation of each meteorological parameter can be described by using regression analysis. The simplest type of relationship of dependent variable and independent variable is a linear relationship [228]. The regression analysis that using a single independent variable for the prediction of dependent parameter is known as simple regression equation (envisaged in Equation 3.1) while multiple independent variable is a multiple regression equation (envisaged in Equation 3.3) [229].

3.6.1 Simple Linear Regression

The simplest way to identify the relation of measured air temperature, relative humidity (RH), and Clearness Index (H/H_0) is through simple linear regression and correlation. Such method able to describe inherent relationships among the parameters and often used in prediction models [229]. Lower degree of polynomial fitting of data pair set able to describe adequately the characteristics of the data [228].

The term linear regression implies that population Y is linearly related to the population X and the general equation are as shown in Equation 3.1 where α and β are estimated from the measured data. The α and β are denoted by a and b respectively so that y can be predicted from fitted regression line in Equation 3.2.

$$Y = \alpha + \beta X \quad \text{Equation 3.1}$$

$$y = a + bx \quad \text{Equation 3.2}$$

The dataset is pair up together and the parameters are substituted in Equation 3.2. Therefore, the general relation of the data pairs is as shown in Table 3.2 where a , b , c and d are the correlation coefficients.

Table 3.2: General Equation of Fitted Regression Line of Data Pairs

Data Pair	Fitted Regression Line General Equation
Temperature Differences- Clearness Index, (ΔT - H/H_0)	$\frac{H}{H_0} = a + b\Delta T$
Relative Humidity- Clearness Index, (RH - H/H_0)	$\frac{H}{H_0} = c + dRH$

3.6.2 Multiple Linear Regression

Multiple linear regression technique can be applied to this research data where more than one independent variable is needed in the prediction model. The response can be predicted adequately and reduces the error of predictions further compared to the linear correlation with a variable. For the case of k independent variables: $x_1, x_2, x_3, \dots, x_k$, the mean of dependent Y is given by multiple linear regression model in Equation 3.3 where each of b_i is regression coefficient from data sample.

$$Y = b_0 + b_1x_1 + b_2x_2 + \dots + b_kx_k \quad \text{Equation 3.3}$$

Therefore, multiple regression models, Equation 3.3, are applied to fit the meteorological data from MMD where measured solar radiation is dependent variable while air temperature, relative humidity and cloud factor are independent variables. Equation 3.4 is

proposed model of solar radiation estimation which formed by substituting the variables into Equation 3.3.

$$\frac{H}{H_0} = b_0 + b_1 \Delta T + b_2 RH + b_3 CF \quad \text{Equation 3.4}$$

During the analysis of each of data, the relation of data is related as in Equation 3.4. The equation may subject to changes depending on the Pearson Distribution analysis of data provide. Figure 3.4 shows the multiple regression analysis of the observational data by inputting H/H_0 as Y variable and RH , ΔT and CF as X variable input. To produce a model that predicts value of solar radiation with less error, the meteorological data provided should meet agreement of:

- i. Pearson distribution with value of less than 0.15 has strong predictive properties in model, thus the data is included in the predictive model
- ii. Pearson distribution with value of more than or equal to 0.15 has weak predictive properties and the data is excluded from the model.

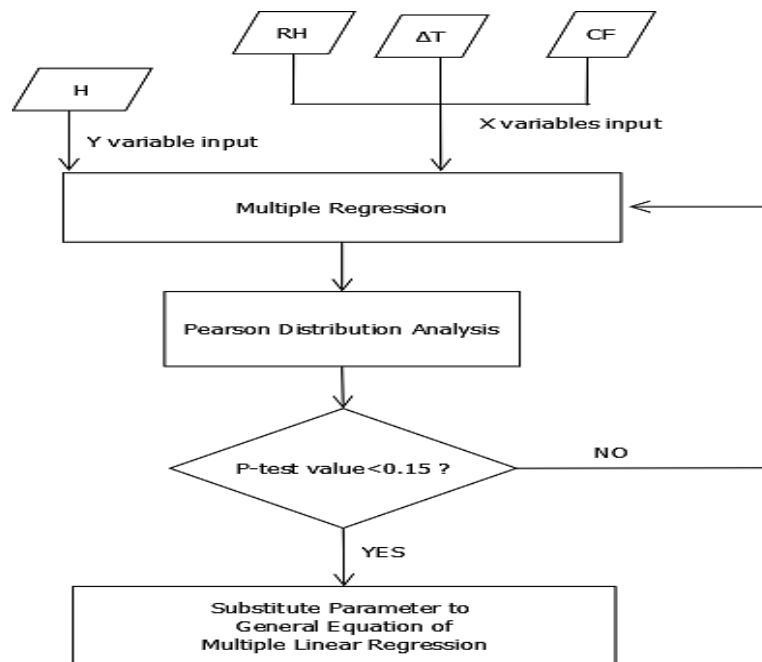


Figure 3.4: Multiple Regression Analysis of Ground Observation Data.

3.7 Estimation of Missing/ Defective Measured Solar Radiation

The empirical solar radiation models that have been developed based on the meteorological data through regression analysis are proposed to estimate the missing or defective measured solar radiation. The first step to estimate solar radiation of local areas is to compute the daily extraterrestrial radiation, H_o [73]. The radiation is computed using Equation 2.1 which has been derived from its instantaneous equation [73]. The solar constants, I_{SC} is radiation that enters earth at constant value that is equal to 1367W/m^2 . Then, the clearness index (fraction of measured solar radiation and extraterrestrial radiation), K_T , can be determined for each day.

The selection of solar radiation model is based on the data availability at the local meteorological station. Frequently, researchers use sunshine based solar radiation model to estimate the missing solar radiation data. Since the local meteorological stations have reliable long term temperature data, temperature based solar radiation model is suggested for the estimation. In addition, other weather parameters such as relative humidity can be added as variable to estimate the radiation as suggested by [13, 45, 141, 158, 159, 166, 168, 171, 232-241].

The temperature-based solar radiation models by previous authors are being used for references in this research: Hargreaves-Samani (HS) Model [147] and Bristow-Campbell (BC) Model [226]. Each equation of the model is presented in Table 3.3. The missing solar radiation (also known as global solar radiation on horizontal surface) data is denoted as H . The solar radiation models are uses air temperature as the parameter in the predictions.

In order to predict the missing solar radiation data, H , the temperature-based solar radiation models HS, and BC are calibrated correspond to air temperature data of local

weather station. Each station has different unique coefficients which contain physical meaning of the local climate characteristics.

Table 3.3: Temperature Based Solar Radiation Model Used in Research

Model	Equation
HS [147]	$\frac{H}{H_o} = K_{rs} \sqrt{T_{\max} - T_{\min}}$
BC [226]	$\frac{H}{H_o} = a \left(1 - e^{-b \Delta T^c} \right)$

The values of both H and H_o then are used to compute clearness index, K_{COMP} . Hence, the beam radiation and diffuse radiation are easily determined using decomposition method where the global solar radiation, H , computed is the totals of beam radiation and diffuse radiation as shown in Equation 3.5.

$$H = H_{\text{diffuse}} + H_{\text{beam}} \quad \text{Equation 3.5}$$

The diffuse radiation can be calculated using Equation 3.6: where H_D , H , and K_T are diffuse solar radiation, estimated solar radiation and clearness index respectively [12, 240]. Equation 3.6 is used without changing the value of the coefficients as there is no recent data on measured beam and diffuse radiation. Hence, it is used due to it has been used to estimate diffuse radiation in tropical country [162]. Figure 3.5 shows the process flow to estimate the solar radiation at each of weather station.

$$\frac{H_D}{H} = 1.390 - 4.047K_T + 5.531K_T^2 - 3.108K_T^3 \quad \text{Equation 3.6}$$

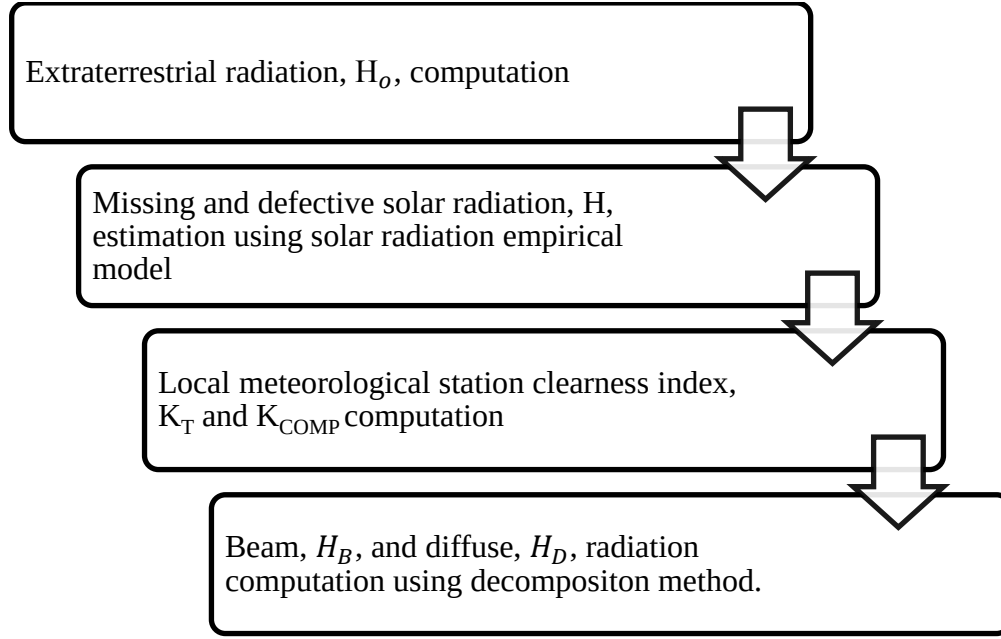


Figure 3.5: Global Solar Radiation, H , Beam Radiation, H_B , and Diffuse Radiation, H_D , Estimation.

3.8 Model Validation

The solar radiation models accuracy is assessed using statistical test as shown in below:

- i. Mean Bias Error (MBE) exhibits overall trend of a model in long run, whether the data generated is overestimated (giving positive value) or underestimated (giving negative value). Equation 3.7 shows the method used to validate the model, where n is the number of observations, $H_{i,calc}$ and $H_{i,meas}$ are calculated and measured values of i^{th} the event.

$$MBE = \frac{1}{n} \sum_{i=1}^n (H_{i,calc} - H_{i,meas}) \quad \text{Equation 3.7}$$

- ii. Mean Percentage Error (MPE) is simply a percentage error of two set data which expressed as in Equation 3.8

$$\text{MPE} = \frac{1}{n} \sum_{i=1}^n \left(\frac{H_{i,\text{calc}} - H_{i,\text{meas}}}{H_{i,\text{meas}}} \right) \times 100\% \quad \text{Equation 3.8}$$

- iii. Root Mean Square Error (RMSE) is used to measure the difference between estimated data with actual data. The smaller the value indicates better performance of the data and expressed as in Equation 3.9

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (H_{i,\text{calc}} - H_{i,\text{meas}})^2} \quad \text{Equation 3.9}$$

- iv. Correlation Coefficient (R) denotes the linear relationship between variable on a scale of +1 (y is directly proportional to x) and -1 (x is directly proportional to y) which shown as in Equation 3.10. Where x_i and y_i are the x and y value for corresponding i^{th} event while $\bar{x}$ and $\bar{y}$ are, respective mean valued.

$$R_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad \text{Equation 3.10}$$

- v. The t-test is used to evaluate the statistical significance of normally distributes model often used to deal with problems related to population mean or comparative sample. It is expressed as in Equation 3.11

$$t = \sqrt{\frac{(\text{MBE})^2 (n-1)}{(\text{RMSE})^2 - (\text{MBE})^2}} \quad \text{Equation 3.11}$$

3.9 Large Area Solar Radiation Estimation

The estimation of solar radiation over large areas is involving the *r.sun* module in the GRASS software. Large areas are modeled by the *r.sun* algorithm using spatially variable parameters which allows the computation of all three components of global solar radiation under clear-sky and overcast conditions. The module works in two modes: Mode 1 calculates solar radiation and incident angle at instant time while Mode 2 estimates the daily solar irradiation within given day. The two modes scripting can be used separately or in a combination.

The *r.sun* module requires a few mandatory input parameters: digital terrain model (elevation, aspect, and, slope), day number (for Mode 2) and local solar time (for Mode 1). Several other parameters (e.g. albedo, clear-sky index for diffuse and beam component) can be set to user definition or else are in default value. Table 2.4 shows the module input parameters. However, the estimation of daily solar radiation will use the few input parameters for Mode 1 simulation. The input names are: *elevation*, *aspect*, *slope*, *lat* and *long*, *horizon_basename*, *horizon_step* and, *day*.

The raster layers of Sarawak DEM, which has been obtained from USGS website, are provided in different tiles of .tiff format. The raster maps are merged together to form a complete mapset of digital elevation of Sarawak. The aspect and slope raster map for input parameters of *r.sun* module are generated from the Sarawak digital elevation map by using *r.slope.aspect* module in GRASS. Meanwhile, horizon angle raster map, latitude and longitude raster map are generated by using *r.horizon* and *r.latlong* module respectively. The single value of *horizon_step* is set to 15. All of the raster layers obtained were reprojected to fit the Coordinate Reference System (CRS) of GDM2000/East Malaysia BRSO EPSG 3376.

Figure 3.6 shows the simulation process of calculating monthly solar radiation at horizontal surface. By means of *r.sun* module application, clear-sky global radiation at horizontal surface can be estimated using following steps:

- i. Obtaining Linke turbidity index (T_{LK}) data and spatial interpolation by employing Regularized Spline Tension method (*r.surf.rst*) in GRASS. The products are monthly maps of T_{LK} index. The spatial resolutions of the maps are applied to 500m in order to incorporate the topography (aspect and slope).
- ii. Constructing monthly solar radiation maps under condition of clear-sky by means of *r.sun* module.
- iii. Constructing point vector layer of ground measured solar radiation on horizontal surface. The point vector layers constructed consist of seven points. The vector layer is used to compute monthly ground measured solar radiation and clear sky index raster maps.
- iv. Developing monthly clear-sky index raster maps via calculation and spatial interpolation (regularize spline tension). The maps are used to support the data that is obtained from MMD.
- v. Generating monthly raster maps for overcast irradiation by multiplying solar radiation under clear-sky condition maps with the clear-sky index maps.

The Linke turbidity data for 164 spatially distributed locations of the study area can be obtained from European Solar Radiation Data2 (SoDA) web database [213]. Monthly T_{LK} of the 164 locations are obtained by inputting points that are defined as x , y and z . It is reported that the accuracy of the source is $RMSE = 0.7 T_{LK}$ units [199]. The effect of elevation, z , on

the T_{LK} is eliminated by normalized it to elevation at sea level, T_{LK_n} [199, 241] as in Equation 3.12.

$$T_{LK_n} = T_{LK} + 0.00035z \quad \text{Equation 3.12}$$

The 164 spatially distributed data layers of T_{LK_n} were interpolated using regularized spline tension (*r.surf.rst*) module in GRASS to derive 12 months of raster layer maps. The daily sum of solar radiation under clear-sky condition is performed using Mode 2 of *r.sun* module and given day for the module simulation is as suggested by [113]. The example of command syntax for calculation of January mean is presented as below:

```
r.sun    elevation=x1_Sarawak_Contour@Bandy    aspect=swkaspect@Bandy
slope=swkslope@Bandy linke=LK1@Bandy lat=swkLat@Bandy long=swklong@Bandy
horizon_basename=horizon horizon_step=15 beam_rad=Beam1 diff_rad=Diffuse1
refl_rad=Reflect1 glob_rad=Glob1 day=15
```

The clear-sky index (K_T) of local meteorological stations in the study area is calculated from ratio monthly measurement of solar radiation data, H_{meas} , and extraterrestrial radiation, H_o for each station. The generation of monthly clear-sky index, K_T raster map is similar procedural process to obtain Linke turbidity raster data is employed. There are seven spatially distributed locations for the K_T ground measured data layer. To increase the interpolation accuracy, another monthly clear-sky index (K_C) raster maps are needed. The clearness index, K_C is computed using model suggested by [242] and as shown in Equation 3.13 where C is the cloud factor expressed in Octas. The data regarding the C is obtained from EarthEnv web database [78]. From the web database, 96 spatially distributed locations with its cloud factors data are obtained. The similar procedural of regularized spline tension (*r.surf.rst*) is employed to build monthly raster layer of the parameter.

$$K_C = 1 - 0.75 \left(\frac{C}{8} \right)^{3.4} \quad \text{Equation 3.13}$$

The final step in developing GIS map of solar radiation is to obtain raster layer of overcast solar radiation by multiplying the monthly solar radiation on horizontal surface with the raster layer of clearness index. The raster layer of K_T and K_C are masked together to fill the missing raster cell values.

The output of PV panel is mainly dependent on amount of solar radiation that being absorbed on the panel. Using the application in GRASS module, annual yield of PV performances can be determined (the step number 9 in Figure 3.2). The estimation of PV panel annual output will be described further in next Subsection.

3.10 Solar Photovoltaic (PV) Potential and Energy Yield Estimation

Solar photovoltaic (PV) produces electrical energy by generating electromotive forces as results from absorption of ionizing radiation. The potential of solar PV is related to the peak power of the panel under solar radiation that is received on panel and the cell temperature, as a function of weather variable (e.g. ambient temperature). Therefore, the two factors are used as consideration in the source collector estimation.

Temperature is known to have adverse effect on the production of the panel. To estimate the efficiency of a PV cell, its performance is examined based on its standard condition and nominal operating cell temperature. For this research, the potential of PV using PV panel of Sunmodule SW 325XL MONO is evaluated. The panel specification is in Appendix A. The operating temperature cell, T_C , can be determined by using Equation 3.14 where T_a and $T_{a,NOCT}$ are ambient temperature and ambient temperature nominal operating cell temperature respectively, T_{NOCT} is nominal operating cell temperature, and H_{av} is monthly average solar radiation.

$$T_C = T_a + (T_{NOCT} - T_{a,NOCT}) \frac{H_{av}}{800Wm^{-2}} \quad \text{Equation 3.14}$$

The standard maximum power of solar PV cell, $P_{K,std}$, can be computed by using Equation 3.15 where P_{peak} is peak power of solar PV panel, γ is temperature coefficient, T_C is cell temperature and $T_{a,std}$ is standard ambient temperature.

$$P_{K,std} = P_{peak} [1 + \gamma(T_C - T_{a,std})] \quad \text{Equation 3.15}$$

Thus, the efficiency of the solar PV system, η_{sys} , can be computed by using Equation 3.16. The maximum power, P_K , for each of the two factors are substitute into the equation and are incorporated with area of solar PV, A , and monthly average solar radiation, H_{av} .

$$\eta_{sys} = \frac{P_K}{AH_{av}} \quad \text{Equation 3.16}$$

The last part of this research is computation of annual electrical output, E , of the solar system by using Equation 3.17 where H_{annual} is annual solar radiation. Therefore, the GIS of the solar PV potential and its electrical output can be computed using Raster Map Calculator (*r.mapcalc*).

$$E = 365P_K\eta_{sys}H_{annual} \quad \text{Equation 3.17}$$

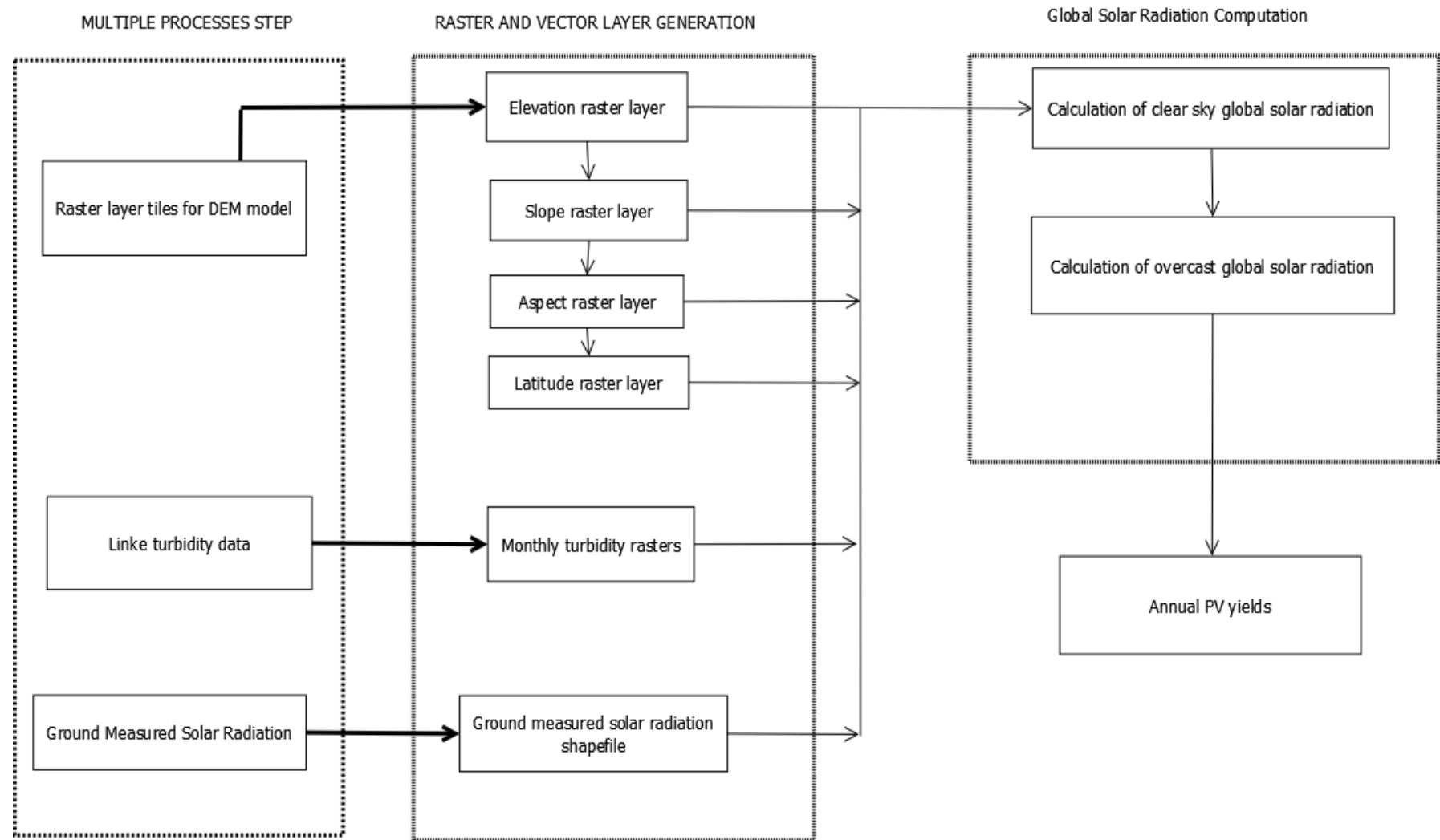


Figure 3.6: The `r.sun` module simulation in GRASS

3.11 Chapter Summary

The targeted research area for this work is tropical Borneo Island, Sarawak which has unpredictable weather where the interior regions receive high rainfall compared to coastline. The weather and climate in Sarawak is observed by Malaysian Meteorology Department (MMD) and there are seven main weather stations available.

The study of solar potential in Sarawak is started by acquisitions of meteorological and topographic data. The meteorological data obtained from the MMD are air temperature, relative humidity, cloud factor and solar radiation with six years period (2010-2015). However, the measured data obtained are not complete due to missing or defective measurements.

The measured meteorological data is processed to undergo regression analysis which then produces solar radiation estimation models (Multiple Linear Regression and Linear Regression). The models are used to estimate the missing and defective measured solar radiation data obtained from MMD. The performances of the estimation models are tested with statistical parameters: MBE, MPE, RMSE, t-test and correlation coefficient, R. Another two air temperature based model by Hargreave-Samani and Bristow-Campbell are used to compare with the models developed. The best model performance is used as *r.sun* simulation parameter.

Meanwhile, the topographic data can be obtained from USGS website which then processed to produce mandatory parameter for *r.sun* module simulations as shown in Figure 3.6. Lastly, the outcomes of the simulation are used to estimate annual solar PV yield in Sarawak. The PV panel of Sunmodule SW 325XL MONO is used as an example in this research simulation.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

The first Subsection of this chapter will discuss on the average of meteorological parameter. The parameters are used in developing temperature range and relative humidity local empirical models which are used to predict the missing or defective value of solar radiation data. The statistical performances of the models then are compared with Hargreaves-Samani Model [147] and Bristow-Campbell Model [226]. The best model will be used to determine the value beam and diffuse solar radiation in Sarawak. The last part of this chapter will be in the estimation of global solar radiation and solar photovoltaic system capacity at larger area using application of *r.sun* module in Geographical Resources Analysis Support System (GRASS).

4.2 Monthly Average of Local Measured Climatic Data

Climatic data measurements of air temperature, relative humidity, solar radiation and cloud factor with period of 2010-2015 are obtained from seven local meteorological stations in Sarawak. Each of the climatic data contains specific characteristics of the site, for instance, the solar radiation barriers, elevation and coordinates [157, 164]. Appendix B shows the monthly average measured data at each of local meteorological stations in Sarawak. The data are evaluated based on the monthly average, maximum and minimum values at each of the local meteorological stations. The recommended monthly average of the data are based on method by Klein [113].

The data recorded in January for five stations (Bintulu, Kapit, Kuching, Sibul and Sri Aman) have similarity of having the lowest ΔT and highest RH and CF. Within that month, the stations recorded the lowest ΔT and it can be as low as 1.9°C at Kuching station. It is also observed that the relative humidity and cloud factor are the highest during that month. The relative humidity during that month can exceed 90% while the cloud factor is at average of 7.0 octas, which can be considered as cloudy according to [243, 244].

Often, the highest ΔT recorded is during June and July which occur at Bintulu, Kapit, Kuching, Limbang and Miri. However, the maximum temperature range, ΔT is 11.8°C at Sri Aman station in September. The dry season at the sites can extended until the month of September. The similar situation also occurs at Sibul site. The generalization of weather at each site is complicated due to its localized properties. The dry seasons at each site may start in May or extended up to September.

The increases of temperature range reduce the relative humidity recorded. The average relative humidity that is recorded at each of the meteorological stations is at the range of 80%-86%. However, unlike the relative humidity, the cloud factor seems unaffected by the changes of temperature range. The measured data of cloud factor obtained from MMD is the daily average measurement. The changes of cloud is often unpredictable and it is suggested by [242, 245, 246] to observed the changes coherently at instant time. Therefore, it is the best to observe the effect of cloud factor changes on the ΔT at instant time.

Unlike the other data, the long term of solar radiation data by MMD is either unavailable or defective measurements at Bintulu and Limbang stations. For the case of Bintulu station, the measured solar radiation is unavailable until December 2015. Meanwhile at Limbang station, there is no measurement of the parameter for the whole year. The other stations have solar radiation measurement but are incomplete due to defective measurement.

4.3 Estimation of Missing/ Defective Measured Solar Radiation

The solar radiation estimation is started by determining extraterrestrial radiation, H_0 [73] at each of meteorological stations in Sarawak. The value of H_0 is computed by using Equation 2.1 [73] which has been derived from its instantaneous equation. Figure 4.1 shows the monthly average daily extraterrestrial solar radiation, H_0 . The variation of extraterrestrial solar radiation is depending on sun-earth distance and time [73]. Earth's axis of rotation is 23.5° with respect to orbit about sun. The extraterrestrial solar radiation computed indicated that during June, the radiation is the lowest with value of 9.32 KW/m^2 . During June, North Pole is inclined 23.5° toward sun and earth surface of 66.5°S latitude experiences 24 hours of darkness. Meanwhile, during March the amount of extraterrestrial solar radiation is 10.48 KW/m^2 which it happened that the sun-earth distance is the closest.

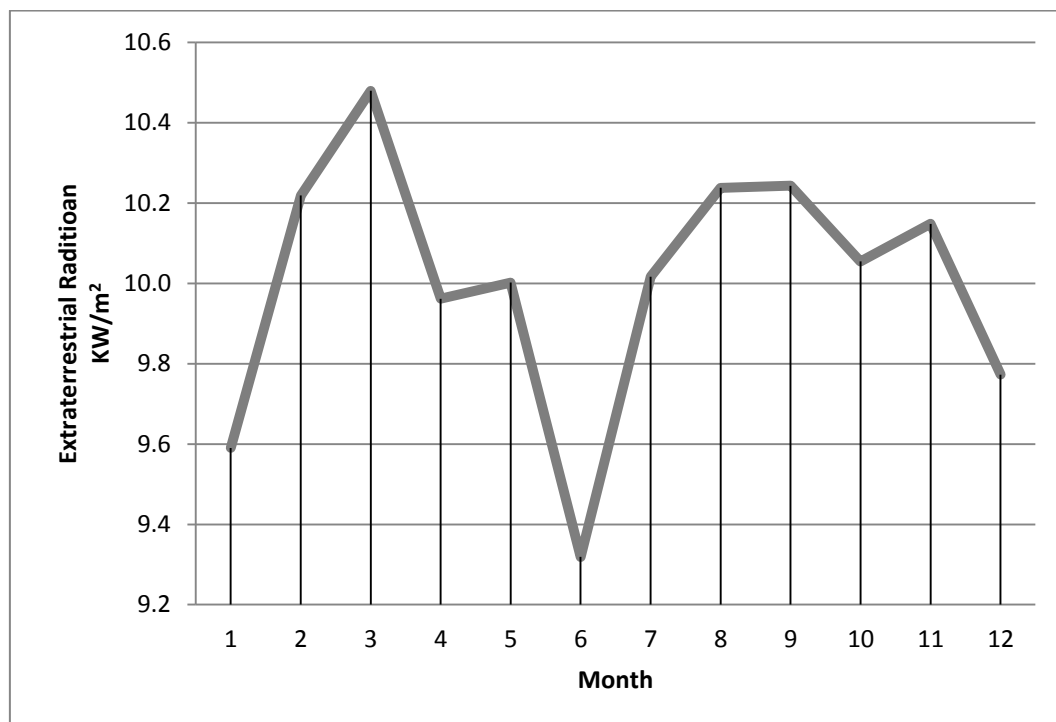


Figure 4.1: Monthly Average Daily Extraterrestrial Solar Radiation

The missing solar radiation data at each of local MMD can be predict depending on the techniques used such as multiple imputation, mean substitution, interpolation and regression. For this study, linear regression and multiple linear regression method (MRM) are used to estimate the missing data.

Linear regression model can provide general relation of global solar radiation, H , to the meteorological parameters used to predict the missing solar radiation data. The differences of linear regression and multiple linear regression approaches is linear regressions uses one parameter to determine H . While MRM uses more than one independent variables. Various authors [13, 80, 126, 154, 247, 248] suggested that to improve model prediction of H , independent parameter can be coupled up with more meteorological parameters. The differences of maximum and minimum air temperature, ΔT , relative humidity, RH and CF are used as independent variable to determine the value of H .

Table 4.1 presents empirical models that are used to estimate H at seven different meteorological stations in Sarawak. Model 1 and 2 are developed from linear relations of each of ΔT and RH with respect to H . Meanwhile model 3 is developed from multiple linear regression method and uses ΔT , RH and CF simultaneously to determine H . Lastly, model 4 and 5 are air temperature based model which are widely implemented and have been established. The last two models are used to compare the outcomes predicted by model 1-3.

Table 4.1: Empirical models used in study.

No.	Model		
1	Linear ΔT	$H = a_1 \Delta T + b_1$	This study
2	Linear RH	$H = a_2 RH + b_2$	This study
3	Multiple Linear Regression (MRM)	$H = a_3 + b_3 \Delta T + c_3 RH + d_3 CF$	This study
4	Hargreaves-Samani	$H = a_4 H_O (T_{\max} - T_{\min})^{0.5}$	[146, 147]
5	Bristow-Campbell	$H = a_5 (1 - e^{-b_5 \Delta T^{c_5}}) H_O$	[226]

4.3.1 Localized Empirical Model

It is found that each of the models has its own empirical coefficients that can be calibrated depending on the sites data provided. The empirical coefficients of model 1-5 for all the seven stations are vary as claimed by [109, 143, 159, 163, 165, 240, 252-256] and are summarized as in Table 4.2. Coefficient a_1 of model 1 is in positive value. The temperature differences, ΔT has properties that can increase the value of H estimated as the range between minimum and maximum temperature is high. While the negative value of coefficient a_2 of model 2 indicated that RH has reduction properties to the value of H predicted. Both of coefficients b of the model 1 and 2 are the intercepts of the model linear relations.

Table 4.2: The Empirical Coefficient of Solar Radiation Model

Model No.	1		2		3				4	5		
Station	a_1	b_1	a_2	b_2	a_3	b_3	c_3	d_3	a_4	a_5	b_5	c_5
Bintulu	5.2E-3	0.2985	-5.1E-3	0.79	1.68	-0.02	-0.01	-0.05	0.16	0.3	-4.3E-4	2.4
Kapit	5.7E-2	2.8E-2	-2.7E-2	2.85	1.28	0.04	-0.01	X	0.16	0.4	-2.0E-3	2.4
Kuching	5.6E-2	2.0E-3	-1.7E-2	1.88	0.78	0.04	-0.01	0.01	0.16	0.2	-2.1E-3	2.4
Limbang	6.5E-2	-2.0E-4	-1.7E-2	1.92	1.60	0.04	-0.01	-0.06	0.16	0.5	-4.9E-5	2.4
Miri	4.5E-2	7.9E-2	-2.0E-2	2.16	1.99	0.04	-0.01	-0.13	0.16	0.4	-2.3E-3	2.4
Sibu	4.6E-2	4.9E-2	-1.3E-2	1.52	1.10	0.04	X	-0.14	0.16	0.3	-1.9E-3	2.4
Sri Aman	4.8E-2	3.7E-2	-1.8E-2	2.02	0.48	0.04	-0.01	0.01	0.16	0.3	-4.627	2.4

X= Inapplicable parameter

The temperature range, ΔT is strongly correlated with H . The ΔT affects H in a way that H increases with increasing value of ΔT . The changes of ΔT are affected by short and long wave radiation of incoming solar radiation which undergoes dimming or brightening effect within a day. Within a day, the maximum daily temperature is mainly affected by the short wave radiation, while, the minimum daily temperature is affected by the long-wave radiation [147, 253]. The variation in ΔT has a complex relation with the cloud cover development, precipitation, water vapor feedback and albedo. Sarawak has high RH which has the properties to reduce the estimated H . The existence of a high concentration of water vapor in

the atmosphere can reduce the intensity of H by diffusing and scattering the incoming solar radiation [73, 159, 163]. The concentration of the water vapor in the atmosphere is induced by the evaporation and transpiration of water from the farm or hydrological landscapes as the temperature during the day increases [144, 145, 170]. Then the temperature drops as the evaporated water condensed into the cloud that reflecting the incoming solar radiation [254, 255].

The coefficients of model 3 are also being summarized in Table 4.2. Kapit and Sibuluan stations are using two types of meteorological parameters. At Kapit, the RH is absent in the model 3 while at Sibuluan station is CF. The absence of the parameters is marked with 'X'. The absences of the two parameters are due to generation of Pearson distribution analysis value, P-value that is more than 0.15. To model a strong predictive property of a model, the P-value of each parameter should be less than 0.15.

Whilst, the value of coefficient a_4 of model 4 are fixed to 0.16 for interior areas and 0.19 for coastal areas as suggested by [147, 256]. For model 5, the value of coefficient a_5 indicates the maximum clear sky characteristic that can be achieved at each of the seven stations. The coefficients are varied from 0.2 until 0.5, where the maximum clear sky of 0.5 is at Limbang station. At Kuching station, the maximum clear sky can be achieved is 0.2. Coefficient b_5 indicates how soon the maximum clear sky can be achieved as ΔT increases. From the values computed, the maximum clear sky is increasing slowly as the ΔT increases. This is perhaps due to the humid condition of Sarawak. It is adequate to set the value of c_5 to default value of 2.4 [226].

4.3.2 Monthly Average Daily Solar Radiation

The models 1-3 are using meteorological data from Sarawak's local weather stations to estimate global solar radiation. The results are compared along with other existing temperature-based models, model 4 and 5. The models predict the values of solar radiation during January are the lowest for all of the stations. During that period, Malaysia is experiencing Northeast Monsoon which brought wet weather to all over Malaysia while dry season during Southeast Monsoon [257]. Overall, the estimation models perform uniquely at different locations of stations based on the empirical model calibrated and the results are presented as follow:

A) Bintulu

The graph indicated in Figure 4.2 shows Monthly Average Daily (MAD) of H estimated by using Model 1-5. The values of H estimated by using Model 4 shows significant large values which with values that are exceed 4KW/m^2 , starting the month of February until December. Based on each of Model 2, 4, and 5 estimated that the highest H is during July with the value of 3649.4W/m^2 , 4934.7W/m^2 and 3510.5W/m^2 respectively. Meanwhile, Model 1 and 3 estimated that the highest H can be received are during September and June respectively.

Table 4.3: MAD Solar Radiation at Bintulu Station

Model		Highest Estimated MAD Solar Radiation		Lowest Estimated MAD Solar Radiation	
		Month	H (W/m^2)	Month	H (W/m^2)
1	Linear ΔT	September	3506.3	January	3012.4
2	Linear RH	July	3649.4	January	2915.9
3	MRM	June	3504.5	January	3052.4
4	HS	July	4934.7	January	2697.4
5	BC	July	3510.5	January	3028.9

Despite of having each of Models 1-5 predicted the highest H at different month, all of the empirical models estimated that the lowest radiation can be received at Bintulu station is during January. The value that being estimated by the models are: Model 1 (3012.4W/m^2), Model 2 (2915.9W/m^2), Model 3 (3052.4W/m^2), Model 4 (2697.4W/m^2), and Model 5 (3028.9W/m^2).

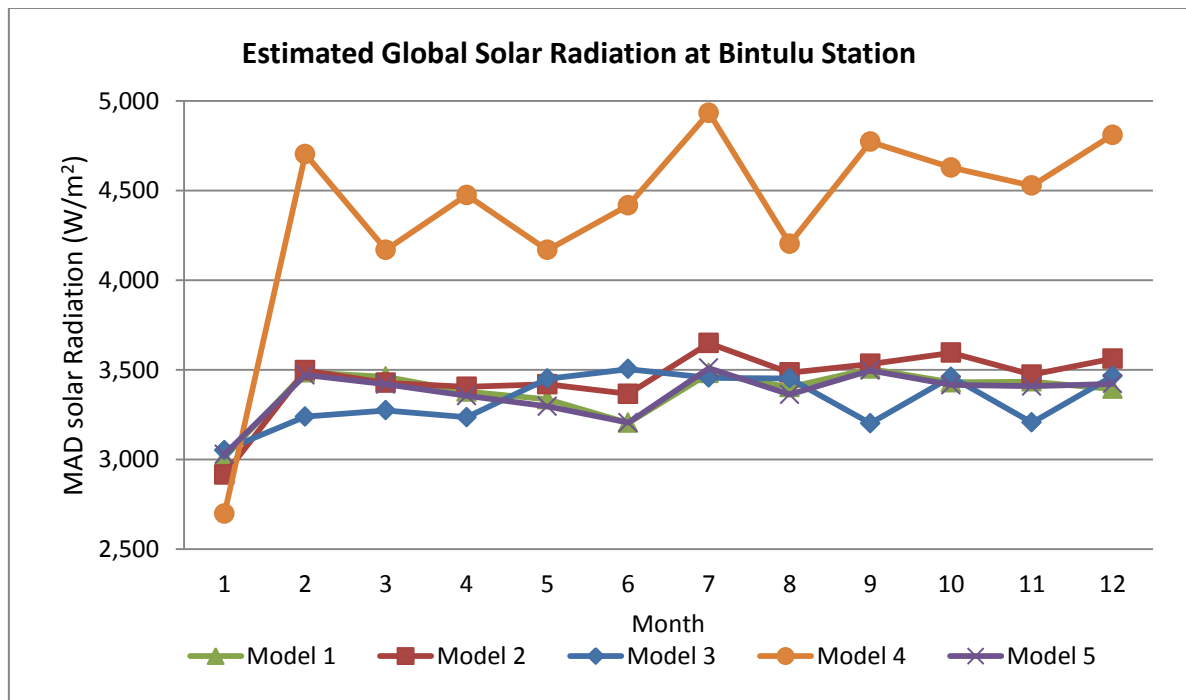


Figure 4.2: Estimated Global Solar Radiation at Bintulu Station

B) Kapit

Figure 4.3 shows the estimated monthly average daily H at Kapit station. The patterns of each model, which almost imitated the sinusoidal wave, indicate there are fluctuations of H during May and September. Based on Table 4.4, all of the five models estimated that the lowest H is during January with values of: Model 1 (2597.5W/m^2), Model 2 (2182.8W/m^2), Model 3 (2530.2W/m^2), Model 4 (3180.5W/m^2) and Model 5 (3636.8W/m^2). The highest solar radiation that can be received often is either during June or July which comes to term with the result of Model 5 with value of 6492.2W/m^2 . However, the highest estimated H by

Model 1, 3 and 4 is during August, while Model 2 is during February. The value estimated by Model 1, 2, 3, and 4 are 6320.0W/m^2 , 6104.9W/m^2 , 6463.2W/m^2 and 5281.7W/m^2 respectively.

Table 4.4: MAD Solar Radiation at Kapit Station

Model		Highest Estimated MAD Solar Radiation		Lowest Estimated MAD Solar Radiation	
		Month	H (W/m^2)	Month	H (W/m^2)
1	Linear ΔT	August	6320.0	January	2597.5
2	Linear RH	February	6104.9	January	2182.8
3	MRM	August	6463.2	January	2530.2
4	HS	August	5281.7	January	3180.5
5	BC	June	6492.2	January	3636.8

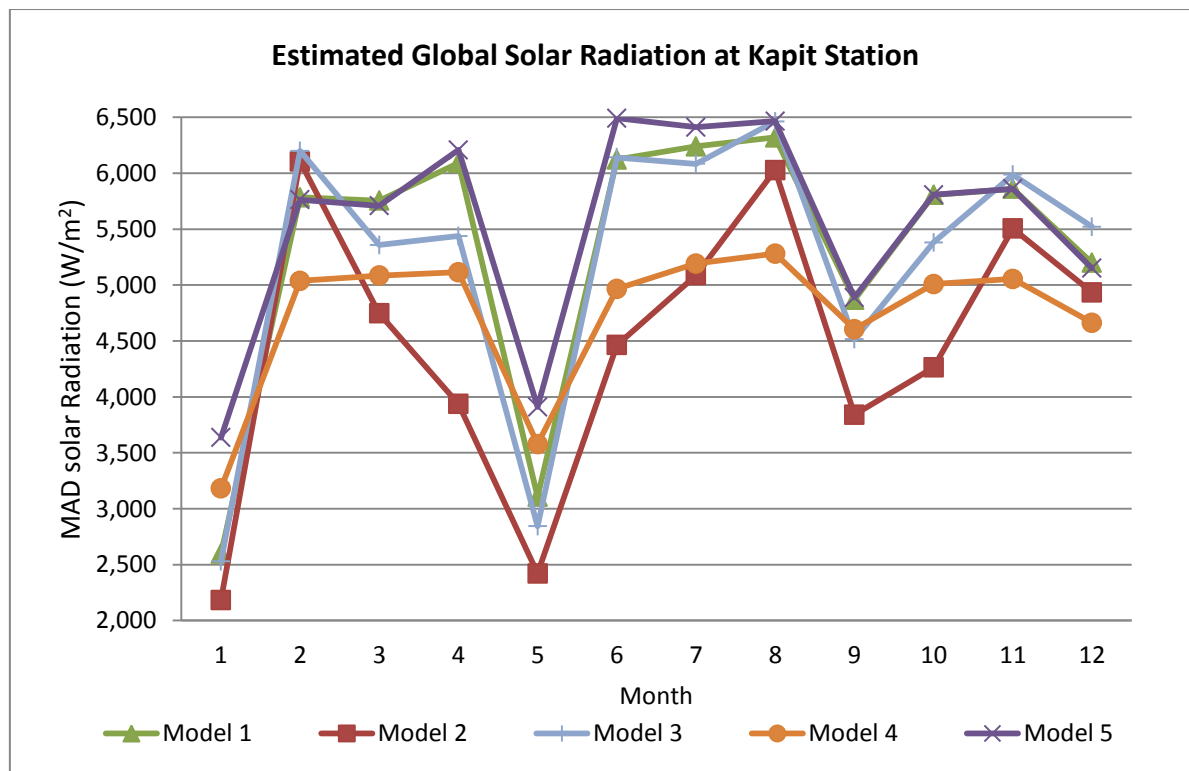


Figure 4.3: Estimated Global Solar Radiation at Kapit Station

C) Kuching

Figure 4.4 shows estimated monthly average daily solar radiation at Kuching Station. The patterns of the graph produced by each model is imitating sinusoidal wave pattern. After experiencing the lowest estimated H during January, the graph of Model 1, 3, 4 and 5 shows fluctuation during May, August, October and December. Meanwhile for Model 2, the fluctuation of estimated H happened during May, August and December.

Based on Table 4.5, all of estimation models predicted that during January is the lowest estimated H: Model 1 (941.2W/m^2), Model 2 (2206.7W/m^2), Model 3 (1181.9W/m^2), Model 4 (2115.1W/m^2) and Model 5 (2373.2W/m^2). Meanwhile, the highest estimated H by Model 1, 3, 4 and 5 is during July. However, Model 2 estimated H is the highest during September. The values of estimated H are: Model 1 (5392.5W/m^2), Model 2 (5723.8W/m^2), Model 3 (5575.1W/m^2), Model 4 (5217.8W/m^2) and Model 5 (5814.8W/m^2).

Table 4.5: MAD Solar Radiation at Kuching Station

Model		Highest Estimated MAD Solar Radiation		Lowest Estimated MAD Solar Radiation	
		Month	H (W/m^2)	Month	H (W/m^2)
1	Linear ΔT	July	5392.5	January	941.2
2	Linear RH	September	5723.8	January	2206.7
3	MRM	July	5575.1	January	1181.9
4	HS	July	5217.8	January	2115.1
5	BC	July	5814.8	January	2373.2

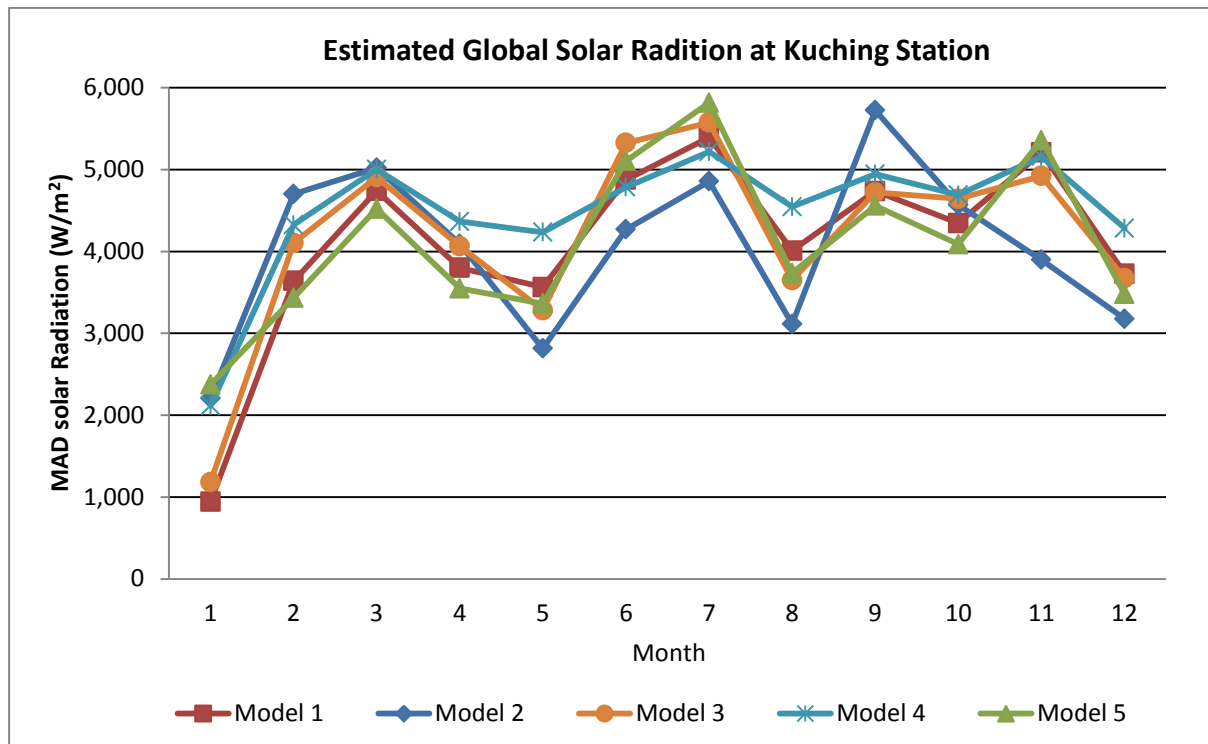


Figure 4.4: Estimated Global Solar Radiation at Kuching Station

D) Limbang

Figure 4.5 presents estimated MAD solar radiation, H at Limbang Station. Overall the patterns generated by each of model are varies. The H predicted during June until August by using Model 3 is higher than the H predicted by the other models and generated the highest H during August with the value of 7205.7W/m^2 . Meanwhile Model 5 shows the lowest fluctuation of H during June with estimated H of 5075.1W/m^2 . Unlike the other models, Model 5 predicted the highest H during January with the value of 5204.5W/m^2 . Model 1, 2 and 4 are also experienced few fluctuations. However, Model 2 shows significant fluctuation during May, with estimated H of 3815.7W/m^2 , compared to Model 1, 3 and 4.

Table 4.6 shows the summarization of estimated solar radiation based on the line graph in Figure 4.5. At Limbang station, both of the highest and lowest H estimated occurred at different months (refer to Table 4.6). Both of Model 1 and Model 4 estimated that highest

estimated H is during November while the lowest is during January. This is perhaps both of the Model 1 and 4 are using single parameter (i.e. temperature differences) to estimate solar radiation.

Table 4.6: MAD Solar Radiation at Limbang Station

Model		Highest Estimated MAD Solar Radiation		Lowest Estimated MAD Solar Radiation	
		Month	H (W/m ²)	Month	H (W/m ²)
1	Linear ΔT	November	5501.8	January	4325.8
2	Linear RH	September	6358.2	May	3815.7
3	MRM	August	7205.7	October	4155.5
4	HS	November	5215.8	January	4429.2
5	BC	March	5689.2	June	5075.1

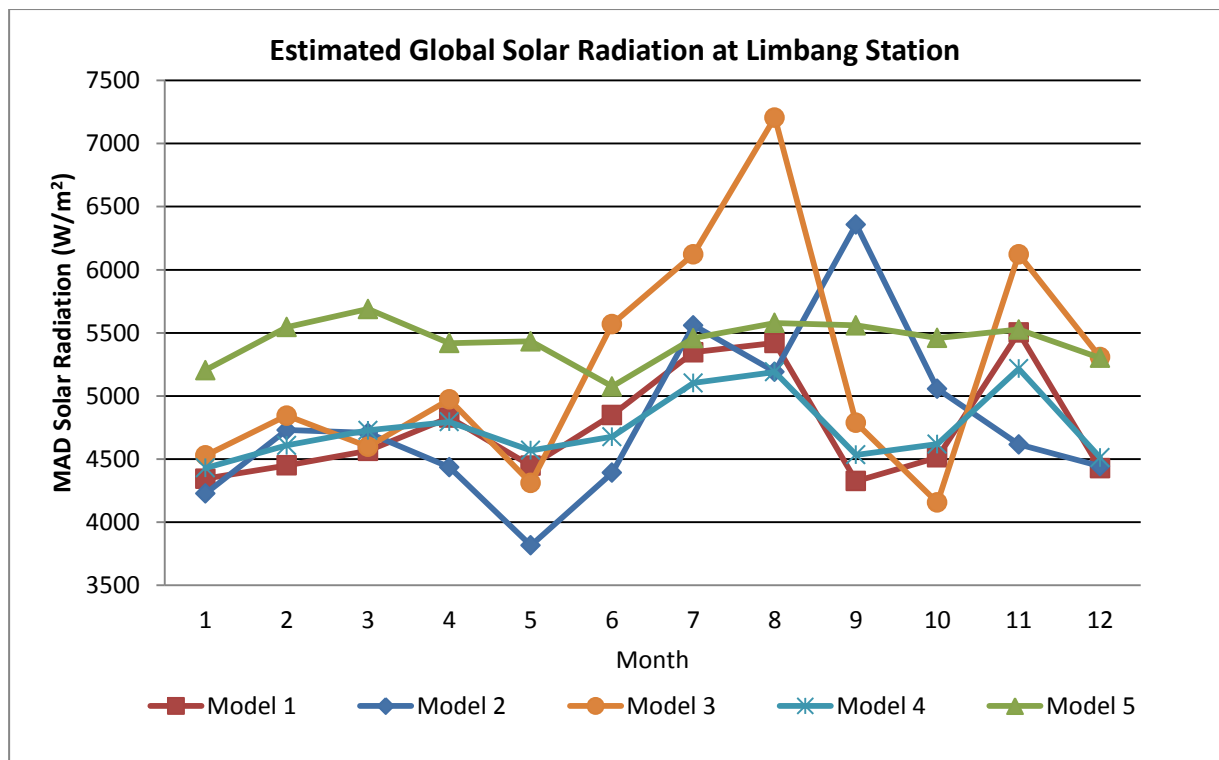


Figure 4.5: Estimated Global Solar Radiation at Limbang

E) Miri

Figure 4.6 shows estimated solar radiation, H at Miri Station. Overall temperature-based model (i.e. Model 1, Model 2, Model 4 and Model 5) shows significant fluctuations during the month of May and August. After experiencing fluctuation during May, the estimated H by temperature-based model is increased until July. Model 3 shows the highest increase of estimated H with the value of 6191.1W/m^2 during July. Meanwhile for Model 2, the predicted H during January is the lowest which is 3750.7W/m^2 and increases for the next six months, where during July the highest H predicted is 5990.4W/m^2 .

The outcomes of the graph in Figure 4.6 are summarized in Table 4.7. At Miri, all of the temperature-based models predicted that the highest H is during July (Model 1: 5422.1W/m^2 , Model 3: 6191.1W/m^2 , Model 4: 4606.1W/m^2 , and Model 5: 5418.1W/m^2) and the lowest during April (Model 1: 3832.6W/m^2 , Model 3: 4244.4W/m^2 , Model 4: 3862.2W/m^2 , and Model 5: 4382.8W/m^2). Meanwhile, Model 2 gave the lowest H during January.

Table 4.7: MAD Solar Radiation at Miri Station

Model		Highest Estimated MAD Solar Radiation		Lowest Estimated MAD Solar Radiation	
		Month	H (W/m^2)	Month	H (W/m^2)
1	Linear ΔT	July	5422.1	April	3832.6
2	Linear RH	July	5990.4	January	3750.7
3	MRM	July	6191.1	April	4244.4
4	HS	July	4606.1	April	3862.2
5	BC	July	5418.1	April	4382.8

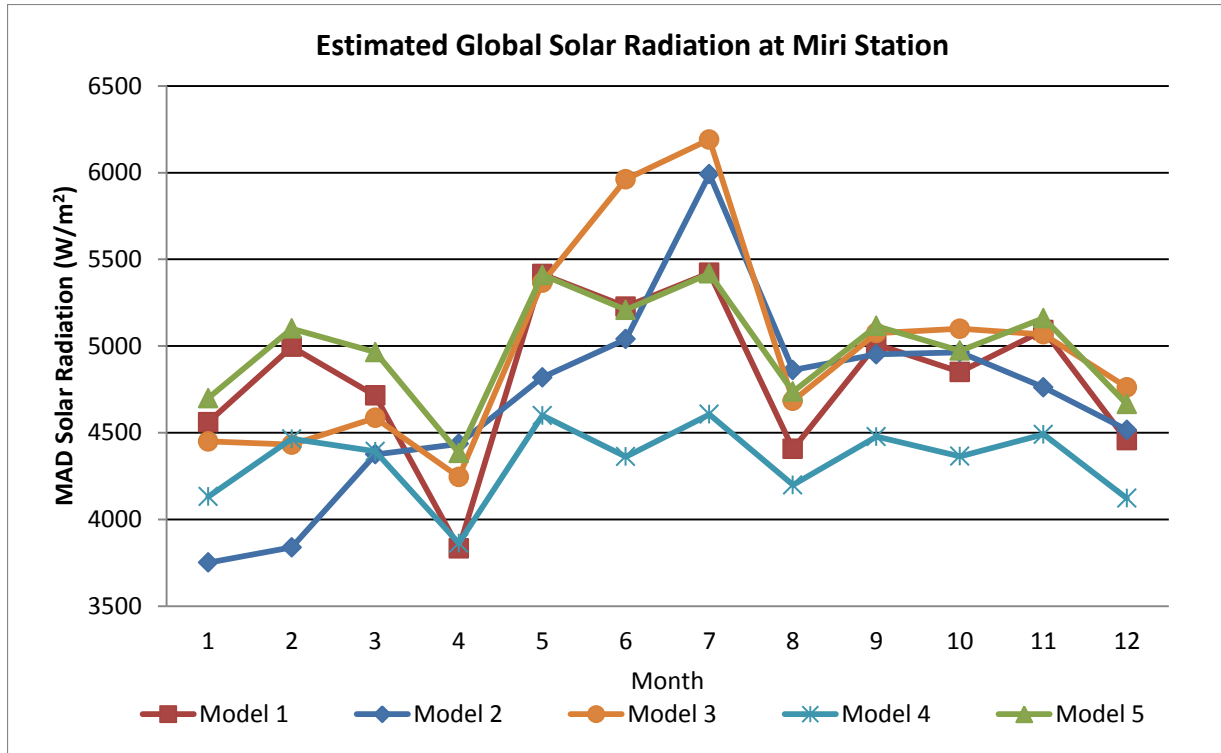


Figure 4.6: Estimated Global Solar Radiation at Miri

F) Sibü

Figure 4.7 shows estimated solar radiation at Sibü Station. Overall the line graph generated by temperature-based models has similar patterns which predicted the lowest H during January and experienced fluctuation of H during April, August and November. Meanwhile, the value of H predicted using Model 2 for January is higher compared to the other temperature-based models. The H increases before decreasing until May which then increases to its highest during July with estimation of 5155.2W/m^2 . The H of Model 2 again undergoes fluctuation for August and November.

Based on Table 4.8, all of the models estimated the lowest H can be obtained during January: Model 1 (1485.6W/m^2), Model 2 (3681.5W/m^2), Model 3 (1386.6W/m^2), Model 4 (1386.6W/m^2) and Model 5 (2668.4W/m^2). Meanwhile the highest H estimated using Model 1, 2 and 5 is during July, Model 3 is during June and Model 4 is during March. The H

estimated are Model 1 (4776.2W/m^2), Model 2 (5155.2W/m^2), Model 3 (4836.1W/m^2), Model 4 (5165.6W/m^2) and Model 5 (4544.8W/m^2).

Table 4.8: MAD Solar Radiation at Sibü Station.

Model		Highest Estimated MAD Solar Radiation		Lowest Estimated MAD Solar Radiation	
		Month	H (W/m^2)	Month	H (W/m^2)
1	Linear ΔT	July	4776.2	January	1485.6
2	Linear RH	July	5155.2	January	3681.5
3	MRM	June	4836.1	January	1386.6
4	HS	March	5165.6	January	2325.7
5	BC	July	4544.8	January	2668.4

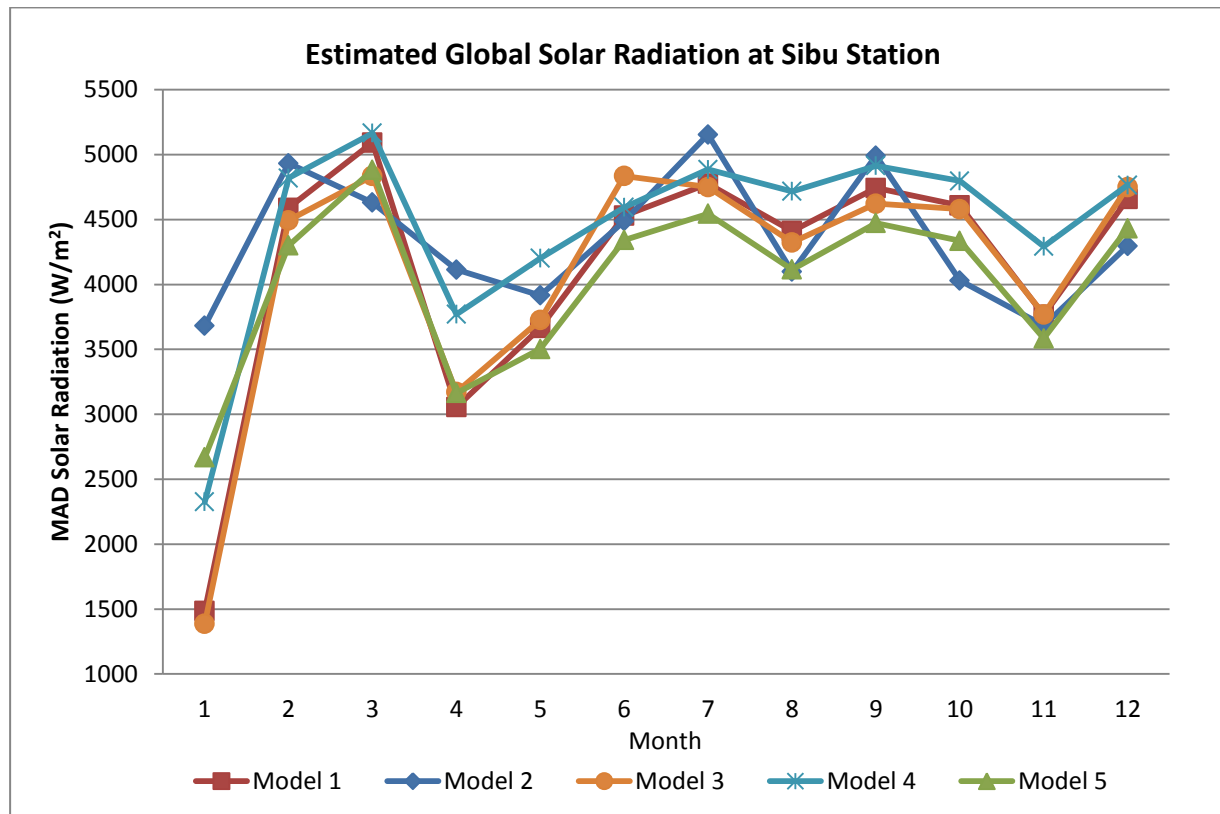


Figure 4.7: Global Solar Radiation at Sibü

G) Sri Aman

Figure 4.8 shows estimated solar radiation, H at Sri Aman Station. The line graph of temperature-based models has similar pattern where fluctuations of H occurs during March, May, August, October and December. The lowest H predicted by the models is during January. Meanwhile, the estimated H of Model 2 during November and December shows slight decrease. Based on Table 4.9, all of the models estimated that highest and lowest H are during September and January respectively.

Table 4.9: MAD Solar Radiation at Sri Aman Station

Model		Highest Estimated MAD Solar Radiation		Lowest Estimated MAD Solar Radiation	
		Month	H (W/m^2)	Month	H (W/m^2)
1	Linear ΔT	September	6136.4	January	2366.9
2	Linear RH	September	6267.7	January	2950.7
3	MRM	September	6161.8	January	2446.4
4	HS	September	5630.6	January	3219.4
5	BC	September	6646.6	January	3056.0

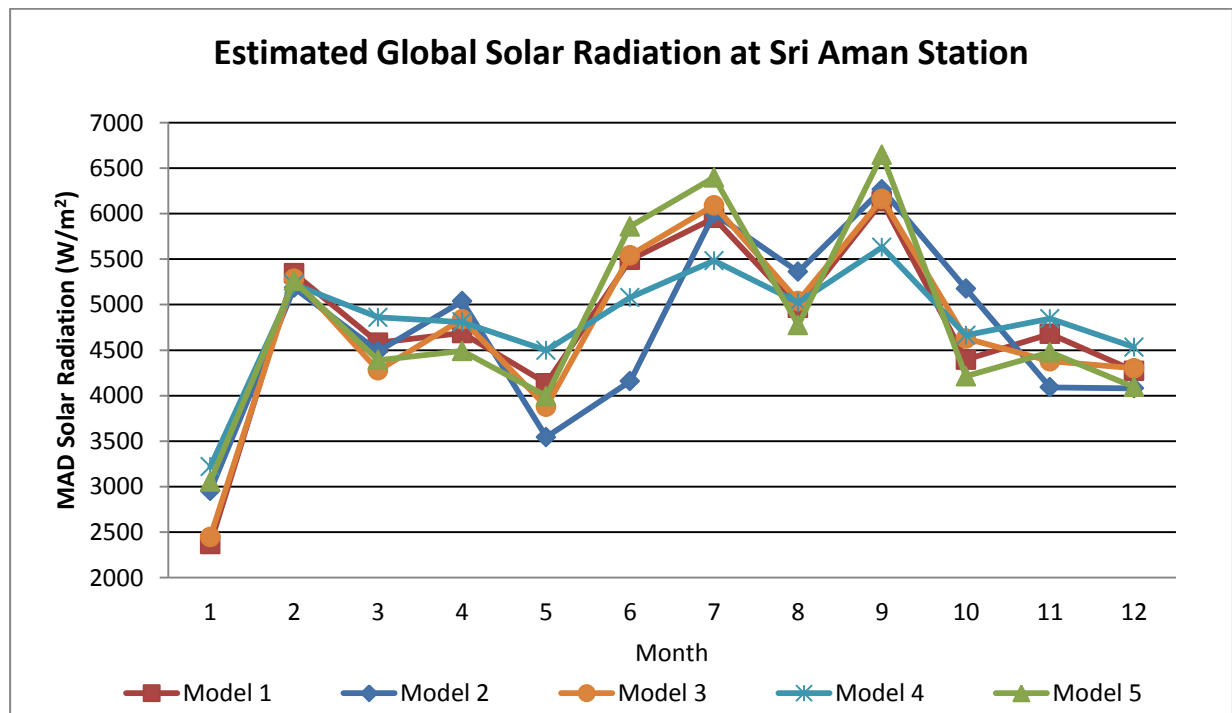


Figure 4.8: Global Solar Radiation for Sri Aman

4.3.3 Model Estimation Performances

Table 4.10 shows the performances of the localized empirical models used in H estimation. The models are tested by using mean biased error (MBE), mean percentage error (MPE), root mean square error (RMSE), t-test and determination values (R) of K_{COMP} against K_T graph. To be noted that the determination value for each of the model is obtained from K_{COMP} against K_T graph which can be envisaged in Appendix C along with further statistical analyses (e.g. Pearson Correlation and t-critical with one-tail and two-tails) in Appendix D.

Each of the empirical models performances will be discussed further in following Subsections based on Table 4.10.

A) Model 1

Model 1, which uses temperature range, underestimated H at Limbang (7.18%), Miri (3.98%), Kuching (0.3%), and Bintulu (0.06%). Meanwhile at Sibü, Sri Aman and Kapit sites are overestimated by 0.08%, 0.09%, and 0.04% respectively. The MBE of the linear relation shows that it has trends that predict H with less bias error in long term. Thus, it apparently performs better than the model 4 and model 5.

In general, the generated MPE at each site is quite high. At each of the sites, the MPE of Model 1 is: Bintulu (7.76%), Kapit (32.57%), Kuching (14.7%), Miri (26.07%), Limbang (16.08%), Sibü (25.03%), and Sri Aman (27.19%). The MPE of Model 1 indicates that the highest generated MPE is at Kapit site while the lowest is at Bintulu.

Meanwhile, Model 1 performance based on RMSE indicates that it does perform with agreeable result over short term. The RMSE produced is at the range of 10%-22%. At each of the sites, the generated RMSE is: Bintulu (11.3%), Kapit (16.59%), Kuching (16.12%), Miri (21.29%), Limbang (17.90%), Sibü (21.75%), and Sri Aman (15.15%).

Model 1 is also being validated by using t-test and determination value, R as shown in Table 4.10. The outcomes of the t-test of model 1 at the seven stations are: Bintulu (0.03), Kapit (-0.07), Kuching (0.97), Miri (7.79), Limbang (5.86), Sibu (-0.10), and Sri Aman (-0.15).

The K_{COMP} against K_T graph is used to determine the value of R. The relationship of K_{COMP} and K_T is theoretically proportional at scale of positive one. The closer the correlation to the value indicates the model estimation is fall to the line and in a good performance. The Kuching station has R which is equal to 0.81 and the closest to the value, thus, indicates that the performance of Model 1 is the best at the station. However, at Bintulu station the model perform the worst by generating lowest R value of 0.21.

Model 1 able to produce agreeable results, however, the performance at each of local sites is inconsistent. For instance, at Bintulu site despite having the best MBE, MPE and RMSE, the correlation value, R is the worst. In term of model prediction in a long run, Model 1 able to produce MBE that is close to zero except for Miri and Limbang sites. Meanwhile, RMSE generated at Sibu sites indicates Model 1 perform the worst and followed by Miri sites.

Table 4.10: Model Performances Validation Using Statistical Parameter

Station	Model	Statistical Parameter						
		MBE		MPE	RMSE		t-test	R
		(%)	(W/m ²)	(%)	(%)	(W/m ²)		
Bintulu	Model 1	-0.06	-1.79	7.76	11.3	366.49	0.03	0.21
	Model 2	0.78	25.46	7.11	10.5	339.77	-0.50	0.43
	Model 3	0.0	0.437	6.43	9.5	307.45	-0.01	0.57
	Model 4	27.6	895.22	30.96	32.4	1051.13	-10.90	0.20
	Model 5	-0.6	-18.9	7.64	11.3	365.96	0.30	0.23
Kapit	Model 1	0.04	2.43	32.57	16.59	907.45	-0.07	0.73
	Model 2	-0.17	-9.40	34.38	17.58	962.31	0.24	0.69
	Model 3	0.002	0.09	30.23	15.08	825.49	0.003	0.78
	Model 4	-12.0	-657.91	36.31	22.1	1211.67	16.08	0.73
	Model 5	3.33	182.30	35.68	18.95	1037.15	-4.47	0.65
Kuching	Model 1	-0.3	-14.49	14.70	16.12	690.35	0.970	0.81
	Model 2	-0.5	-21.09	20.33	19.53	836.45	1.165	0.70
	Model 3	0.0	0.5	12.5	13.78	590.1	-0.041	0.86
	Model 4	7.5	320.20	22.75	19.92	853.45	-18.701	0.81
	Model 5	0.5	21.24	19.03	19.98	855.69	-1.147	0.72
Miri	Model 1	-3.98	-197.79	26.07	21.29	1058.65	7.79	0.61
	Model 2	-3.65	-181.35	25.88	21.14	1051.33	7.17	0.61
	Model 3	0.01	0.45	23.95	19.09	948.97	-0.02	0.69
	Model 4	-13.5	-671.22	28.64	26.06	1295.76	24.90	0.62
	Model 5	0.84	41.64	30.06	22.35	1111.33	-1.55	0.53
Limbang	Model 1	-7.18	-382.17	16.08	17.90	953.14	5.86	0.55
	Model 2	-7.18	-382.17	14.77	17.90	953.14	5.86	0.26
	Model 3	0.00	0.00	12.89	13.68	728.65	-2.73E-05	0.65
	Model 4	-8.90	-473.98	17.81	20.33	1082.70	6.55	0.57
	Model 5	2.09	111.17	23.03	22.85	1217.17	-1.21	0.49
Sibu	Model 1	0.08	3.74	25.03	21.75	997.43	-0.10	0.64
	Model 2	0.13	5.92	30.65	25.05	1149.13	-0.14	0.46
	Model 3	0.00	0.00	25.06	21.88	1003.46	0.00	0.63
	Model 4	3.74	171.10	29.56	23.27	1065.50	-4.21	0.63
	Model 5	-0.67	-30.80	30.80	23.88	1093.10	-1.96	0.56
Sri Aman	Model 1	0.09	4.36	27.19	15.51	746.78	-0.15	0.78
	Model 2	-0.51	-24.36	30.99	18.46	888.91	0.70	0.67
	Model 3	0.12	5.63	24.79	14.18	682.45	0.21	0.82
	Model 4	0.98	47.15	31.41	17.28	832.02	-1.45	0.79
	Model 5	1.55	74.46	30.95	18.62	896.54	-2.13	0.69

B) Model 2

Model 2 shows that the trend of predicted H is underestimated at five sites: Kapit (0.17%), Kuching (0.5%), Limbang (7.18%), Miri (3.65%), and Sri Aman (0.51%). While at Bintulu and Sibul are overestimated by 0.78% and 0.13% respectively. Overall the estimation of Model 2 over a long run contributes MBE that are close to zero except for Miri and Limbang stations. The MBE generated by Model 2 is similar to Model 1. Both of the Model 1 and 2 generated high MBE at Miri and Limbang stations.

Meanwhile, the MPE of Model 2 at each of the sites are: Bintulu (7.11%), Kapit (34.38%), Kuching (20.33%), Miri (25.88%), Limbang (14.77%), Sibul (30.65%), and Sri Aman (30.99%). This model performs the best at Bintulu with MPE of 7.11% and RMSE of 10.5% (339.77 W/m^2). The predicted value by the model is the closest to the actual measured value compared to the other site. But comparing with the performances of Model 1 at Bintulu, this model gives smaller RMSE. The highest MPE generated by Model 2 is at Kapit. Despite having high MPE, the RMSE generated is considerable to produce good estimation at short term.

Model 2 is tested to determine t-test and R value. The t-test generated at each of the meteorological stations is: Bintulu (-0.05), Kapit (0.24), Kuching (1.165), Miri (7.17), Limbang (5.86), Sibul (-0.14), and Sri Aman (0.70).

The correlation value, R, of Kuching station gives the highest value, which equal to 0.7, and it is the closest to +1 scale of the two clearness index relation. Model 1 and Model 2 has similar performances at Limbang, as its generated similar MBE (-7.8%) and RMSE (17.90%). However, the determination values, R, of the two models differentiate them. The R value of Model 2 at Limbang station is off with a value of 0.26, unlike R value of Model 1 which is 0.55. For Bintulu, Kapit, Miri, Sibul and Sri Aman stations the computed R are 0.43, 0.69,

0.61, 0.46 and 0.67 respectively. The variability of model proportion is considered satisfying with range at 0.4 to 0.6.

Overall this estimation model produces agreeable outcomes but it is inconsistent at each of the local stations. Model 2 performances are considered to be worst at Limbang site. The MBE generated is the highest compared to the other sites and correlation value, R is the lowest. However, the estimation over a short run is considered to be good. The performances of Model 1 and Model 2 are quite similar. This is perhaps the models is based on a single parameter in estimation.

C) Model 3

Model 3 uses measured meteorological data of ΔT , RH and CF. This model is developed to increase the accuracy of the two linear relation models (Model 1 and 2). The results of MBE shows that Sri Aman is overestimated H for 0.12% in long run. The other sites provide 0% of bias error. The model performs the best at Bintulu site with MPE of 6.43% and 9.5% of RMSE while the worst is at Sibul with MPE of 25.06% and RMSE of 21.88%.

The computed R values at each station are: Bintulu (0.57), Kapit (0.79), Kuching (0.86), Limbang (0.8), Miri (0.69), Sibul (0.63), and Sri Aman (0.82). Kuching station gives the highest R which is the closest of the model relation scale +1. The value computed indicates rather good proportionality of K_{COMP} and K_{MEAS} .

Model 3 performs the best consistently at five sites (Bintulu, Kapit, Kuching, Miri and Limbang) by contributing MBE that is close to zero, small MPE and RMSE, and close to +1 of R. Despite of having zero MBE, the value of MPE, RMSE and R generated by Model 3 are slightly off compared to Model 1. Meanwhile at Sri Aman site, Model 3 generated MBE of 0.12% which is slightly more than MBE of Model 1.

D) Model 4

The values of H predicted by model 4 are higher compared to the other models used in this study. Overall trend of data at long run or MBE shows that this model overestimated the data at Bintulu (27.6%), Kuching (7.5%), Sibul (3.7%), and Sri Aman (0.98%) stations. While at Miri (-13.5%), Kapit (-12%), and Limbang (-8.9%) stations are underestimated.

In term of generated MPE, the values at each of the local stations are: Bintulu (30.96%), Kapit (36.31%), Kuching (22.75%), Miri (28.64%), Limbang (17.81%), Sibul (29.56%), and Sri Aman (31.41%). The model prediction by using Model 4 generates very high MPE, which indicates high difference between measured dataset and estimated data.

The closeness of the predicted values to the actual measured data in short term is tested using RMSE. The generated RMSE are: Bintulu (32.4%), Kapit (22.1%), Kuching (19.9%), Miri (26.06%), Limbang (20.33%), Sibul (23.27%), and Sri Aman (17.28%). The results show that the data predicted at Sri Aman site is closest to the actual data by 17.28%. This model performs worst at Bintulu site as the differences of the predicted data and actual data is 32.4%.

The statistical significance of Model 4 is tested by using t-test. The outcomes of the t-test shown in Table 4.10 give rather high number compared to other prediction models. The results at each station are: Bintulu (-10.9), Kapit (16.08), Kuching (-18.7), Miri (24.9), Limbang (6.55), Sibul (-4.21), and Sri Aman (-1.45). Meanwhile, the determination value, R, of Model 4 is also presented in Table 4.10 where Bintulu, Kapit, Kuching, Limbang, Miri, Sibul, and Sri Aman are 0.2, 0.73, 0.81, 0.57, 0.62, 0.63, and 0.79 respectively. The value of R indicates the relationship of K_{COMP} and K_{MEAS} which theoretically is proportional on the scale of +1. The R value at Kuching is closer to the value, which means the model estimation is tend fall to the line.

This model may seem to look very simple but in term of accuracy are not suitable for the estimation of solar radiation. Consistent with findings by Irwanto [154], the performances of Model 4 produces high MBE and RMSE for prediction of H in Perlis. The recommended model coefficient by the author [147] is 0.16 for the interior region and 0.19 for the coastal area. But in this model, geographical profiles of sites are not taken into consideration. Since geographical characteristic of Sarawak consist of complex terrain, model 4 prediction of solar radiation is unstable and will contributes to high error prediction.

E) Model 5

The trends of predicted H value by Model 5 in long term indicate that the MBE generated is less than 5% when overestimate and less than 1% if it is underestimate. This model underestimates H value by -0.6% at Bintulu and -0.67% at Sibul sites. Meanwhile it overestimates the value at Kapit by 3.33%, Limbang by 2.09%, Sri Aman by 1.55%, Miri by 0.84% and Kuching by 0.5%.

In term of MPE, the percentage errors that being generated in Kapit site is the highest among the other sites, which is 35.68%. Then, the MPE for Sri Aman site is 30.95%. Bintulu site has the smallest MPE of 7.64%. The differences of predicted value are the closest to the mean measured value compared to the other sites. Meanwhile the RMSE value at Bintulu site indicates that the Model 5 performs the best with value of 11.3% (365.96 W/m²). The outcomes of t-test and R for Model 5 are also presented in Table 4.2. The generated t-test are Bintulu (0.30), Kapit (-4.47), Kuching (-1.147), Limbang (-1.21), Miri (-1.55), Sibul (-1.96), and Sri Aman (-2.13). Meanwhile, Kuching station produces R value that is the closest to +1 scale with the value of 0.72.

Model 5 performs slightly off from Model 1 when compared in term of RMSE and correlation value, R. Model 5 tends to produces RMSE that is in the range of 19-24%, which higher than RMSE of Model 1. However, both of Model 1 and 5 generated same RMSE at Bintulu site with values of 11.3%. Meanwhile in term of model performance in long run, the MBE of Model 5 is better than Model 1, where the maximum MBE produced is 3.33% at Kapit site. The accuracy of Model 5 can be enhanced perhaps by calibrating the coefficient c^5 to suit the local environment properties. Thus, measured atmospherics condition would be needed for the purpose.

When comparing all of tested model at each station, Model 3 performs the best compared to the other four models (except for Sibuloh site) and is highlighted in bold fonts. The data generated by it shows that the biased error is neither overestimated nor underestimated. The MBE of the model at the seven sites is as close to zero. Meanwhile, its RMSE indicates that the performances of Model 3 are the best which produces small differences of estimated and measured H. In term of R values, the model gives the estimation values that tend to fall in linear line of K_{COMP} and K_T relation.

Linear model of Model 1 and Model 2 are also can perform with agreeable results at each sites of Sarawak. But the two linear relations are not taking consideration of other factor such as cloud factor in predicting the value of H. This perhaps leads to inconsistency of the model performances at each of sites. Model 1, 4 and 5 are the model that using the temperature differences, ΔT in the estimation of H. But when predicting, there are various factor that dampen the temperature range, ΔT . It is either existence of high water molecules, aerosol, or dust particles in the atmosphere. Even though the prediction Model 2 is slightly off compared to Model 1, it is an important parameter which allows in understanding the effects of RH on the H. Sarawak has high RH that is range between 85-90% throughout the year and

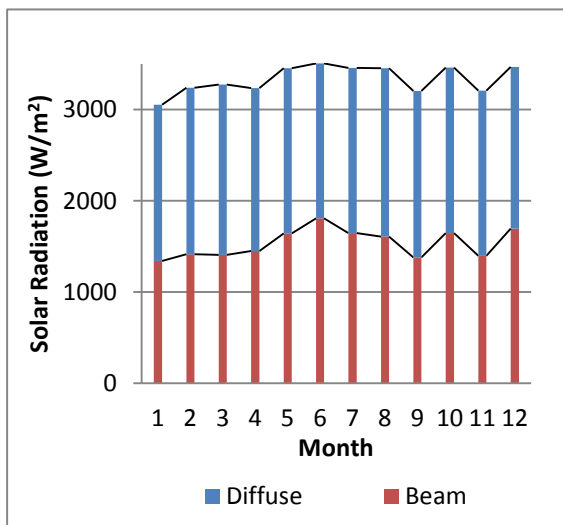
heavy cloud cover at average of 7 Octas daily. The two factors thus are known as the factor that reduces the ΔT .

4.3.4 Beam and Diffuse Radiation Prediction

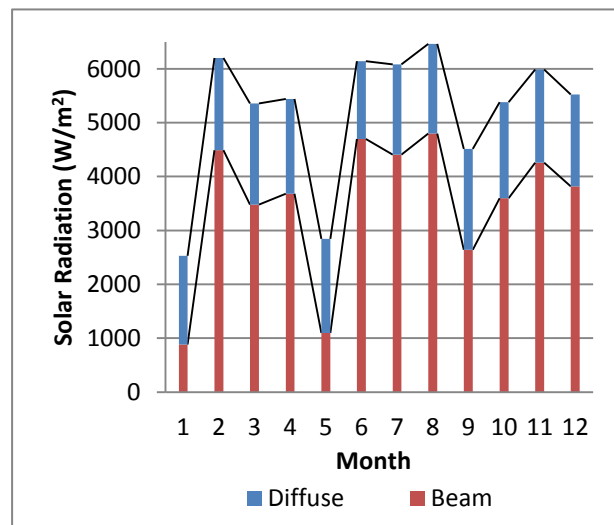
Figure 4.9 shows the graph of beam and diffused radiation components at each of MMD in Sarawak. The summation of the two components produces H at each of the stations. It is found that Bintulu, Kapit, Kuching, Sibul and Sri Aman receive high diffused radiation during January. The portion of diffused radiation to beam radiation as components of H is subtended more than half. The intensity of diffused radiation at Bintulu, Kapit, Kuching, Sibul and Sri Aman station are 1713W/m^2 , 1644W/m^2 , 1145W/m^2 , 1263W/m^2 , and 1629W/m^2 respectively. The portion of diffuse radiation to beam radiation at Bintulu, viewed in Figure 4.9(a), is quite consistent throughout the year which diffuse radiation is at range of 1600 to 1800W/m^2 . The similar phenomenon also occurs at Miri site which has diffused radiation within 1400W/m^2 to 1800W/m^2 . Meanwhile, Limbang and Miri received high portion of beam radiation with value of 2790W/m^2 and 1740W/m^2 respectively.

High intensity of diffused radiation at the five sites (Bintulu, Kapit, Kuching, Sibul and Sri Aman) is perhaps due to Northeast Monsoon season. The existence of thick and rain forming cloud (e.g. cumulonimbus and nimbostratus) attenuates the traversing solar radiation by absorbing and scattering it. Thus, depletes the portion of beam radiation in H . The condition further worsens by high relative humidity of the sites surrounding. The phenomenon can be seen at Kuching and Sibul sites, as shown in Figure 4.9(c) and (f), where the diffused radiation nominates the portion in H . But at Limbang and Miri station, beam radiations are rather high compared to diffused radiation. Perhaps the latitude of the two sites (Limbang: 4.775°N and Miri: 4.3995°N) affect the portion of the radiation component.

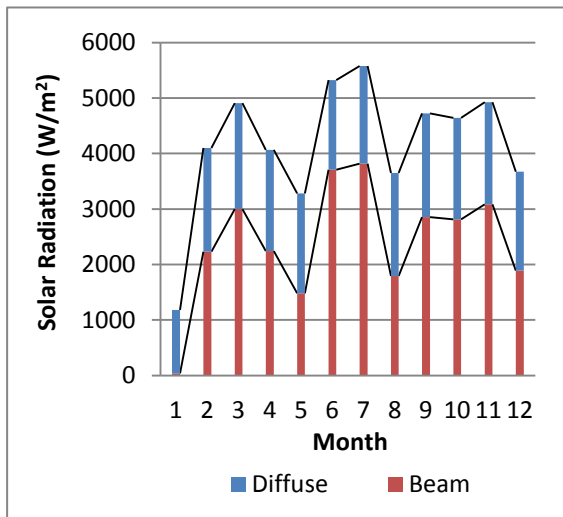
The diffused radiation component is estimated by using empirical correlation which is proposed by [162]. The author used the model to estimate diffused solar radiation in India and found out that the radiation is high for that region due to thick clouds and tropical area [162]. Since there is no ground measured data of these two radiation components, the diffuse radiation component is estimated by using that model and hence beam radiation component can be determined from the subtraction of H and computed diffused solar radiation component.



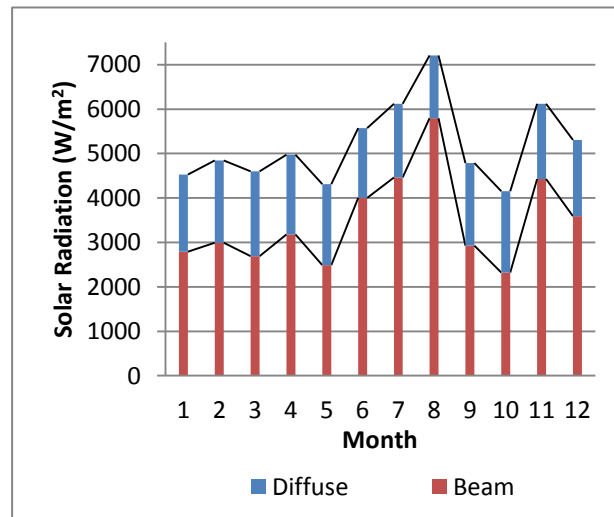
(a) Bintulu



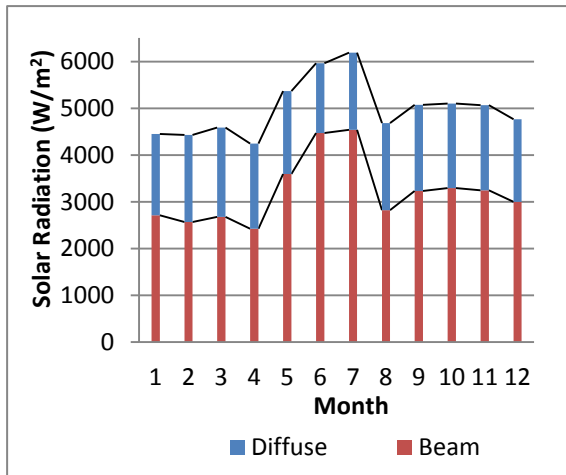
(b) Kapit



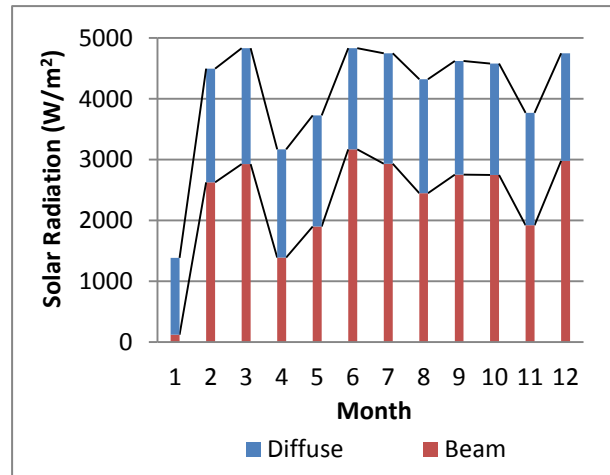
(c) Kuching



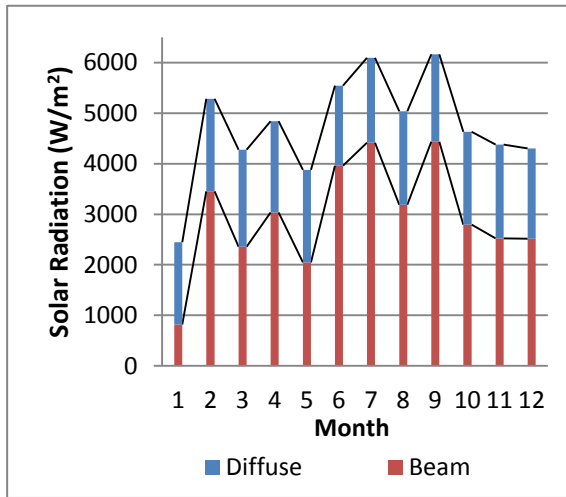
(d) Limbang



(e) Miri



(f) Sibuluan



(g) Sri Aman

Figure 4.9: Beam and Diffuse Radiation at Local Meteorological Stations

4.3.5 Sky Conditions

The sky condition can be quantified into clear, partially cloudy and cloudy either by utilizing clearness index, $\overline{K_T}$ [73] or cloudiness degree in octas and tenth [258]. The daily cloud coverage measured by MMD (see Appendix B) is at average of 7 octas which is classified as cloudy based on the latter method. The two methods are necessary data filters that categorize the day type with the basis of related parameters magnitude. The advantage of method proposed by [73] lies on the fact that solar global radiation measurements, which are

usually reported hourly, are required. However, utilizing the [258] method to quantify sky conditions requires concurrent observation of data as it is intermittent.

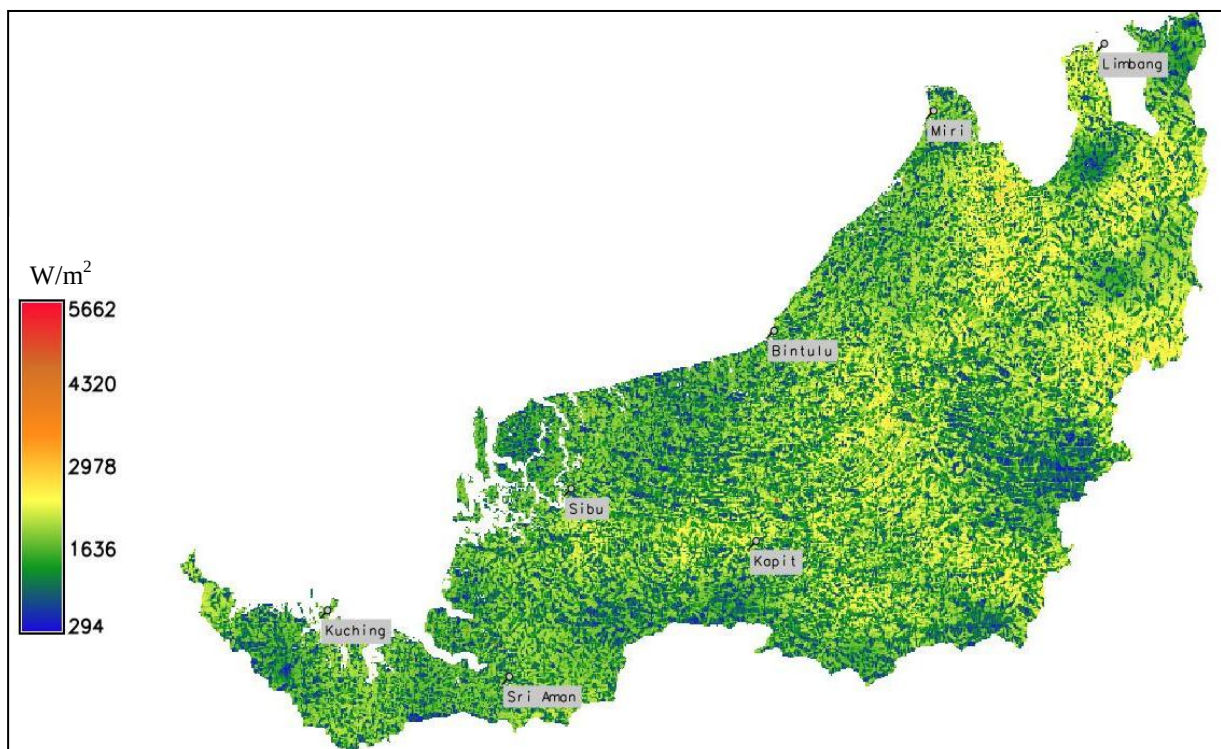
Table 4.11 shows the $\overline{K_T}$ computed for each of MMD with respect of models. The sky condition is determined from the ratio of computed H and extraterrestrial solar radiation, H_0 , which known as clear sky index, $\overline{K_T}$ [73, 233, 259]. Being a tropical country, Sarawak experiences partially cloudy sky. The sky condition in Sarawak is classified as partially cloudy [73, 238] despite the index being varies from 0.3 to 0.6. The $\overline{K_T}$ of Kuching, Limbang, Sibul and Sri Aman sites are consistent for all of the models. At Kapit site, the $\overline{K_T}$ computed using H computed by Model 5 indicated that the index is 0.6 which is the highest. From the index, it is noted that the H_0 is attenuated (due to temperature, cloud factor and relative humidity of the site) 50%-70% as it falls on the earth surface.

Table 4.11: Clearness Index, $\overline{K_T}$

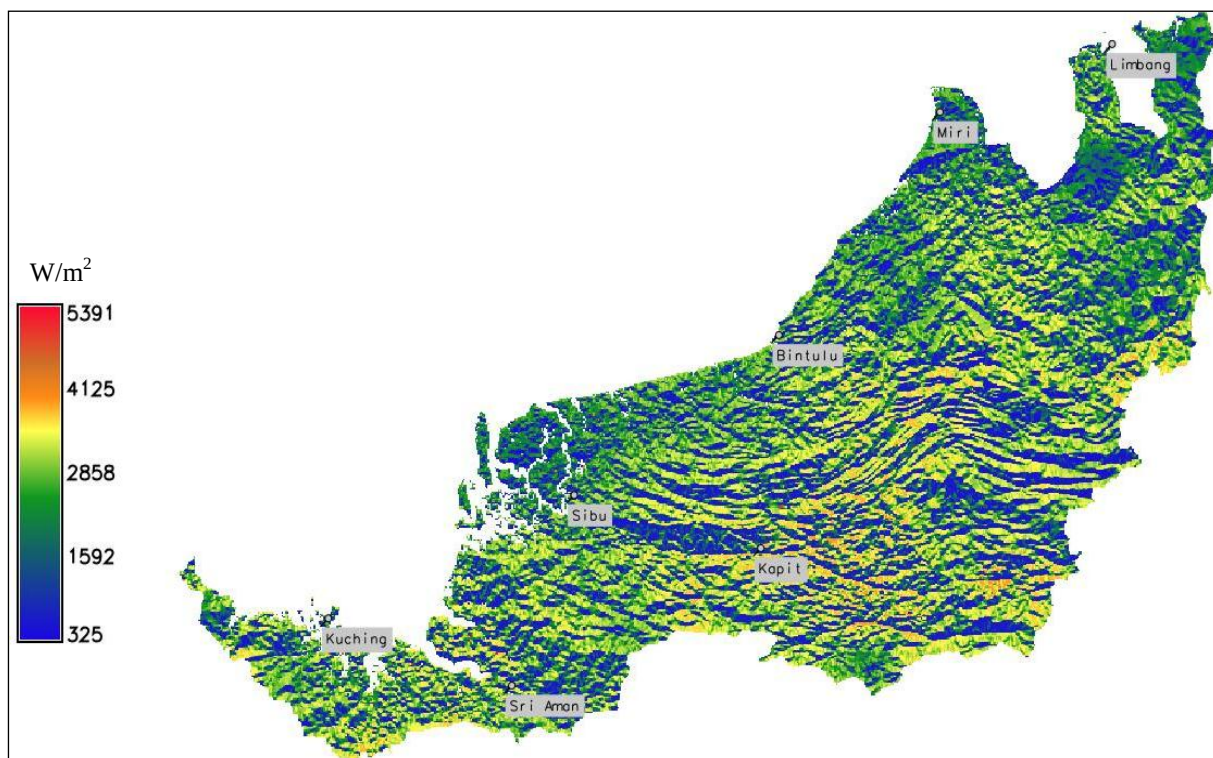
Clearness Index, $\overline{K_T}$					
	Model 1	Model 2	Model 3	Model 4	Model 5
Bintulu	0.3	0.3	0.3	0.4	0.3
Kapit	0.5	0.4	0.5	0.5	0.6
Kuching	0.4	0.4	0.4	0.4	0.4
Limbang	0.5	0.5	0.5	0.5	0.5
Miri	0.5	0.5	0.5	0.4	0.5
Sibu	0.4	0.4	0.4	0.4	0.4
Sri Aman	0.5	0.5	0.5	0.5	0.5

4.4 Overcast Solar Radiation Map

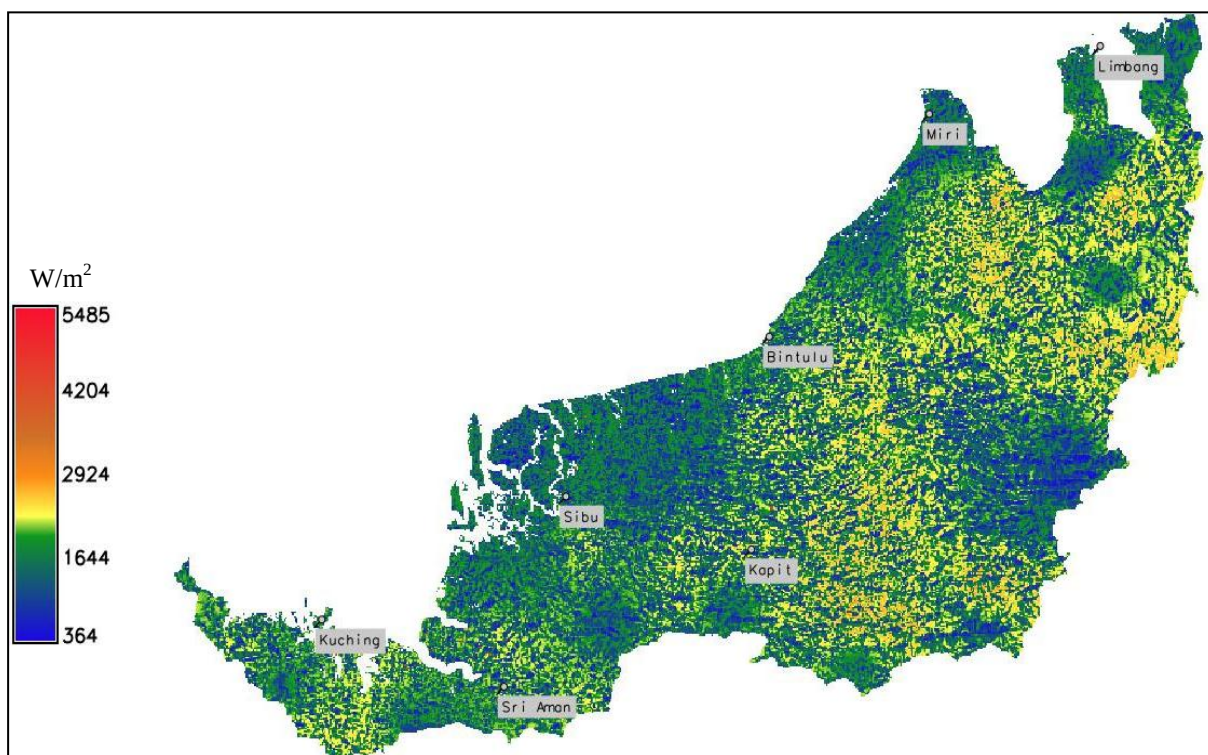
The overcast solar radiation maps are obtained by means of *r.sun* module with spatial resolution of 100m. The monthly overcast solar radiation maps are available in Appendix G. Whilst, Figure 4.10 shows the representative monthly maps of overcast solar radiation (March, June, September and December). Noted that the color scale for each the four solar radiation maps are different values.



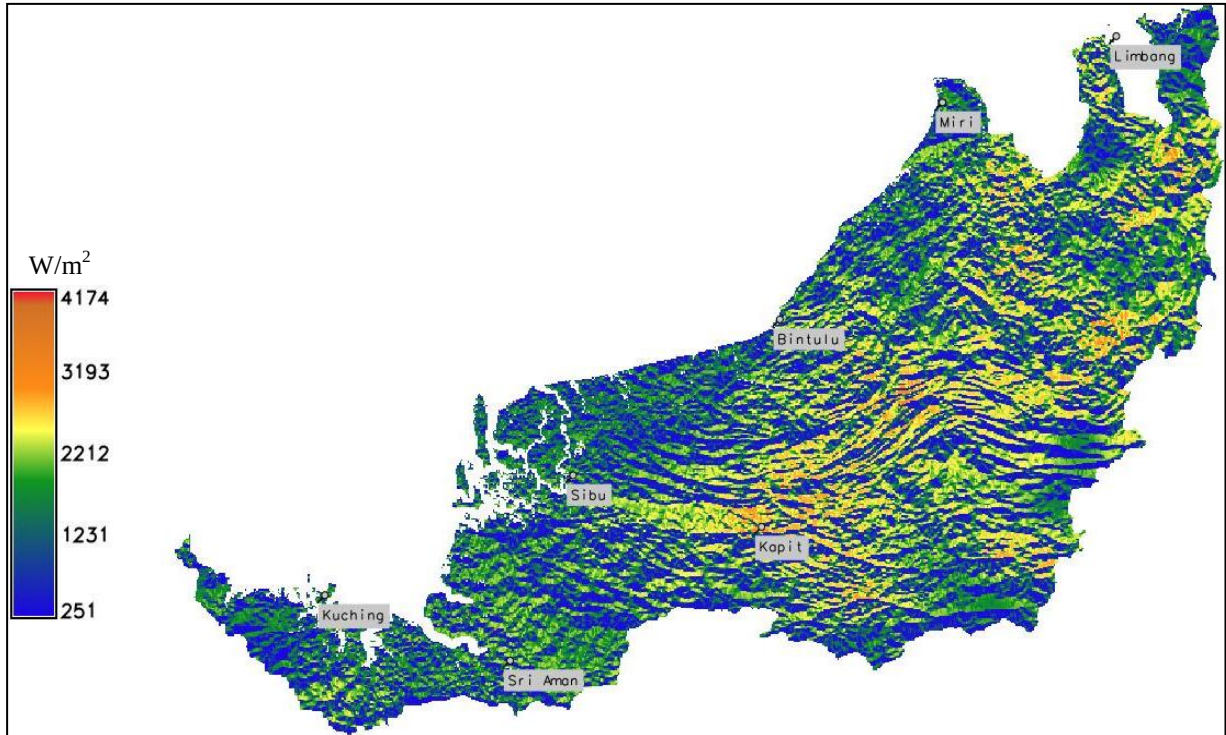
(a) March



(b) June



(c) September



(d) December

Figure 4.10: Sarawak Overcast Solar Radiation Maps

From GIS map generated, the maximum overcast solar radiation intensity received is 5391 W/m^2 in June while 4173 W/m^2 in December. Figure 4.11(b) and (d) the raster counts of the maximum intensities are small which happened to be less the 10 count of raster cells. There are high numbers of raster cell which has value less than 700 W/m^2 . The outcomes are due to solar radiation intensity at lower areas is dampened as the locations experience shadowing effects from positions of the sun within the day and neighboring terrains. In addition, the effects of the cloud cover exacerbate dampening of the solar radiation intensity. The average ground measured cloud coverage of in Sarawak is 7 Octas and average clearness index, K_C of 0.6 which is considered as partially cloudy [73].

Whilst in March and September, the solar radiation maps generated are quite similar. The average overcast radiation computed for the two months are 1628.34 W/m^2 and 1682.46 W/m^2 respectively. Figure 4.11 (a) and (c) shows the raster cells count of each raster

cell value for solar radiation maps generated. Both of the graphs trend indicated that the highest raster cell counts fall within 1900W/m^2 for March and September. Unlike the raster counts in June and December, there is no sudden spike of raster cells count that is below that 700W/m^2 . Instead, after the value of 700W/m^2 the overcast solar radiations intensity of March and September are rising.

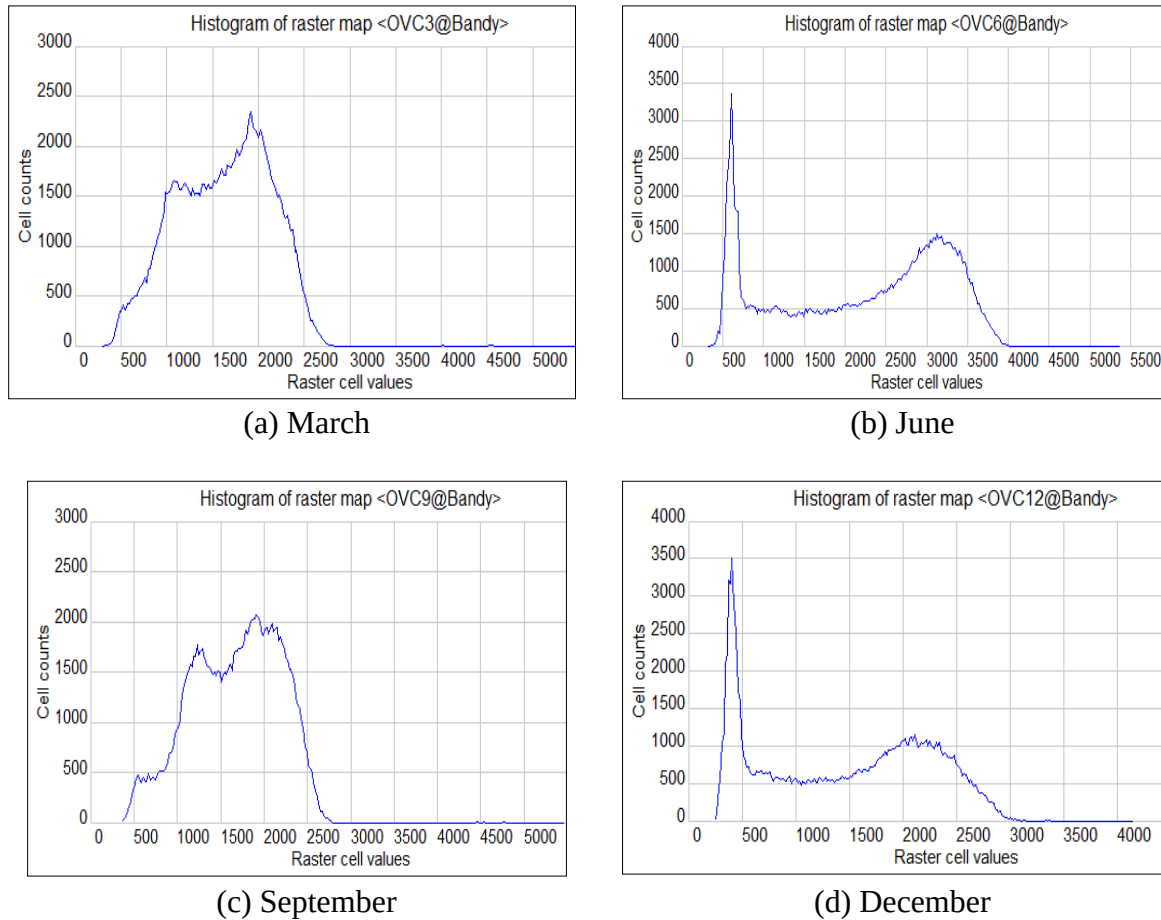


Figure 4.11: Solar Radiation Map Raster Cell Count

It is significant that the solar radiation which falls on the surface is varies throughout the places of Sarawak and the year. Sarawak receives different intensity of solar radiation due to complicated geographical surfaces (e.g. difficult terrains and thick jungle) [65]. The locations with higher elevation receive high intensity of solar radiation especially during June and December. The solar radiation that propagates from the sun is interacted with earth's

atmosphere and surface which is categorized into three groups: (i) earth geometry, revolution and latitude, (ii) terrain, (iii) atmospheric attenuation [198, 199]. Thus, the solar radiation intensity received by the earth is varied throughout the places and time.

Research study by [224] using the same *r.sun* module application found that the solar radiation intensity is varied during a year which the effects of the clear sky index and elevation are found to be factor affecting the intensity. Unlike the intensity during June, the South-Central Chilean received the lowest solar radiation intensity. Meanwhile, the mapping of monthly solar radiation intensity by using satellite images in Malaysia found that 4.96KW/m² on average and maximum of 5.56KW/m² [217]. The results generated by using two different methods (*r.sun* module and satellite image), indicated that the outcomes are in slight different in values.

4.5 Solar Radiation Capacity

Figure 4.12 shows solar photovoltaic annual capacity map and Appendix E is annual solar capacity at each district which has been extracted from the map shown. Throughout Sarawak, the capacity of electricity that can be generated by the system (using single panel) is at average of 93.85KW and maximum of 173.05KW, whereas at Belaga the maximum capacity generated is 42.151KW. The value predicted is the highest compared to other districts in Sarawak. The amount of electricity estimated is subjected to the type of solar PV panel chosen, panel sitting orientation, and surrounding environment (i.e. solar radiation received and ambient temperature).

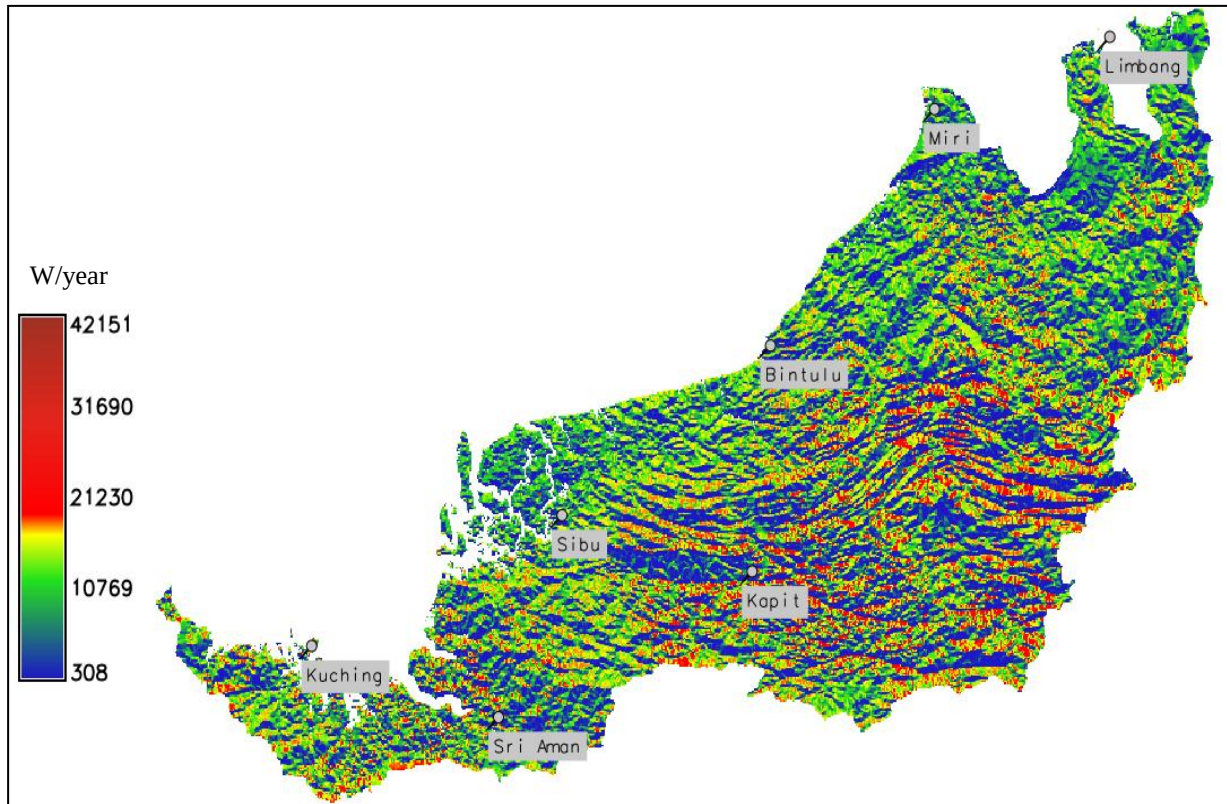


Figure 4.12: Annual PV Panel Energy Harvest

The generation of solar PV capacity map enables determination of location for solar panel system sitting. One of the most practical results from the map is the orientation of the PV system installation. The tilt angle of the PV panel is varied throughout the places and time. The orientation of panel is facing the south at optimum angle and solar radiation incident is calculated based on time of the year and location. From the finding of [12], solar panel that is installed in Kuching is fixed toward south at 11° to obtain optimum incident solar radiation during cloudy day.

Using the application of module extension in GRASS GIS, the solar radiation incident angle is calculated and developed to produce horizon raster layers which contain sun positions at different angles. Annual energy harvest is affected by the shadowing effects due to complex terrain surface of Sarawak [181, 260, 261]. Therefore, the orientation of the solar panel is also installed based on the aspect and slope layers generated from the DEM layers. The aspect

raster layer generated provides direction indication that the slope raster layer facing, while the slope raster map contains degrees of inclination from the horizontal surface.

Figure 4.13 and Figure 4.14 show the maximum and minimum air temperature maps of Sarawak respectively. The average maximum and minimum temperature are 29.3°C and 21.3°C respectively. It is noted that the air temperature is lower towards the inner parts of Sarawak (i.e. Lawas, Song, Lubok Antu, Belaga, Long Lama and Kapit). The efficiency of the solar panel is also affected by temperature in a way as shown in Equation 3.15. The solar radiation that received upon the earth also comes in form of long waves which heats up the surrounding temperature. Solar cell performance decreases with increasing temperature. This is due to the fact that high temperature of operating solar cell can cause the band gap to the intrinsic carriers to reduce, hence reducing the photovoltaic effect of the panel [94, 266-268]. Therefore, the potential to generate more solar capacity is at the area where the temperature is low.

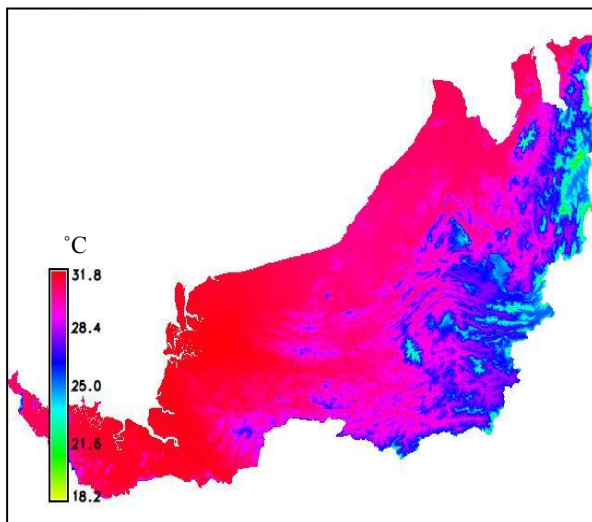


Figure 4.13: Maximum Air Temperature (°C) Map

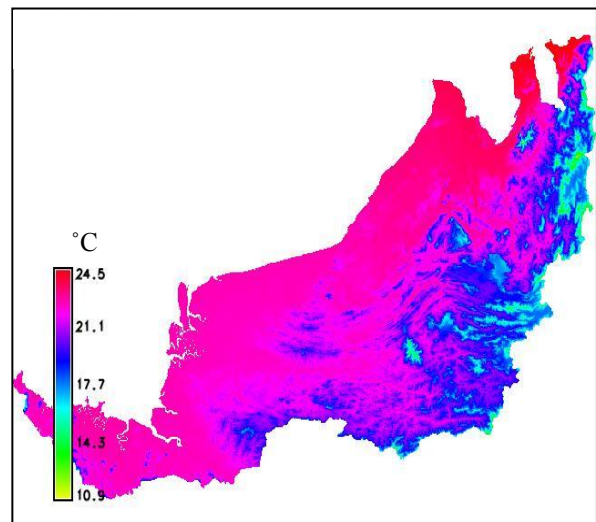


Figure 4.14: Minimum Air Temperature (°C) Map

Sarawak has its own potential in generating its clean energy from the sun. Appendix F shows the intensity of monthly global solar radiation. During June, when dry season occurs, the highest global solar radiation on horizontal surface that can be received in Sarawak is 6673.91W/m^2 . It is noted that the intensity of global solar radiation is varies throughout the year and places. This can give a bigger picture of solar radiation intensity and potential variation in Sarawak. The estimation of solar radiation at large area using local empirical models is inapplicable as its accuracy is the best within 20km from the MMD sites [8, 265]. Interpolation technique is used in the generation of mapset in this study which also implemented in [78, 224, 241, 266]. The interpolation techniques used in this research requires data points up to 50 points to generate map. Therefore, ground measured data obtained from MMD is integrated with satellite data.

The values from maps generated are extracted to obtain the value at each of seven meteorological stations as presented in Figure 4.15. The global solar radiation is estimated at the horizontal surface which defines as summation of diffuse radiation component and beam radiation component. The orientation of the panel itself does not optimize the collection of solar radiation because the intensity of beam radiation is proportional to the incident angle of solar radiation that hits the panel [272-274]. In a highly diffuse environment as in Kapit station, the beam component is a small fraction of the global solar radiation. The presence of the clouds cover and atmospheric turbidity causes some part of solar radiation to be diffused [222, 241]. While at the other station, beam radiation component is high fraction of the total components.

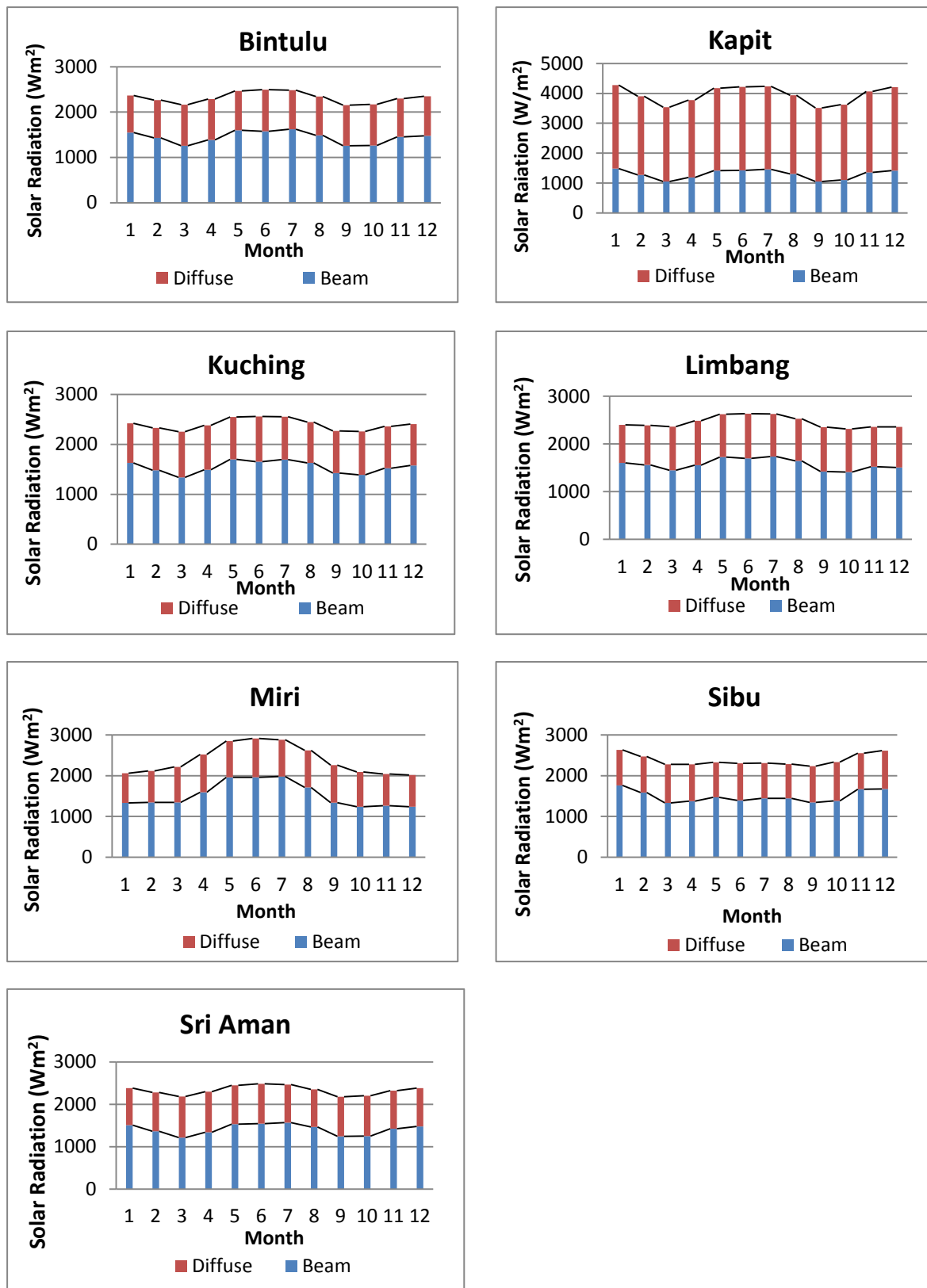


Figure 4.15: Global Solar Radiation on Horizontal Surface at Meteorological Stations.

The sum of the components obviously indicates the clear-sky condition of solar radiation at horizontal surface. Figure 4.16 presented the ratio of diffuse radiation to global solar radiation on horizontal surface at the seven meteorological stations. The ratios are varied between 0.5 and 0.7. This indicates that the solar radiation is attenuated by atmospheric (e.g. cloud, gases, and aerosols) via scattering and absorption [73, 270]. The attenuation of the solar radiation can be described by Linke Turbidity index [199, 276-278] which defined the optical thickness of the atmosphere.

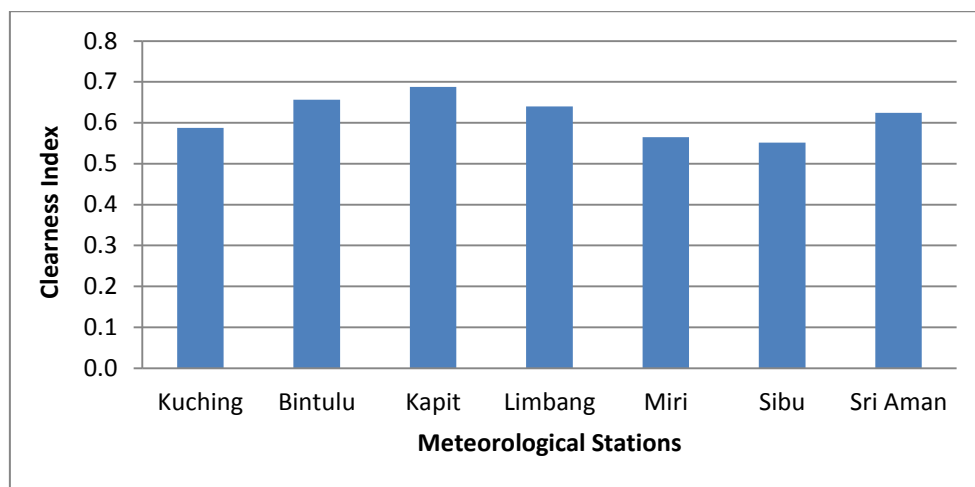


Figure 4.16: Diffuse Radiation to Global Solar Radiation Ratio

4.6 Chapter Summary

The meteorological data obtained from MMD are evaluated based on monthly average as recommended by [113]. It is found that the measured meteorological data of stations is localized to its site and has its own weather properties. The localized characteristic of the data is proven by the results in Table 4.2. Each of solar radiation estimation models are calibrated based on respective sites and have varied empirical coefficients.

The missing and defective solar radiation data are estimated by using the calibrated empirical models. In general, the models perform uniquely at different stations. The outcome of the estimations shows that the solar radiation is the lowest during January. This is due to

monsoon changes that bring wet seasons all over Malaysia. During dry season, the estimated solar radiation can be twice as the solar radiation in January. Often the dry season is during June until August. But for the site such as Sri Aman, the highest solar radiation estimated is during September.

Model 1-3 is developed based on regression analysis by using measured data obtained from MMD (refer to Table 4.1). Meanwhile Model 4 and 5 are developed by previous author [145, 225, 226] which used in this study as comparison with models developed. The model performances are tested by using statistical parameters (i.e. MBE, MPE, RMSE, t-test, and correlation coefficient). The outcomes shows that Model 3 performs the best by generated correlation coefficient that the closest to +1 and small values of MBE, MPE, and RMSE. Model 1 and 2 performs agreeable results but performs inconsistently for the sevens meteorological sites.

The best model performance is then used in solar potential estimation in wide area by using *r.sun* module in GRASS GIS. In general, the solar potential across Sarawak is varies due to complicated geographical surface factors and atmospheric conditions. The outcome of the simulation shows that the interior region of Sarawak has high solar potential due to high elevations. Furthermore, high capacity of solar PV systems can be generated at the interior regions as the temperature at the areas is low. Other factors such as solar PV panel used and panel sitting should be considered in solar system capacity estimation and system optimization. Thus through this, solar energy can be used as clean energy alternative to cope energy poverty at the rural areas of Sarawak. Overall, the objectives of this research are achieved pertinently to the conceptual framework in Figure 3.2.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The objectives of this research work are achieved. The missing and defective solar radiation data is predicted by using solar radiation models through calibration of the model's empirical coefficients. Meanwhile the estimation of solar radiation at the areas that are uncovered by meteorological stations is done through the development of GIS maps. Hence, the development of solar potential maps allows the study of solar capacity in Sarawak.

Sarawak is greatly dependent on fossil fuel as the source of electricity generation. As the number of population increases, the demand of the electricity is increasing. However, this source is depleting and exacerbates the global warming effect. Therefore, solar energy, as an alternative, is one of renewable energy that is clean, abundant and freely available. Sarawak is seen to have a big potential to generate its own clean energy from the sun.

The interest of this research is to enhance the electricity generation through application of solar energy technology (e.g. standalone PV system) especially in rural communities of Sarawak. The development of solar energy potential and capacity maps will benefit to engineers, system integrators and manufacturers as well as policy makers. The goals of this research study are to evaluate the potential solar radiation received on earth surface and its capacity at different locations in Sarawak.

The data involved in this study are meteorological data (e.g. solar radiation, air temperature, relative humidity and cloud cover) and DEM layer maps of Sarawak. The meteorological data being used in this study were obtained from MMD for periods of six

years (2010-2015) at seven stations in Sarawak. Meanwhile, DEM layer maps are obtained from USGS website. The acquired data were process to fit the needs for this research study.

The solar radiation is measured by using pyranometer at horizontal surface. It is found that there are missing and defective measured data from the MMD. The monthly average measured meteorological data are shown in Appendix B. Whilst, The DEM layer maps are used to generate horizon, elevation, aspect and slope raster maps through the application of GRASS extension module, *r.slope.aspect* with map projection of GDM2000/East Malaysia BRSO EPSG 3376.

The missing and defective solar radiation data is predicted by using regression analysis (linear regression and multiple linear regressions). The outcomes of the prediction are compared with Hargreaves-Samani model and Bristow-Campbell Model. The performances of the models used are tested using MBE, MPE, RMSE, t-test and R. The best model performance is used to estimate solar potential at wide area. Multiple linear regressions predicted the closest value of solar radiation to the measured data. The MBE, MPE and RMSE generated are the smallest compared to the other models used at the stations in Sarawak. Meanwhile, the determination value, R, indicates that the predicted values by using multiple linear regression method are tends to falls in linear line of computed clearness index, K_{COMP} and measured clearness index, K_{MEAS} relation.

When comparing all of tested model at each station, the multiple linear regression method performs the best compared to the other four models and is highlighted in bold fonts. The data generated by it shows that the biased error is neither overestimated nor underestimated. The MBE of the model at the seven sites is as close to zero. Meanwhile, its RMSE indicates that the performances of multiple linear regression method are the best which produces small differences of estimated and measured H. In term of R values, the model gives

the estimation values that tend to fall in linear line of computed clearness index, K_{COMP} and measured clearness index, K_{MEAS} relation.

Linear model of ΔT and RH are also can perform with agreeable results at each sites of Sarawak. But the two linear relations are not taking consideration of other factor such as cloud factor in predicting the value of H. Linear model ΔT , Hargreaves-Samani Model and Bristow-Campbell Model are the model that using the temperature differences, ΔT in the estimation of H. But when predicting, there are various factor that dampen the temperature range, ΔT . It is either existence of high water molecules, aerosol, or dust particles in the atmosphere. Even though the prediction Linear Model RH is slightly off compared to the Linear Model ΔT , it is an important parameter which allows in understanding the effects of RH on the H. Sarawak has high RH that is range between 85-90% throughout the year and heavy cloud cover at average of 7 Octas daily. The two factors thus are known as the factor that reduces the ΔT .

The potential and capacity of solar energy of Sarawak is done by means of GIS application. The software being used in this study is GRASS environment. The potential of solar energy is simulated by using *r.sun* module of GRASS. The simulation requires DEM raster layer (to generate elevation, aspect and slope raster layer), monthly Linke Turbidity raster maps, monthly cloud covers raster maps and vector layer maps developed from the predicted solar radiation data. The result of the simulation indicated that the highest overcast solar radiation can be received is during June with average of 5391 W/m^2 . It is noted that the simulated value of solar radiation is further reduced as the simulation took account the cloud effects and turbidity in the calculation. The generated monthly potential maps give a bigger picture of solar radiation in Sarawak and it is greatly affected by the complex terrains.

Last yet important part is the capacity of solar energy generated. Annually the possible PV capacity that can be generated for Sarawak is at average of 93.85 KW which is sufficient for basic electrification needs for a household. One of the most practical results from these maps is the orientation of suggested PV panel installation which is due to south depending on the location in Sarawak. Other factors such as type of solar panel used, surrounding temperature and radiation received by the panel are also considered in the development of the solar capacity map.

5.2 Limitation of Study and Future Recommendations

The conducted study herein is sufficient to provide wider pictures of solar potential and its system capacity properties. However, the outcomes are limited and dependent on the ground measured data from the seven MMDs in Sarawak. The measured data can be varying based on data availability, weather changes and seasonal effects. Thus, the outcomes cannot be generalized for the entire regions in the state.

This study is limited to this scope but able to provide a platform to extend further studies on the potential and capacity of solar energy in Sarawak. The suggestions for future works recommendation are:

- i. Mathematical model which used to estimate missing and defective solar radiation data can be further examined by using hourly data. This allows more understandings of the changes of solar radiation due to cloud effects, atmospheric turbidity and other environment surroundings.
- ii. Further study on the effects of geographical variations on the performance of PV systems by taking consideration of land use and demographic properties of Sarawak.

Road network can be included to allow feasibility and economic study of PV system installation at inner regions of Sarawak.

- iii. Improving solar PV capacity GIS map which includes more technical data of PV system assessment (e.g. sun-tracking system, real time PV system performance and radiation absorptance). The study of building integrated solar PV system or roof-top solar PV system capacity can also be investigated by means GIS application.
- iv. The solar potential maps generated can be generated by acquiring more ground measured data from minor and independent weather monitoring stations. The study conducted in this research is limited to the data obtained from the major meteorological stations in Sarawak. To obtain more realistic result of interpolation of maps, the ground measured data should be obtained at least at forty different places of location.
- v. The simulation of solar potential and capacity in Sarawak requires further practical validations. A hands-on practical validation is needed to carry at selected sites with different height, temperature, geographical variations, and atmospheric conditions (e.g. rainfall, clouds, and wind speed).
- vi. The study of solar potential and capacity can be further extended with different methods such as using Artificial Neural Network (ANN). This allows different types of variables that affect the solar potential to be considered.

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APPENDICES

Appendix A: Solar Photovoltaic Panel Specification

Sunmodule[®]

SW 325 XL MONO (33mm frame)



PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

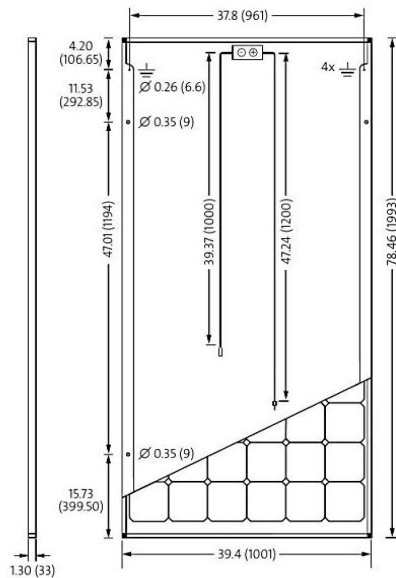
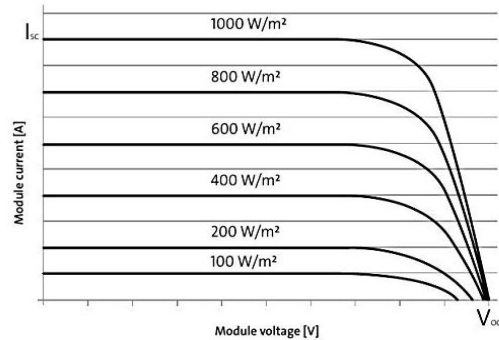
Maximum power	P_{max}	325 Wp
Open circuit voltage	V_{oc}	46.1 V
Maximum power point voltage	V_{mpp}	37.0 V
Short circuit current	I_{sc}	9.48 A
Maximum power point current	I_{mpp}	8.84 A
Module efficiency	η_m	16.29 %

*STC: 1000 W/m², 25°C, AM 1.5

1) Measuring tolerance (P_{max}) traceable to TUV Rheinland: +/- 2% (TUV Power Controlled).

THERMAL CHARACTERISTICS

NOCT	46 °C
TC I_{sc}	0.042 %/°C
TC V_{oc}	-0.304 %/°C
TC P_{mpp}	-0.43 %/°C
Operating temperature	-40°C to 85°C



PERFORMANCE AT 800 W/m², NOCT, AM 1.5

Maximum power	P_{max}	247.7 Wp
Open circuit voltage	V_{oc}	40.2 V
Maximum power point voltage	V_{mpp}	34.0 V
Short circuit current	I_{sc}	7.88 A
Maximum power point current	I_{mpp}	7.28 A

Minor reduction in efficiency under partial load conditions at 25°C: at 200 W/m², 100% (+/-2%) of the STC efficiency (1000 W/m²) is achieved.

COMPONENT MATERIALS

Cells per module	72
Cell type	Mono crystalline
Cell dimensions	6.17 in x 6.17 in (156.75 x 156.75 mm)
Front	Tempered glass (EN 12150)
Frame	Clear anodized aluminum
Weight	47.6 lbs (21.6 kg)

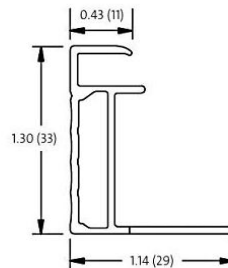
SYSTEM INTEGRATION PARAMETERS

Maximum system voltage SC II / NEC		1000 V
Maximum reverse current		25 A
Number of bypass diodes		3
Design Loads*	Two rail system	113 psf downward 64 psf upward
Design Loads*	Edge mounting	178 psf downward 23 psf upward

* Please refer to the Sunmodule installation instructions for the details associated with these load cases.

ADDITIONAL DATA

Power sorting	-0 Wp / +5 Wp
J-Box	IP65
Module leads	PV wire per UL4703 with H4 connectors
Module type (UL 1703)	1
Glass	Low iron tempered with ARC



- Compatible with both "Top-Down" and "Bottom" mounting methods
- ⚡ Grounding Locations:
 - 4 locations along the length of the module in the extended flange.

Appendix B: Ground Measured Data at Meteorological Sites

Bintulu							
Time		Measured Meteorological Data					Calculated Data
		Air Temperature (°C)		Relative Humidity	Solar Radiation	Cloud Factor	Air Temperature (°C)
Day	Month	Max	Min	(%)	(W/m ²)	(octas)	ΔT
17	1	26.8	23.7	94.7	N/A	7.5	3.1
46	2	31.4	23.1	87.2	N/A	7	8.3
75	3	29.9	23.7	90.2	N/A	7	6.2
105	4	31.7	23.8	87.3	N/A	7.1	7.9
135	5	31.3	24.5	87.3	N/A	7	6.8
162	6	32.7	23.9	83.5	N/A	7	8.8
198	7	33.9	24.4	82.9	N/A	7	9.5
228	8	30.8	24.2	87.6	N/A	7	6.6
259	9	32.5	24	86.7	N/A	7.1	8.5
289	10	32.8	24.5	84.2	N/A	7.1	8.3
319	11	32.4	24.6	87.2	N/A	7.2	7.8
345	12	33.6	24.1	82.8	3386.1	7	9.5
Average		31.65	24.04	86.80	3386.10	7.08	7.61

Kapit							
Time		Measured Meteorological Data					Calculated Data
		Air Temperature (°C)		Relative Humidity	Solar Radiation	Cloud Factor	Air Temperature (°C)
Day	Month	Max	Min	(%)	(W/m ²)	(octas)	ΔT
17	1	28.1	23.8	92.8	2483.3	7.2	4.3
46	2	33.7	24.2	80	6300	7	9.5
75	3	32.6	23.4	85	5777.7	7	9.2
105	4	33.7	23.4	87	DEFECT	7	10.3
135	5	29.6	24.6	92.3	2475.0	7.1	5
162	6	34.3	23.2	84.1	6836.1	7	11.1
198	7	35.9	25.4	83.1	6163.9	7	10.5
228	8	34.1	23.7	80.3	6144.4	7	10.4
259	9	33	25.1	87.7	DEFECT	7	7.9
289	10	33.8	24.1	86	4705.6	7	9.7
319	11	34.5	24.8	81.9	6002.8	7.1	9.7
345	12	33.8	24.9	83.2	5400.0	7	8.9
Average		33.09	24.22	85.28	4853.67	7.03	8.88

Kuching							
Time		Measured Meteorological Data					Calculated Data
		Air Temperature (°C)		Relative Humidity	Solar Radiation	Cloud Factor	Air Temperature (°C)
Day	Month	Max	Min	(%)	(W/m ²)	(octas)	ΔT
17	1	25.6	23.7	92.3	550	7.8	1.9
46	2	31.1	24.1	80.2	4883.3	7	7
75	3	31.5	22.6	79.2	5466.7	7	8.9
105	4	31.6	24.1	82.8	4702.8	7	7.5
135	5	31.4	24.4	89.6	2222.2	7	7
162	6	34.1	23.8	80.3	5394.4	6.8	10.3
198	7	35.2	24.6	78.9	5055.6	7	10.6
228	8	30.7	23	88.4	2586.1	7	7.7
259	9	33.9	24.8	75	4102.8	DEFECT	9.1
289	10	32.8	24.3	80.5	4008.3	7	8.5
319	11	33	22.9	84.2	5258.3	7	10.1
345	12	32	24.5	87.3	3630.6	7	7.5
Average		31.91	23.9	83.23	3988.43	7.05	8.01

Limbang							
Time		Measured Meteorological Data					Calculated Data
		Air Temperature (°C)		Relative Humidity	Solar Radiation	Cloud Factor	Air Temperature (°C)
Day	Month	Max	Min	(%)	(W/m ²)	(octas)	ΔT
17	1	31.6	23.2	86	N/A	7.2	8.4
46	2	31.6	23.6	84.9	N/A	6.8	8
75	3	32.1	24.1	85.6	N/A	7	8
105	4	34.2	25.1	85.8	N/A	7	9.1
135	5	32.7	24.5	89	N/A	7	8.2
162	6	33.2	23.3	84.5	N/A	6.8	9.9
198	7	34.7	24.5	80.3	N/A	6.8	10.2
228	8	33.9	23.8	82.7	N/A	5.2	10.1
259	9	32.9	25.2	82.8	N/A	7	7.7
289	10	31.8	23.5	90.8	N/A	7	8.3
319	11	34.4	24	82.6	N/A	6.6	10.4
345	12	32.8	24.4	83.5	N/A	6.6	8.4
Average		32.99	24.1	84.88	0	6.75	8.89

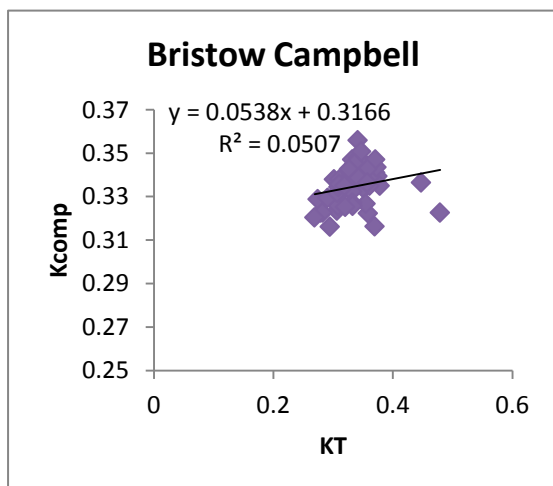
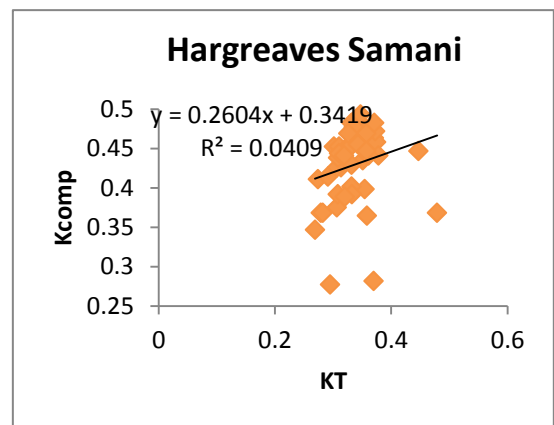
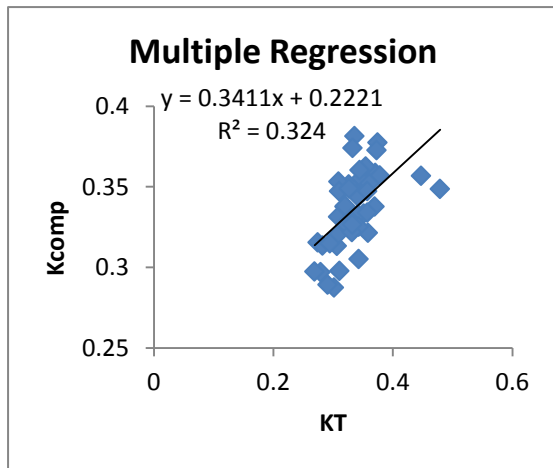
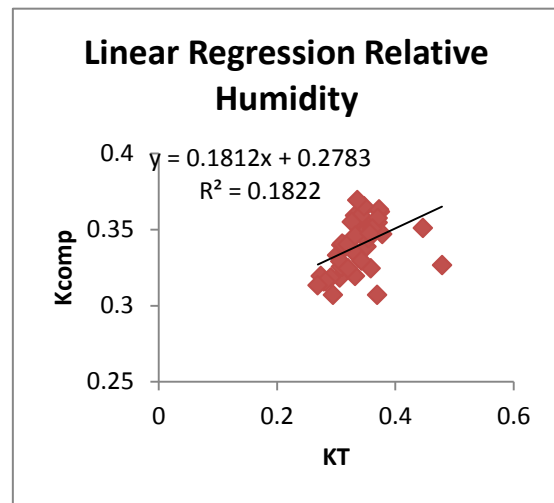
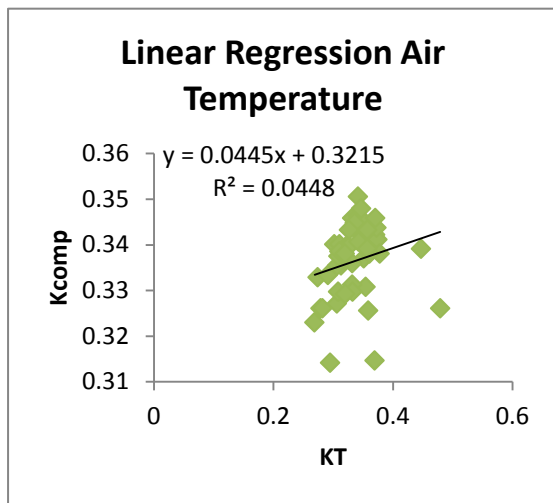
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Time		Measured Meteorological Data					Calculated Data
		Air Temperature (°C)		Relative Humidity	Solar Radiation	Cloud Factor	Air Temperature (°C)
Day	Month	Max	Min	(%)	(W/m ²)	(octas)	ΔT
17	1	31.3	24	87.9	3305.6	7	7.3
46	2	31.7	24.2	88.8	3158.3	7	7.5
75	3	30.9	24	86.4	5308.3	6.9	6.9
105	4	31.4	25.5	84.8	5127.8	7	5.9
135	5	32.4	24.1	82.7	5325	7	8.3
162	6	31.9	23.3	79.3	6663.9	6.9	8.6
198	7	34	25.7	76	6313.9	6.9	8.3
228	8	31.5	24.9	83.1	5216.7	7	6.6
259	9	32.9	25.4	82.6	4427.8	7	7.5
289	10	32.1	24.7	82	5044.4	7	7.4
319	11	32	24.3	83.4	6211.1	7	7.7
345	12	31.8	24.8	83.8	4977.8	7	7
Average		31.99	24.58	83.4	5090.05	6.98	7.42

Sibu							
Time		Measured Meteorological Data					Calculated Data
		Air Temperature (°C)		Relative Humidity	Solar Radiation	Cloud Factor	Air Temperature (°C)
Day	Month	Max	Min	(%)	(W/m ²)	(octas)	ΔT
17	1	26	23.7	90.2	1769.4	7.3	2.3
46	2	32.1	23.4	82.7	5358.3	7	8.7
75	3	33	23.5	82.6	5013.9	7	9.5
105	4	30.4	24.8	84.9	4644.4	7	5.6
135	5	31.7	24.8	87.8	3219.4	7	6.9
162	6	33.7	24.2	82.6	6136.1	7	9.5
198	7	34.3	25	81.1	DEFECT	7	9.3
228	8	31.9	23.6	87.8	4605.6	7	8.3
259	9	34.5	25.5	79	5136.1	7	9
289	10	32.9	24	86.2	4202.8	7	8.9
319	11	31.5	24.5	89.8	3208.3	7	7
345	12	33.1	23.8	84.5	6288.9	7	9.3
Average		32.09	24.23	84.93	4507.56	7.03	7.86

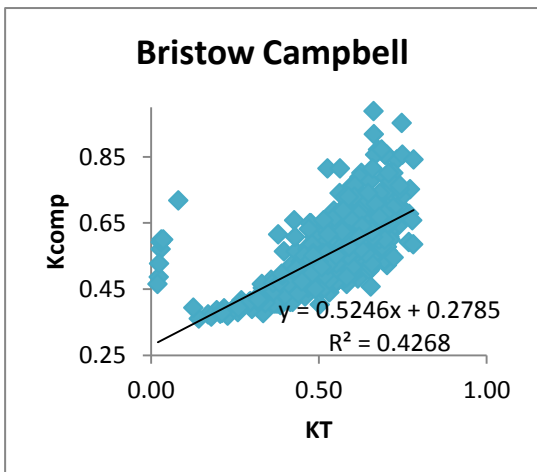
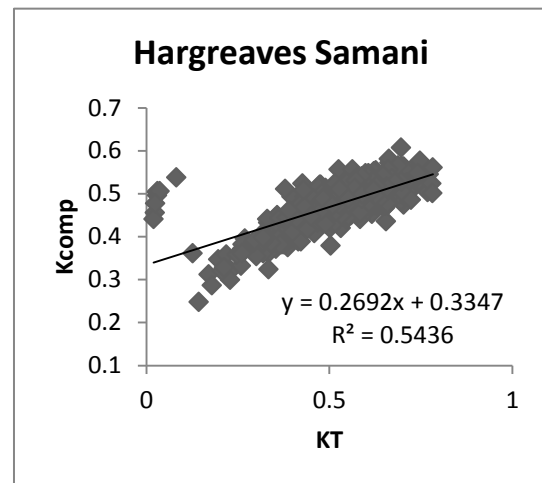
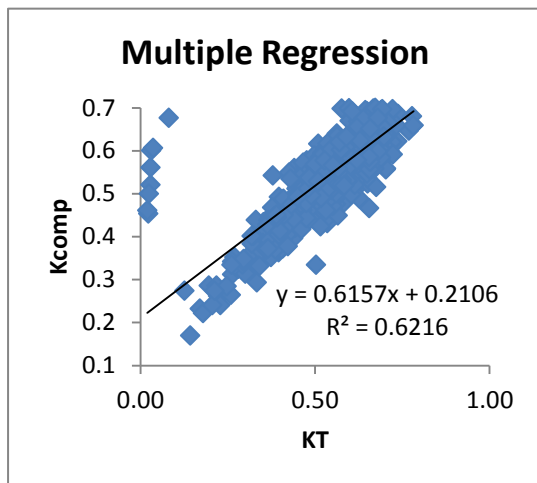
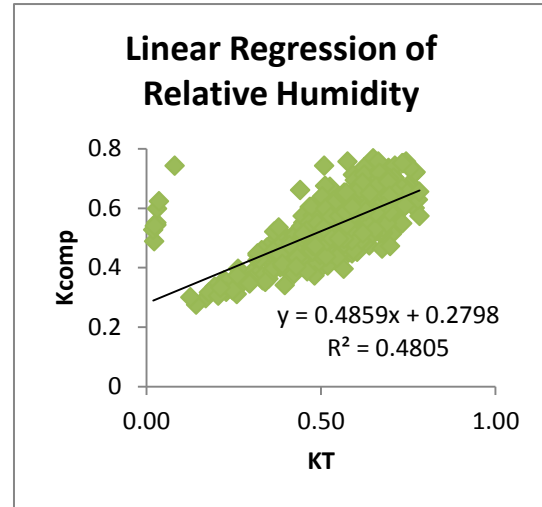
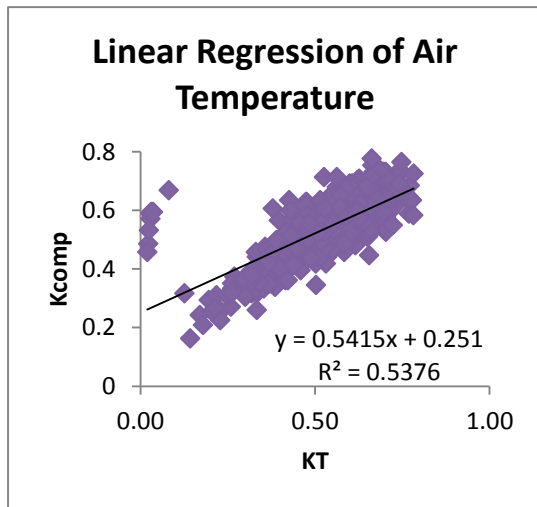
Sri Aman							
Time		Measured Meteorological Data					Calculated Data
		Air Temperature (°C)		Relative Humidity	Solar Radiation	Cloud Factor	Air Temperature (°C)
Day	Month	Max	Min	(%)	(W/m ²)	(octas)	ΔT
17	1	28	23.6	95	2300	7.5	4.4
46	2	33.7	23.5	83.9	4983.3	7	10.2
75	3	31.9	23.5	88.3	3652.8	6.6	8.4
105	4	33.2	24.1	84	DEFECT	6.8	9.1
135	5	32.7	24.8	92.4	3700	7	7.9
162	6	33.9	22.3	87.3	5827.8	6.5	11.6
198	7	36.5	24.8	78.8	4925	6.3	11.7
228	8	32.7	23.3	83	4952.8	7	9.4
259	9	35.6	23.8	78.1	5419.4	6.2	11.8
289	10	33.5	25.1	83.5	5230.6	7	8.4
319	11	32.1	23.2	89.7	5130.6	6.6	8.9
345	12	32.5	24.1	88.9	5083.3	7.1	8.4
Average		33.03	23.84	86.08	4655.05	6.8	9.18

Appendix C: Model Fitting

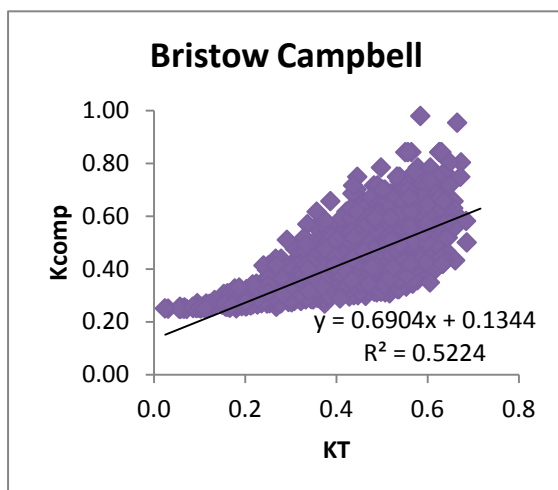
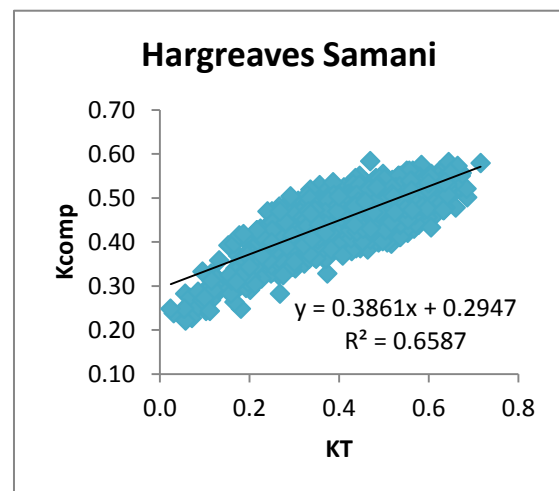
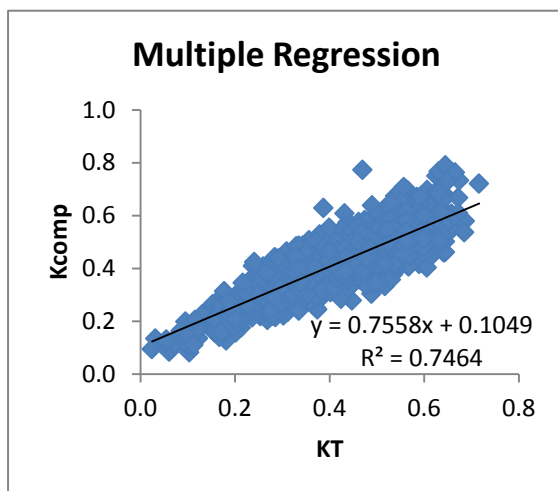
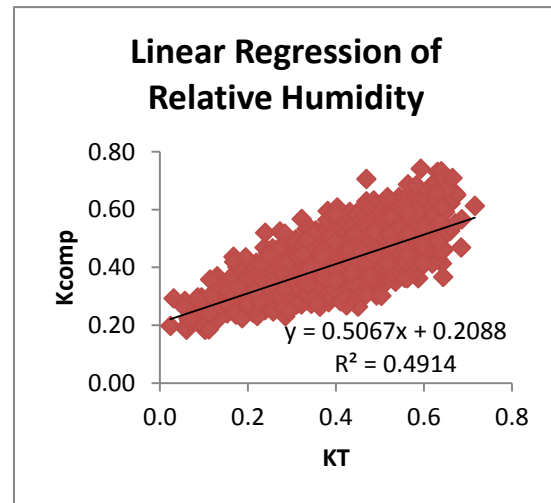
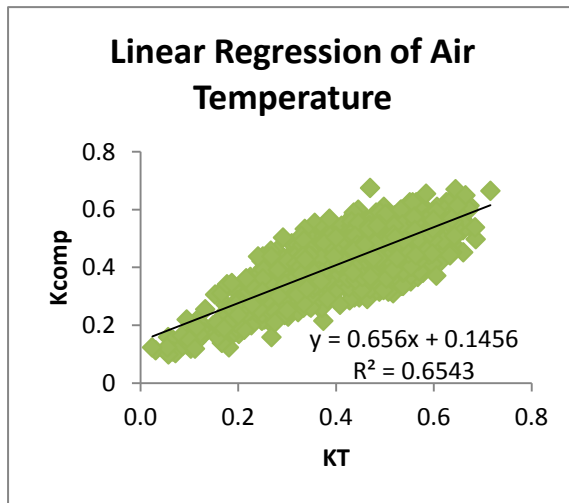
Appendix C.1: Models Fitting of Bintulu Site



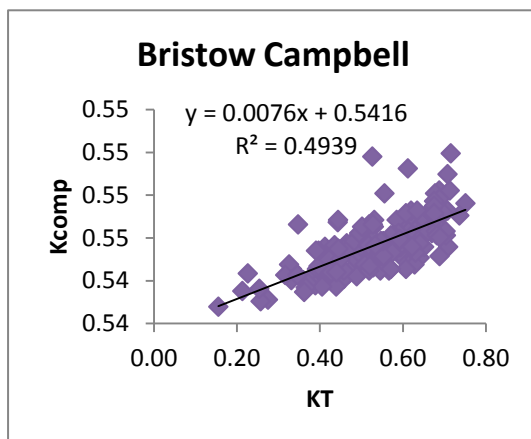
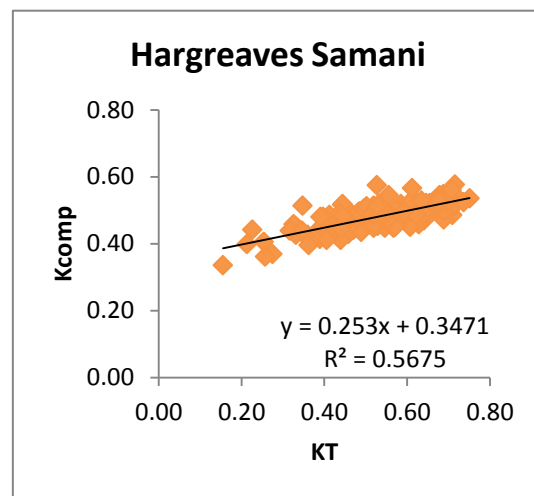
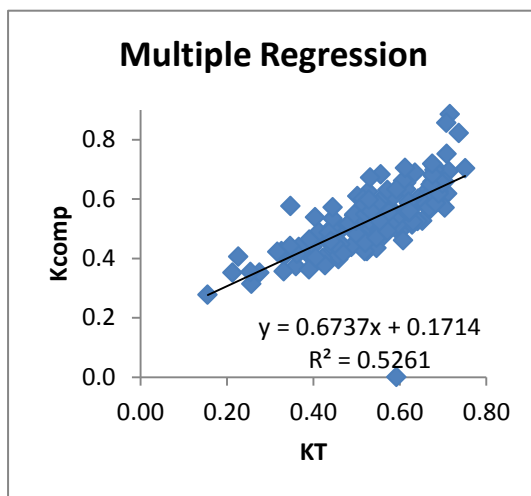
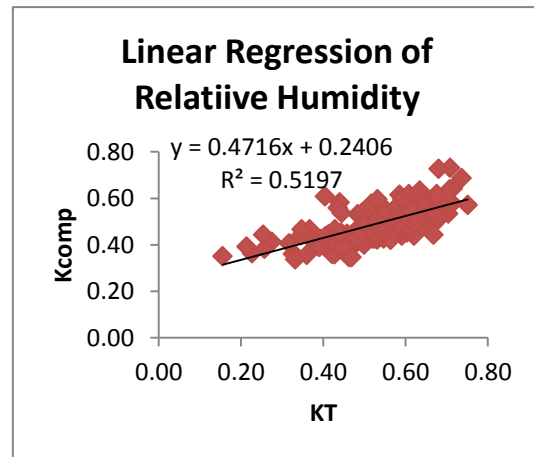
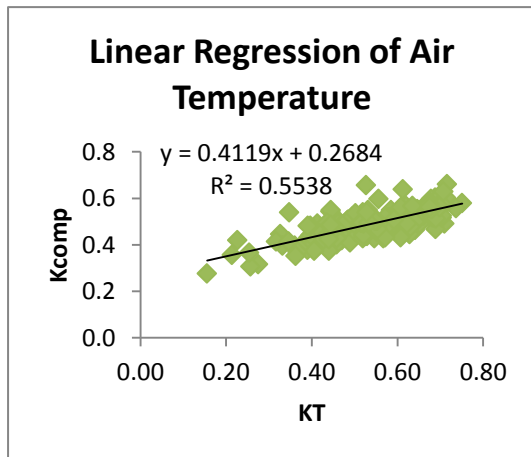
Appendix C.2: Models Fitting of Kapit Site



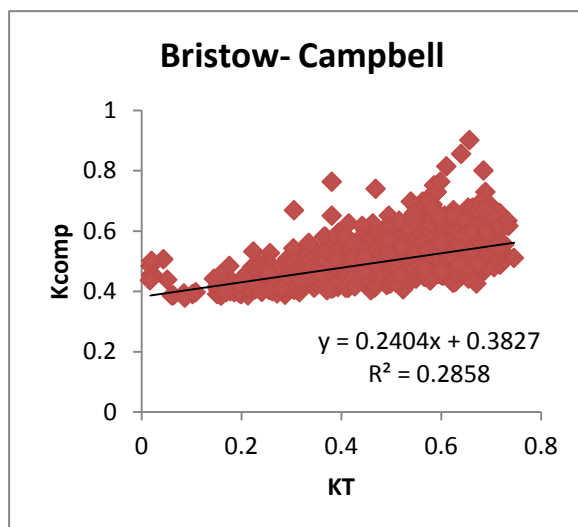
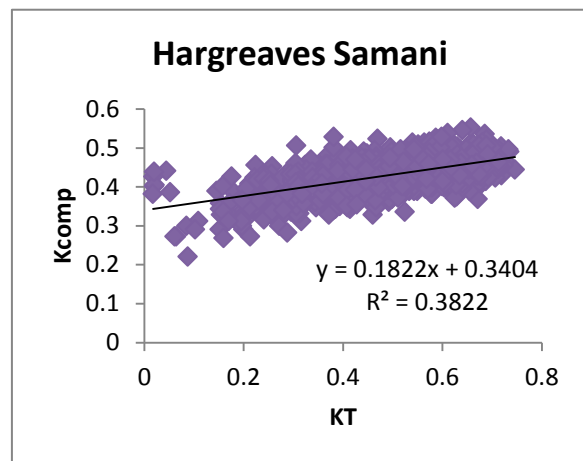
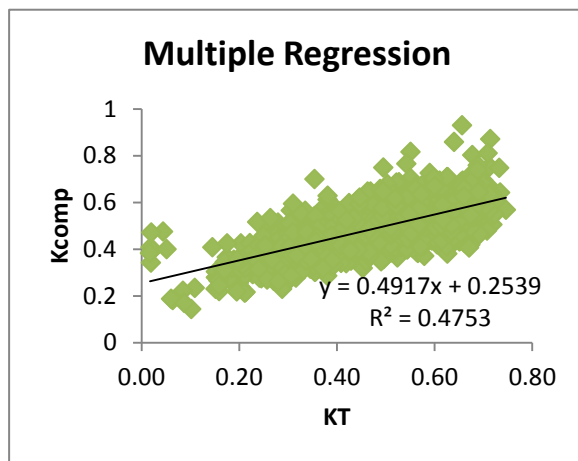
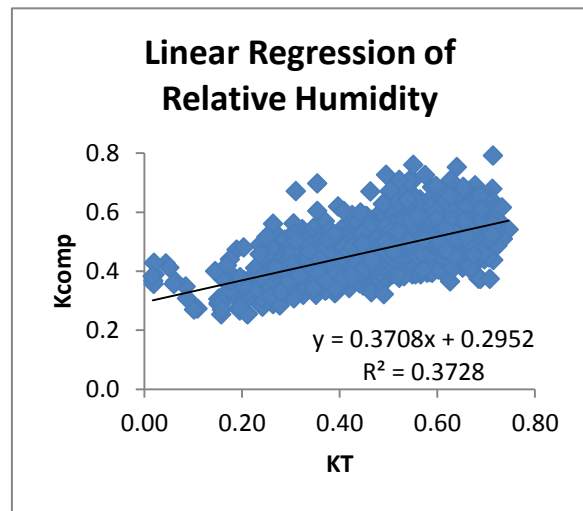
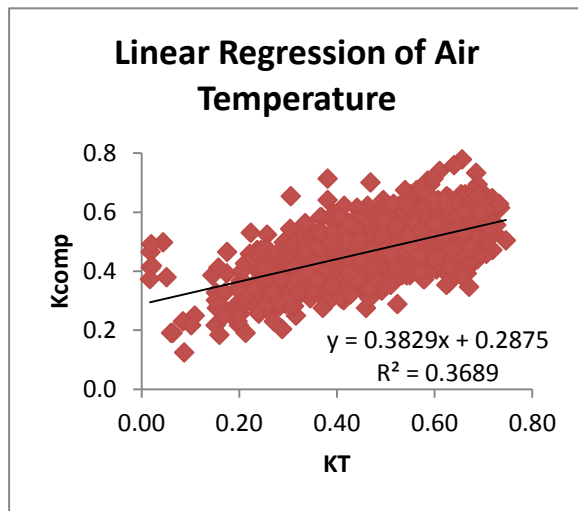
Appendix C.3: Models Fitting of Kuching Site



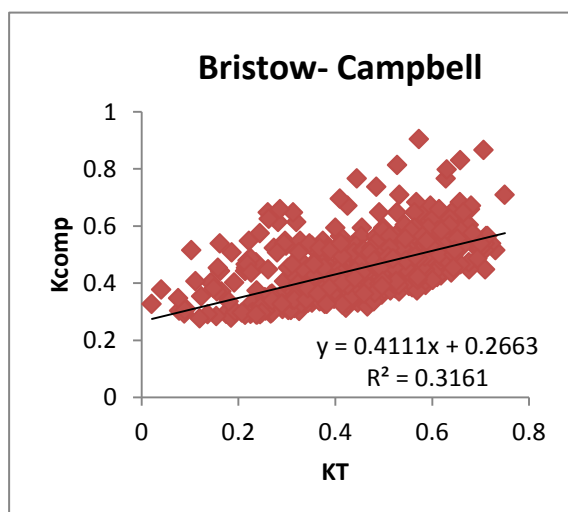
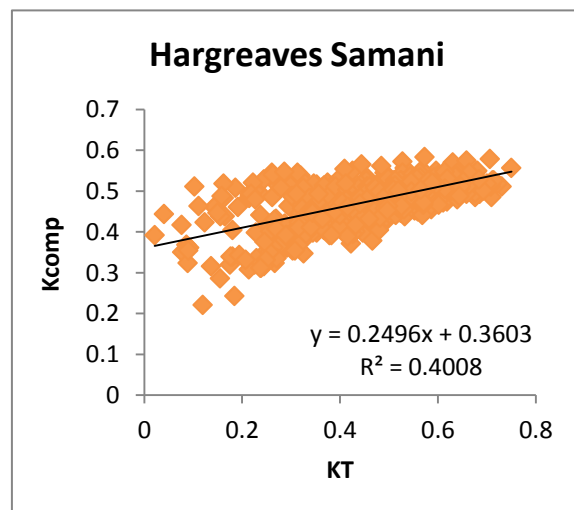
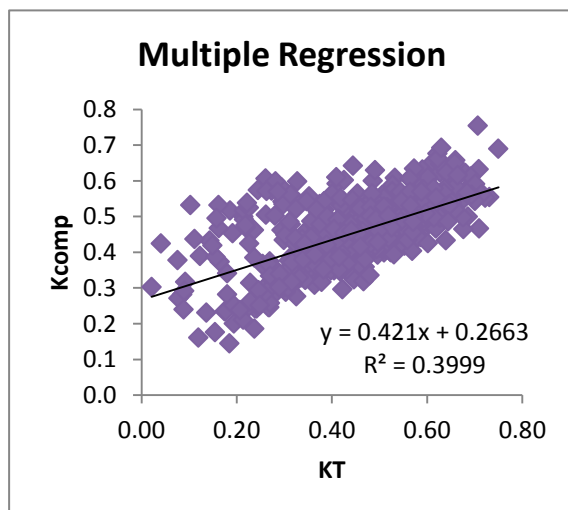
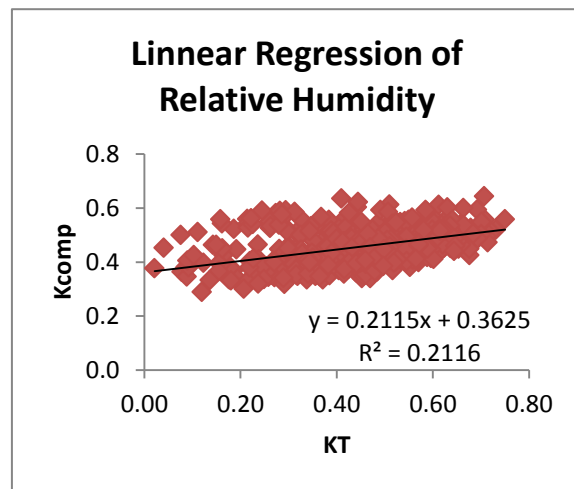
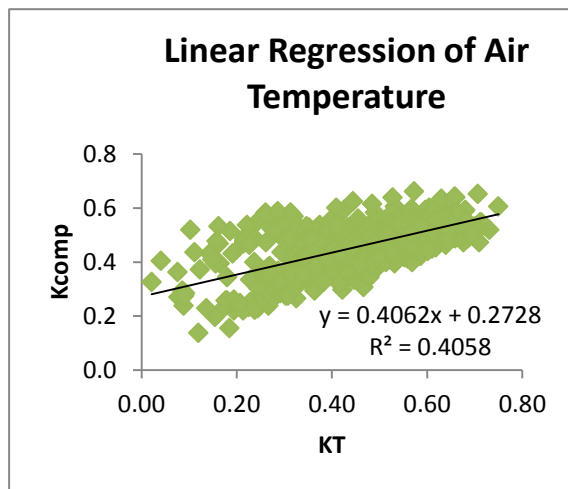
Appendix C.4: Models Fitting of Limbang Site.



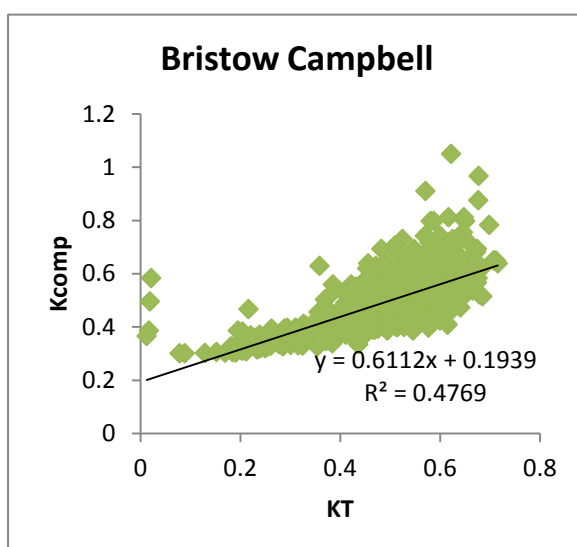
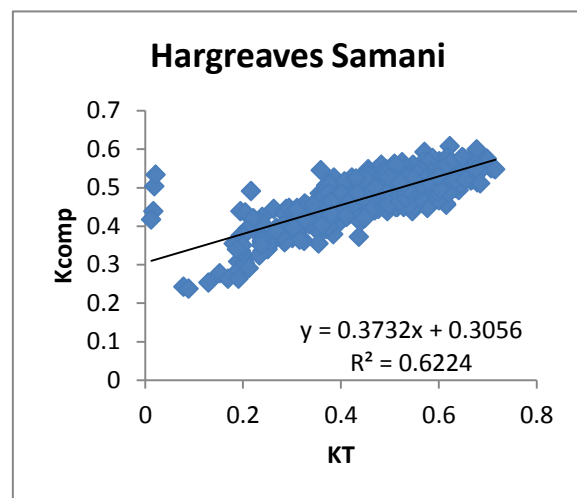
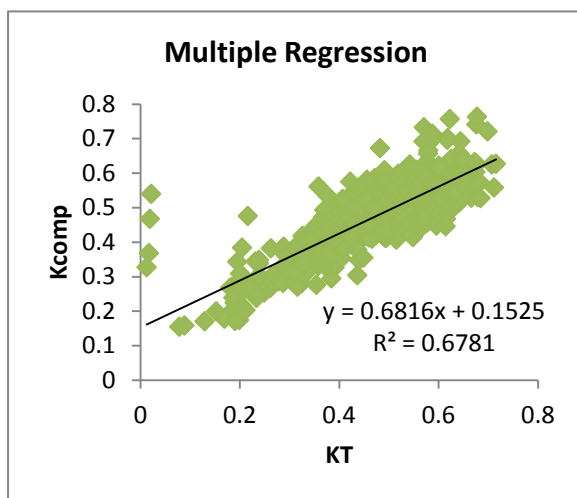
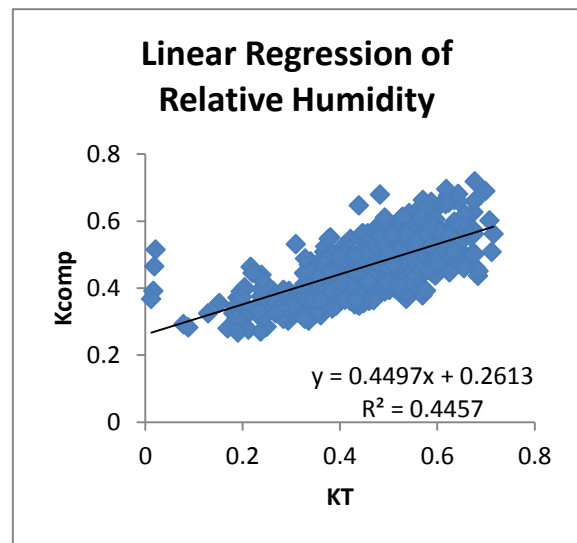
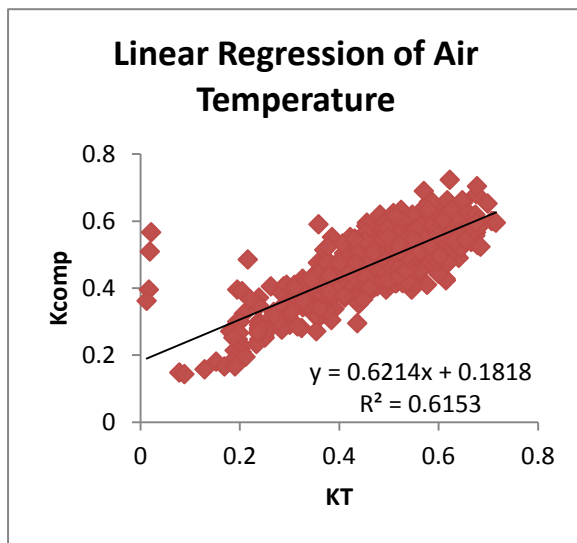
Appendix C.5: Models Fitting of Miri Site



Appendix C.6: Models Fitting of Sibu Site



Appendix C.7: Models Fitting of Sri Aman Site



Appendix D: t-Test: Paired Two Sample for Means

STATION: BINTULU	t-Test: Paired Two Sample for Means					
	Measured	Model 1	Model 2	Model 3	Model 4	Model 5
Meteorological parameter		ΔT	RH	T-RH-CF	ΔT	ΔT
Mean	3243.357	3241.567	3268.817	3243.795	4138.575	3224.418
Variance	142609.6	13050.41	32807.93	45982.9	252235.7	15263.72
Observations	46	46	46	46	46	46
Pearson Correlation		0.212834	0.424494	0.567854	0.223133	0.228682
Hypothesized Mean Difference		0	0	0	0	0
df		45	45	45	45	45
t Stat		0.032773	-0.50407	-0.00955	-10.9014	0.347628
P(T<=t) one-tail		0.487	0.308334	0.49621	1.63E-14	0.36487
t Critical one-tail		1.679427	1.679427	1.679427	1.679427	1.679427
P(T<=t) two-tail		0.974001	0.616668	0.99242	3.25E-14	0.729741
t Critical two-tail		2.014103	2.014103	2.014103	2.014103	2.014103

STATION: KAPIT	t-Test: Paired Two Sample for Means					
	Measured	Model 1	Model 2	Model 3	Model 4	Model 5
Meteorological parameter		ΔT	RH	T-RH-CF	ΔT	ΔT
Mean	5473.794	5476.22	5464.397	5473.704	4812.288	5656.094
Variance	1703511	973976.6	946506	1021203	312364.3	1114999
Observations	624	624	624	624	624	624
Pearson Correlation		0.719169	0.678288	0.774171	0.650836	0.643737
Hypothesized Mean Difference		0	0	0	0	0
df		623	623	623	623	623
t Stat		-0.06675	0.243742	0.002709	16.08399	-4.45659
P(T<=t) one-tail		0.473402	0.403755	0.49892	3.14E-49	4.94E-06
t Critical one-tail		1.647303	1.647303	1.647303	1.647307	1.647303
P(T<=t) two-tail		0.946804	0.807511	0.997839	6.27E-49	9.87E-06
t Critical two-tail		1.963779	1.963779	1.963779	1.963785	1.963779

STATION: KUCHING	t-Test: Paired Two Sample for Means					
	Measured	Model 1	Model 2	Model 3	Model 4	Model 5
Meteorological parameter		ΔT	RH	T-RH-CF	ΔT	ΔT
Mean	4283.569	4269.082	4262.481	4284.088	4603.767	4304.811
Variance	1373530	938213.3	752039.6	1024799	346442.7	1292708
Observations	2136	2136	2136	2136	2136	2136
Pearson Correlation		0.808297	0.701556	0.863937	0.792839	0.725756
Hypothesized Mean Difference		0	0	0	0	0
df		2135	2135	2135	2135	2135
t Stat		0.969819	1.165265	-0.04064	-18.7018	-1.14741
P(T<=t) one-tail		0.166123	0.122021	0.483794	1.07E-72	0.12567
t Critical one-tail		1.645568	1.645568	1.645568	1.645568	1.645568
P(T<=t) two-tail		0.332246	0.244042	0.967588	2.13E-72	0.251339
t Critical two-tail		1.961076	1.961076	1.961076	1.961076	1.961076

STATION: LIMBANG	t-Test: Paired Two Sample for Means					
	Measured	Model 1	Model 2	Model 3	Model 4	Model 5
Meteorological parameter		ΔT	RH	T-RH-CF	ΔT	ΔT
Mean	5325.869	4909.906	4909.906	5325.871	0.542211	5446.875
Variance	1491541	624257.7	624257.7	956980.2	1.87E-14	45142.13
Observations	147	147	147	147	147	147
Pearson Correlation		0.712642	0.712642	0.801002	0.63344	0.115178
Hypothesized Mean Difference		0	0	0	0	0
df		146	146	146	146	146
t Stat		5.860769	5.860769	-2.7E-05	52.86732	-1.20722
P(T<=t) one-tail		1.47E-08	1.47E-08	0.499989	2.12E-97	0.11465
t Critical one-tail		1.655357	1.655357	1.655357	1.655357	1.655357
P(T<=t) two-tail		2.94E-08	2.94E-08	0.999978	4.25E-97	0.2293
t Critical two-tail		1.976346	1.976346	1.976346	1.976346	1.976346

STATION:MIRI	t-Test: Paired Two Sample for Means					
	Measured	Model 1	Model 2	Model 3	Model 4	Model 5
Meteorological parameter		ΔT	RH	ΔT -RH-CF	ΔT	ΔT
Mean	4972.232	4774.438	4790.878	4972.677	4303.376	5014.622
Variance	1726153	716569.4	661238.7	824987	176972.7	384616.2
Observations	1677	1677	1677	1677	1677	1677
Pearson Correlation		0.61163	0.615121	0.691364	0.605737	0.53754
Hypothesized Mean Difference		0	0	0	0	0
df		1676	1676	1676	1676	1676
t Stat		7.786026	7.169444	-0.01919	24.90	-1.55
P(T<=t) one-tail		6.01E-15	5.62E-13	0.492347	2.8E-117	0.06096
t Critical one-tail		1.645763	1.645763	1.645763	1.645749	1.645749
P(T<=t) two-tail		1.2E-14	1.12E-12	0.984694	5.7E-117	0.121921
t Critical two-tail		1.96138	1.96138	1.96138	1.961359	1.961359

STATION: SIBU	t-Test: Paired Two Sample for Means					
	Measured	Model 1	Model 2	Model 3	Model 4	Model 5
Meteorological parameter		ΔT	RH	T-CF	ΔT	ΔT
Mean	4586.827	4590.569	4592.745	4586.827	4749.274	4547.377
Variance	1731800	734657.4	384093.4	723400.4	308721.4	949726.1
Observations	691	691	691	691	691	691
Pearson Correlation		0.651697	0.651697	0.646309	0.642801	0.580972
Hypothesized Mean Difference		0	0	0	0	0
df		690	690	690	690	690
t Stat		-0.10	-0.10	0.00	-4.21	0.73
P(T<=t) one-tail		0.460756	0.460756	0.5	1.42E-05	0.23295
t Critical one-tail		1.647065	1.647065	1.647065	1.647131	1.647131
P(T<=t) two-tail		0.921511	0.921511	1	2.85E-05	0.465899
t Critical two-tail		1.963408	1.963408	1.963408	1.963511	1.963511

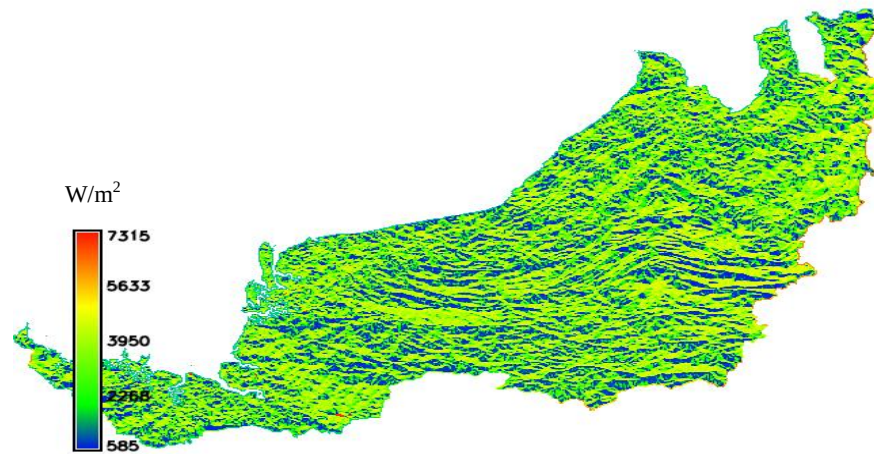
STATION: SRI AMAN	t-Test: Paired Two Sample for Means					
	Measured	Model 1	Model 2	Model 3	Model 4	Model 5
Meteorological parameter		ΔT	RH	T-RH-CF	ΔT	ΔT
Mean	4814.36	4818.721	4789.999	4808.733	4861.512	4888.825
Variance	1377090	916102.2	702690.5	926870.7	351658.2	1114585
Observations	654	654	654	654	654	654
Pearson Correlation		0.772211	0.655185	0.813237	0.745562	0.68295
Hypothesized Mean Difference		0	0	0	0	0
df		653	653	653	653	653
t Stat		-0.15	0.70	0.21	-1.45	-2.13
P(T<=t) one-tail		0.440715	0.2419	0.416589	0.073698	0.01678
t Critical one-tail		1.64719	1.64719	1.64719	1.64719	1.64719
P(T<=t) two-tail		0.88143	0.4838	0.833178	0.147395	0.033559
T Critical two-tail		1.963603	1.963603	1.963603	1.963603	1.963603

Appendix E: Annual Solar Photovoltaic Capacity Based on Districts

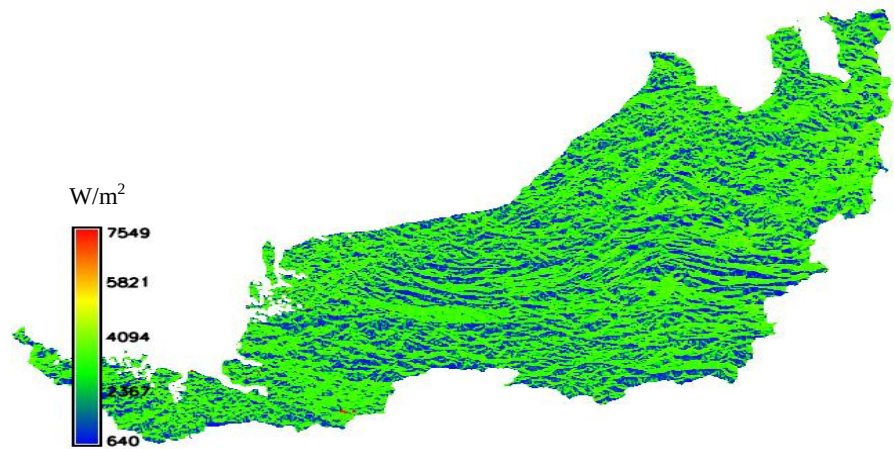
District	Annual Solar Capacity (W/year)		
	Min	Max	Average
Kuching	340.76	37269.61	9448.90
Long Lama	307.85	39467.31	9391.24
Balingian	477.76	35685.84	9587.84
Bau	438.19	19805.79	10017.70
Belaga	419.74	42151.15	9445.37
Belawai	398.77	36595.78	7935.67
Beluru	391.75	34967.86	8566.70
Betong	586.54	20654.99	8877.24
Bintulu	469.29	40524.33	9494.54
Nanga Budu	560.26	19483.74	9175.73
Dalat	449.52	35202.95	9215.08
Daro	388.19	28097.68	6129.05
Debak	560.78	40594.00	7629.50
Engkilili	549.04	20324.07	7695.05
Mukah	461.93	37624.76	9375.95
Ng. Medamit	318.88	21071.41	9129.27
Nanga Merit	590.95	38686.21	7840.06
Niah Suai	434.39	36201.28	8845.23
Oya	438.06	32351.90	9451.37
Padawan	429.91	20000.23	10468.64
Pakan	564.96	20459.98	10811.83
Sadong Jaya	530.36	40176.12	10102.44
Pusa	541.84	39718.02	9956.84
Roban	526.07	38214.78	8252.70
Samarahan	362.51	40178.60	11175.17
Saratok	533.71	19842.83	8278.25
Sarikei	516.50	19402.73	11991.27
Sebuyau	527.90	20578.24	11184.78
Sematan	379.01	39374.11	11253.74
Serian	504.29	23293.01	10782.08
Sibu	397.36	35939.45	7279.63
Sibuti	450.23	35966.90	8863.46

District	Annual Solar Capacity (W/year)		
	Min	Max	Average
Julau	549.80	19921.28	10084.49
Kabong	503.29	38794.98	9950.96
Kanowit	553.38	37826.08	9730.38
Kapit	494.44	22940.99	9709.07
Lawas	313.19	20308.37	8714.76
Limbang	468.06	35805.72	9486.06
Lingga	586.51	20610.09	9405.04
Lubok Antu	554.95	40364.78	7463.07
Lundu	447.52	39122.24	9731.32
Maludam	528.21	39935.56	9703.82
Marudi	395.13	37484.74	7661.63
Matu	405.61	30836.52	8394.98
Meradong	533.10	19900.00	10320.81
Miri	388.91	32947.05	9981.59
Simunjan	537.68	40140.46	10116.58
Song	536.57	20633.81	9881.09
Spaoh	567.56	40945.38	9054.27
Sri Aman	544.31	40219.82	9631.72
Sundar	433.04	15942.38	8382.79
Tatau	503.84	34751.71	9502.30
Asajaya	510.32	38291.22	9101.45
Pantu	547.46	41036.66	10384.73
Tebedu	489.60	19731.31	9401.28
Trusan	390.81	17601.33	8454.63

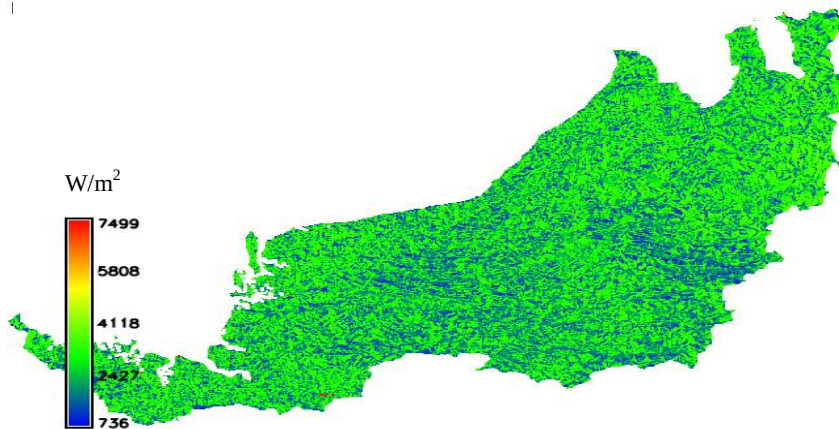
Appendix F: Monthly Global Solar Radiation Map



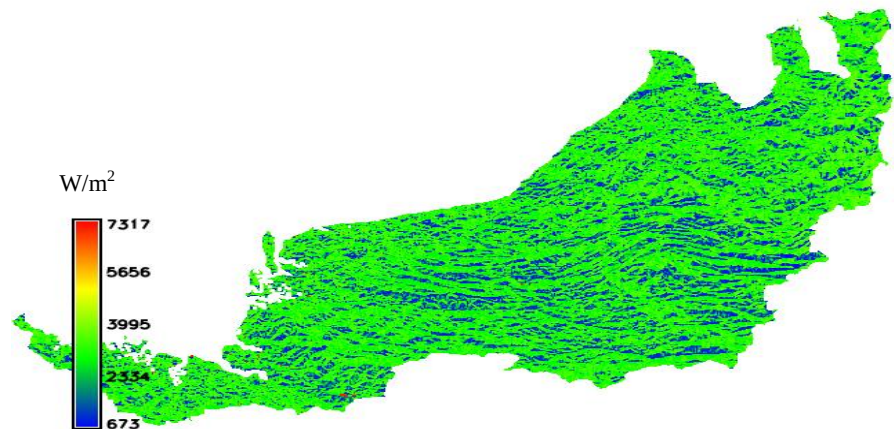
a) January



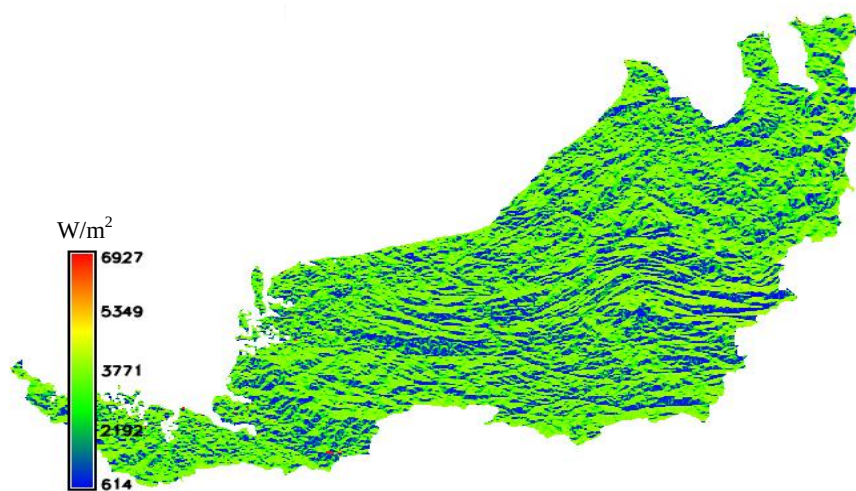
b) February



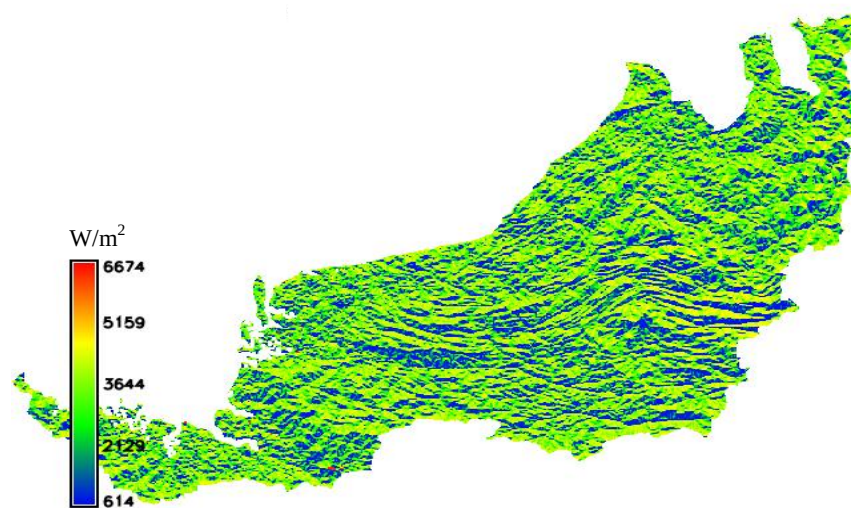
c) March



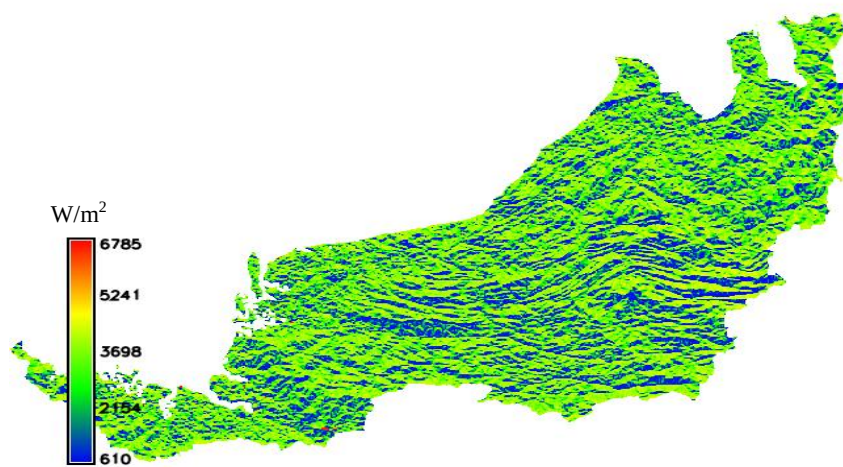
d) April



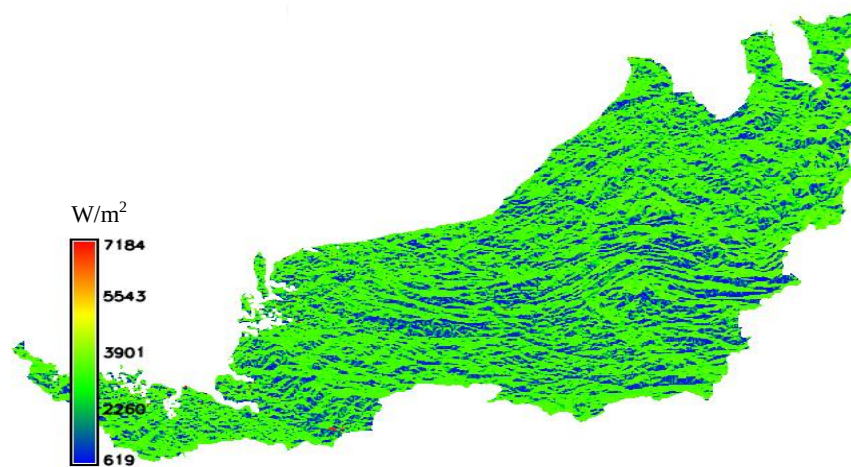
e) May



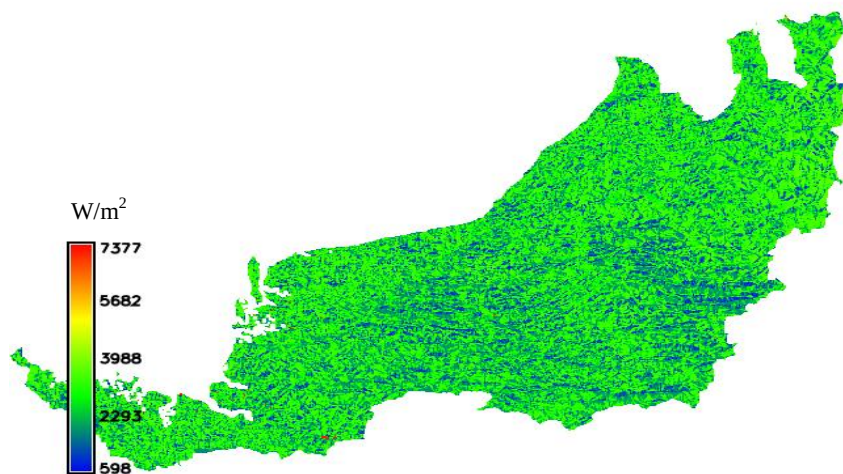
f) June



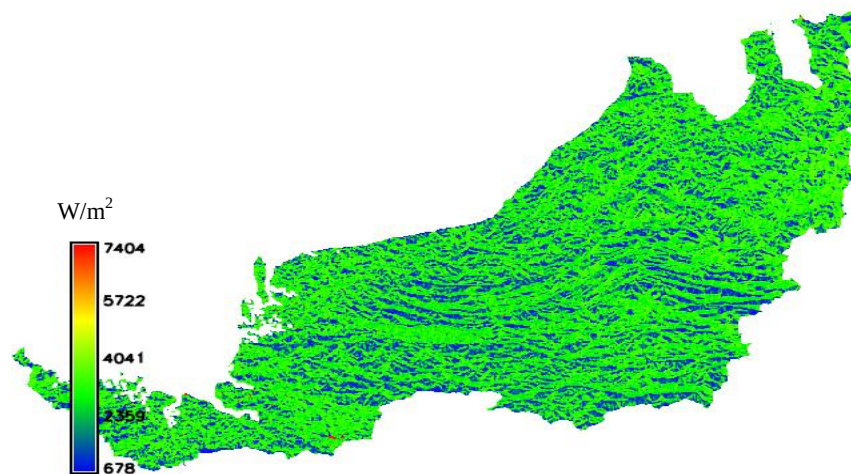
g) July



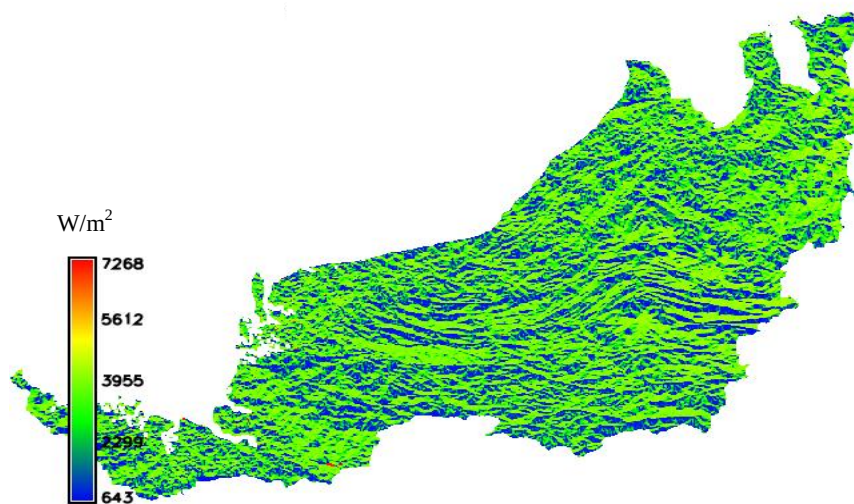
i) August



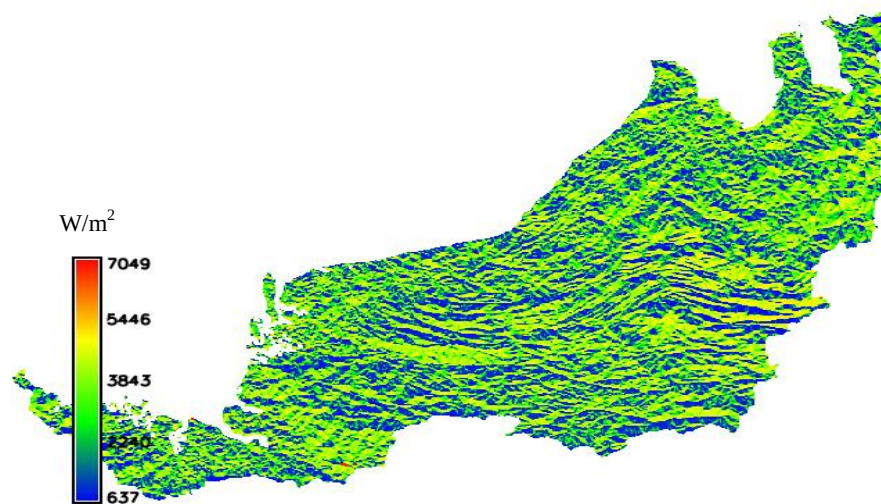
h) September



j) October

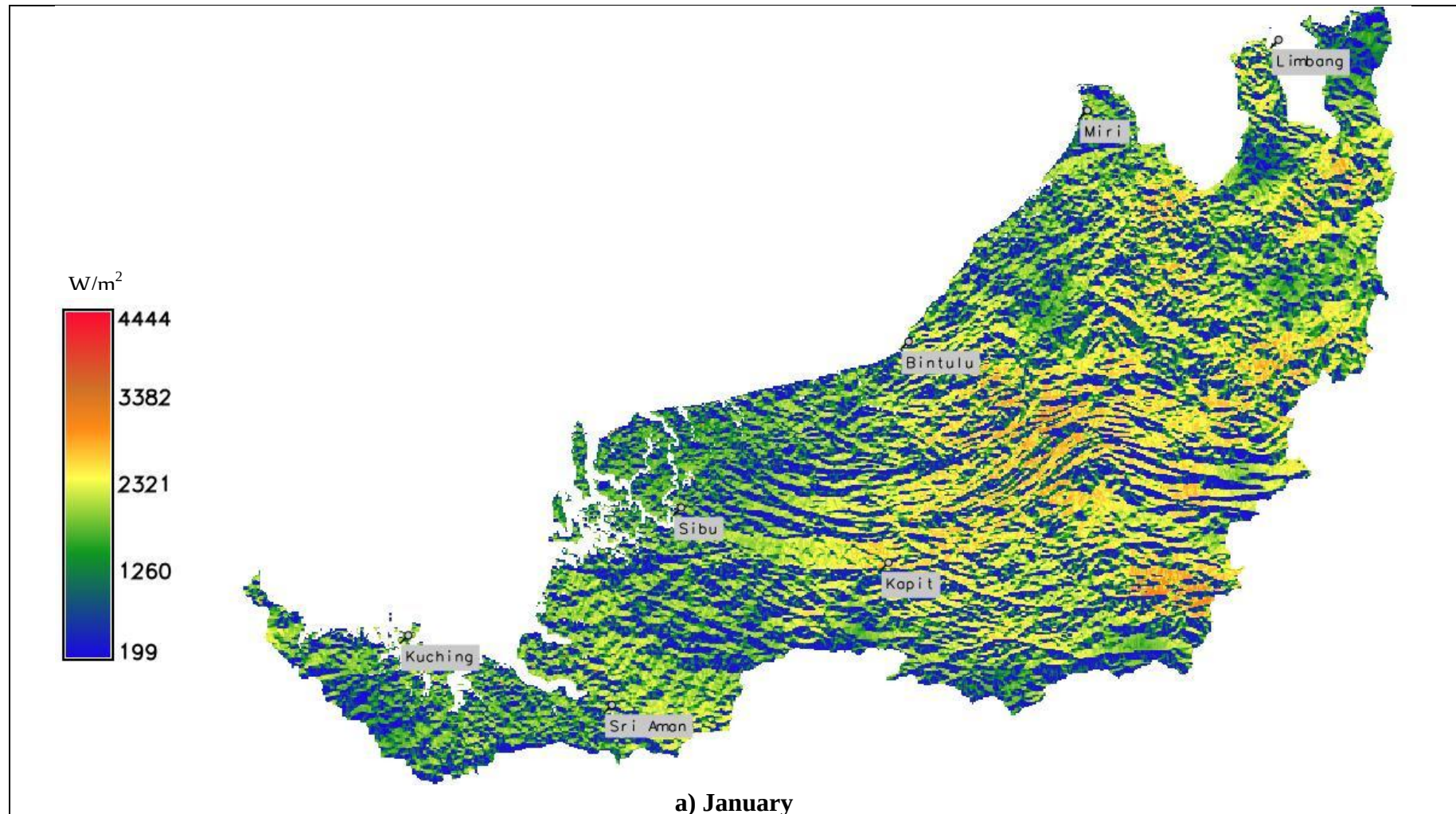


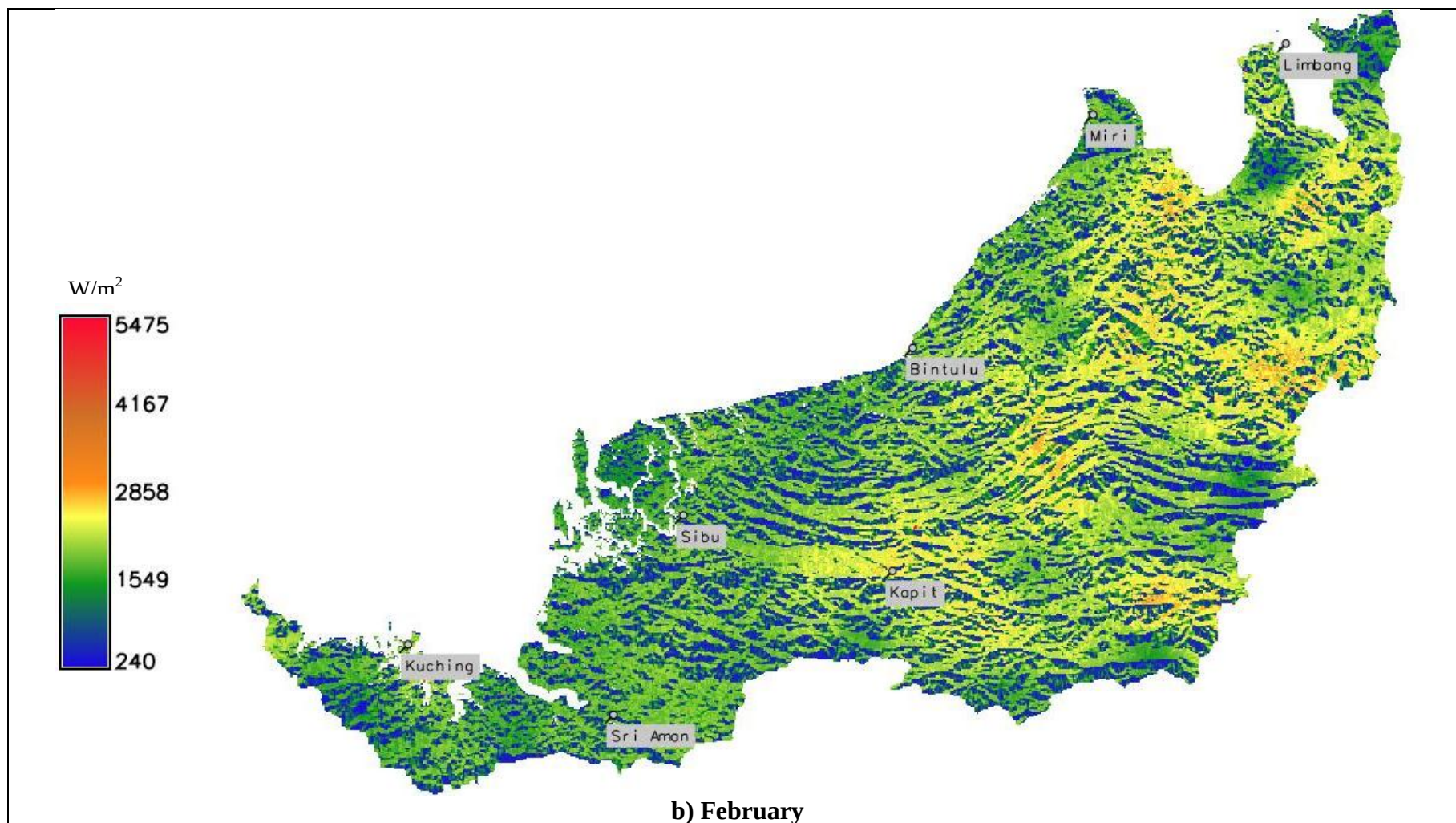
k) November

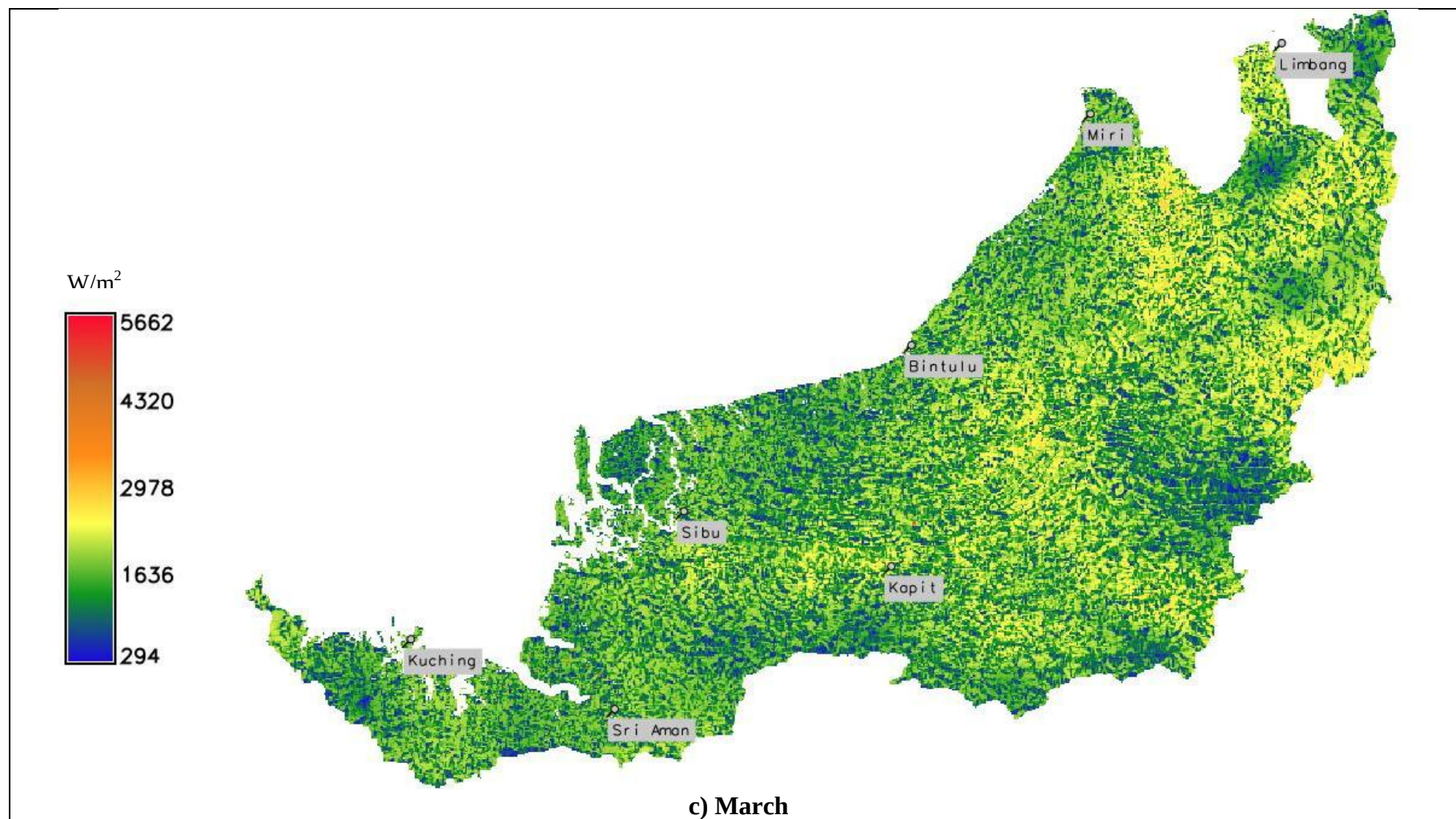


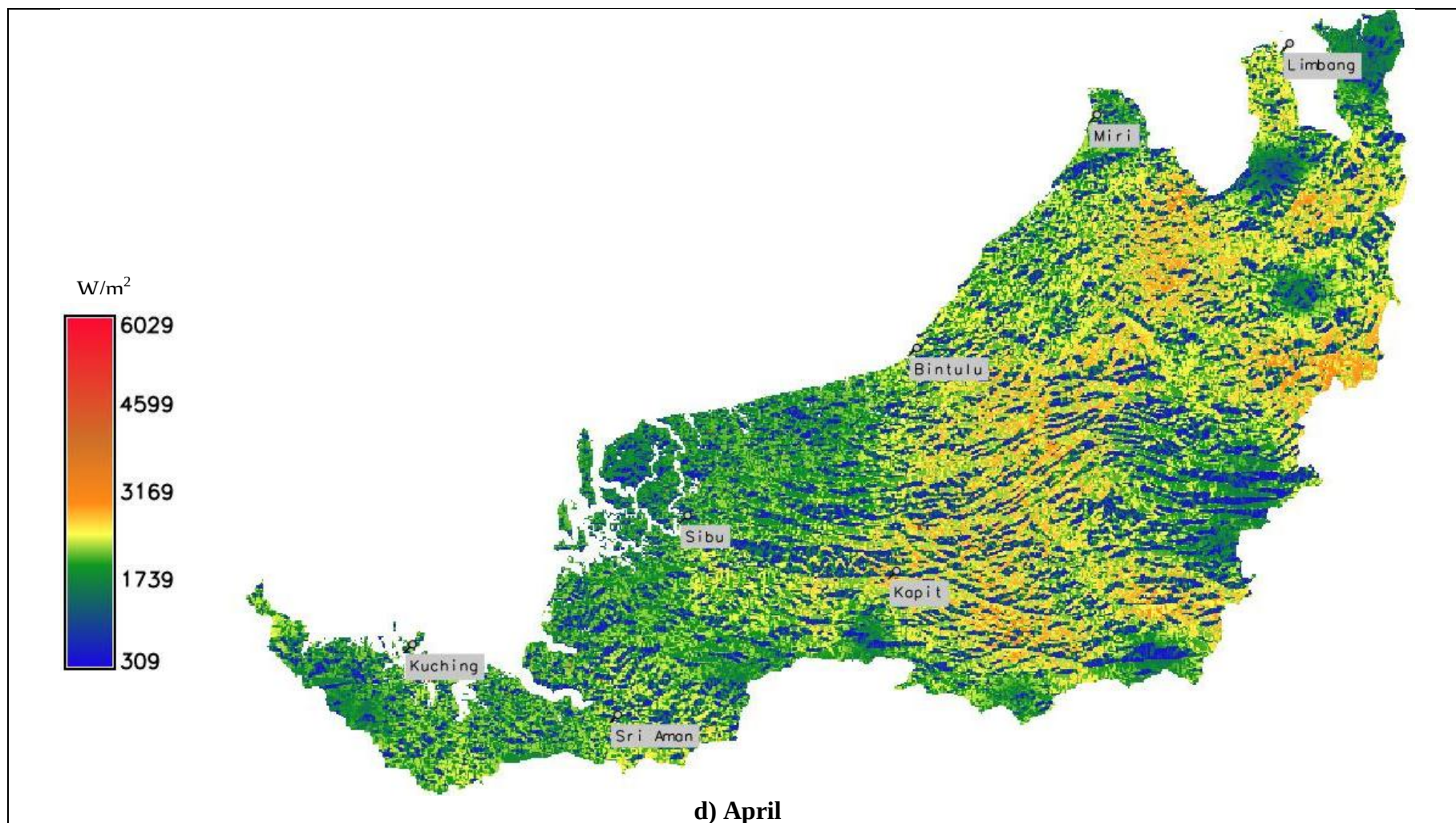
l) December

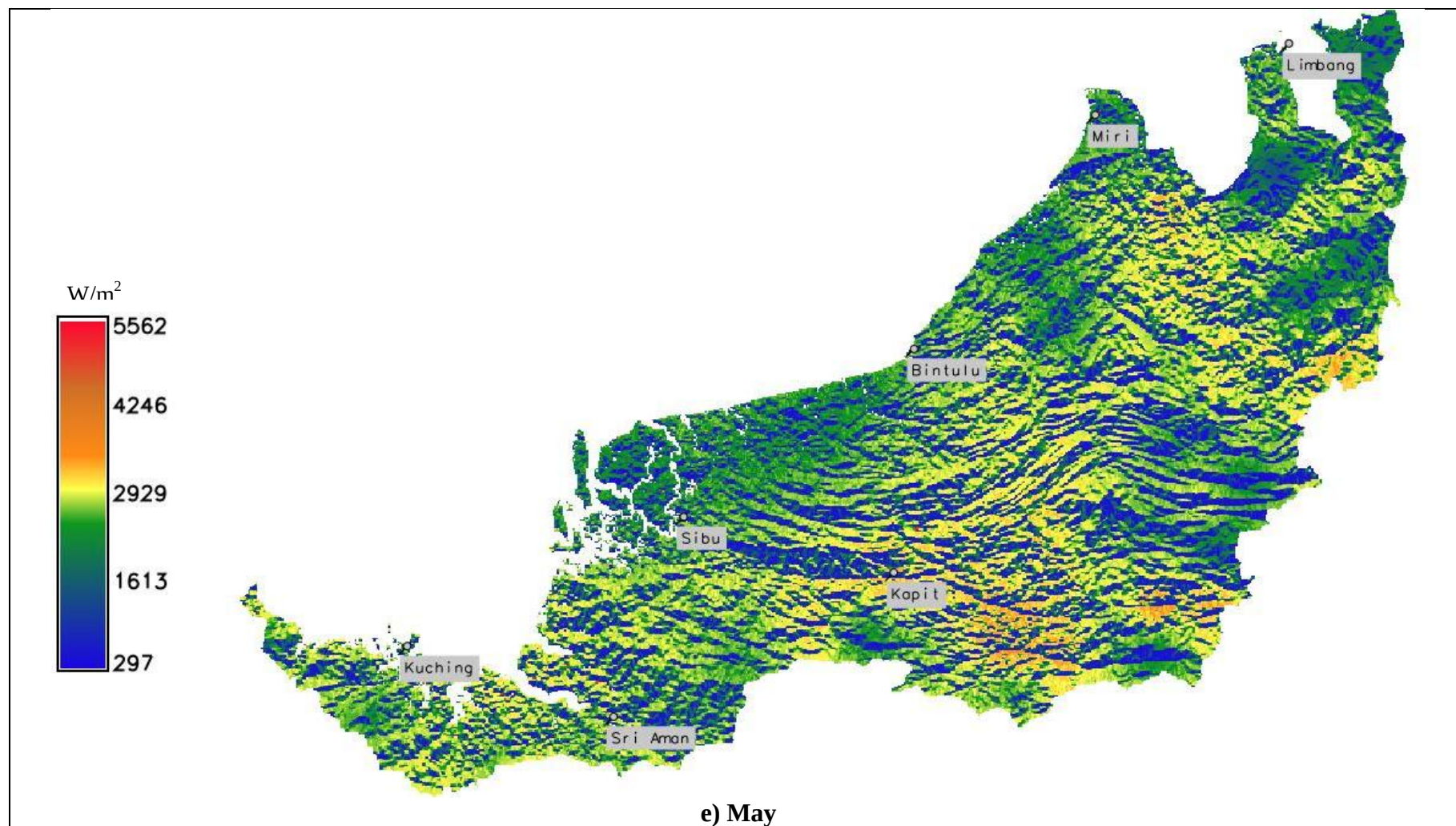
Appendix G: Monthly Overcast Solar Radiation Map

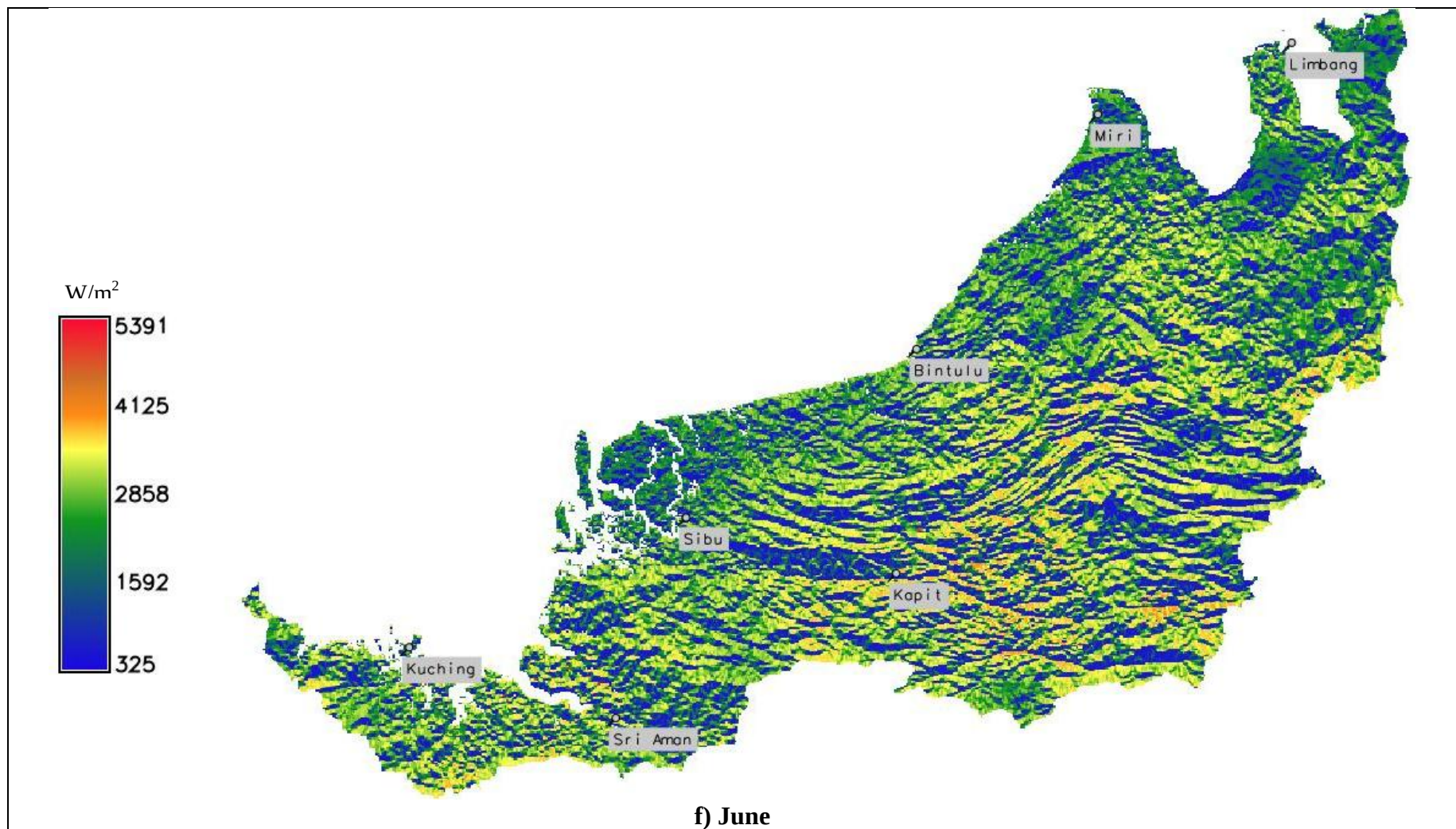


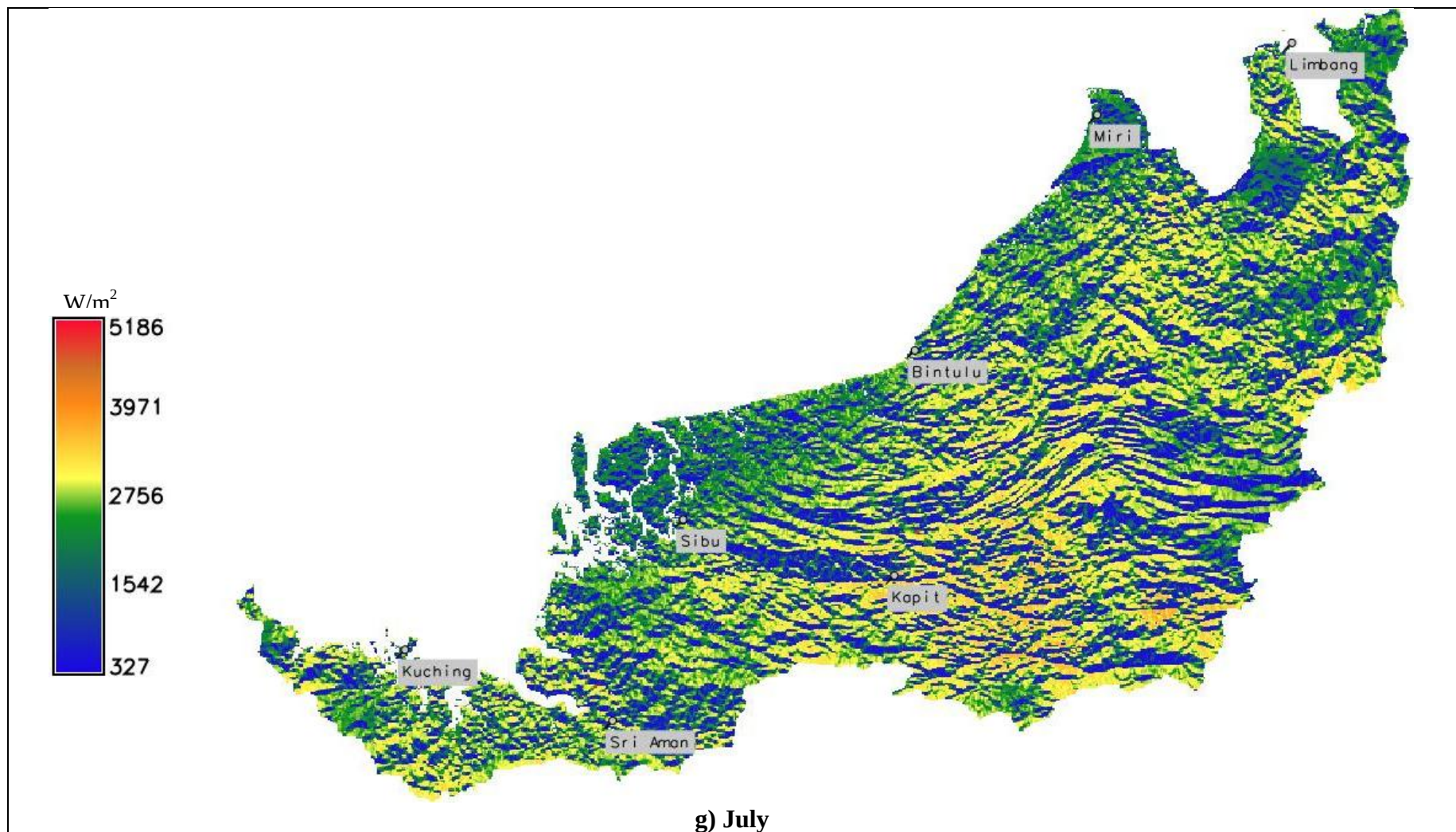


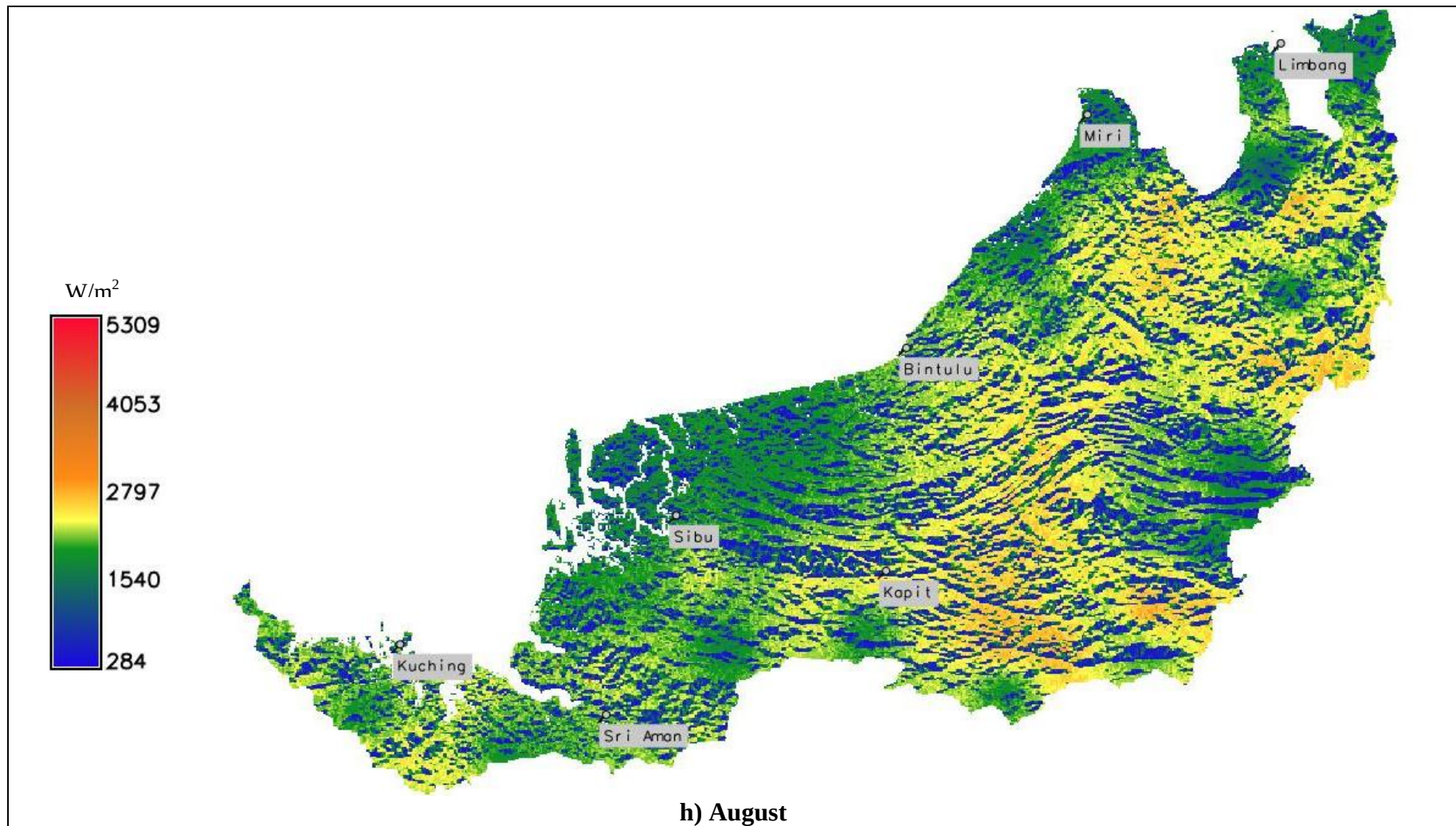


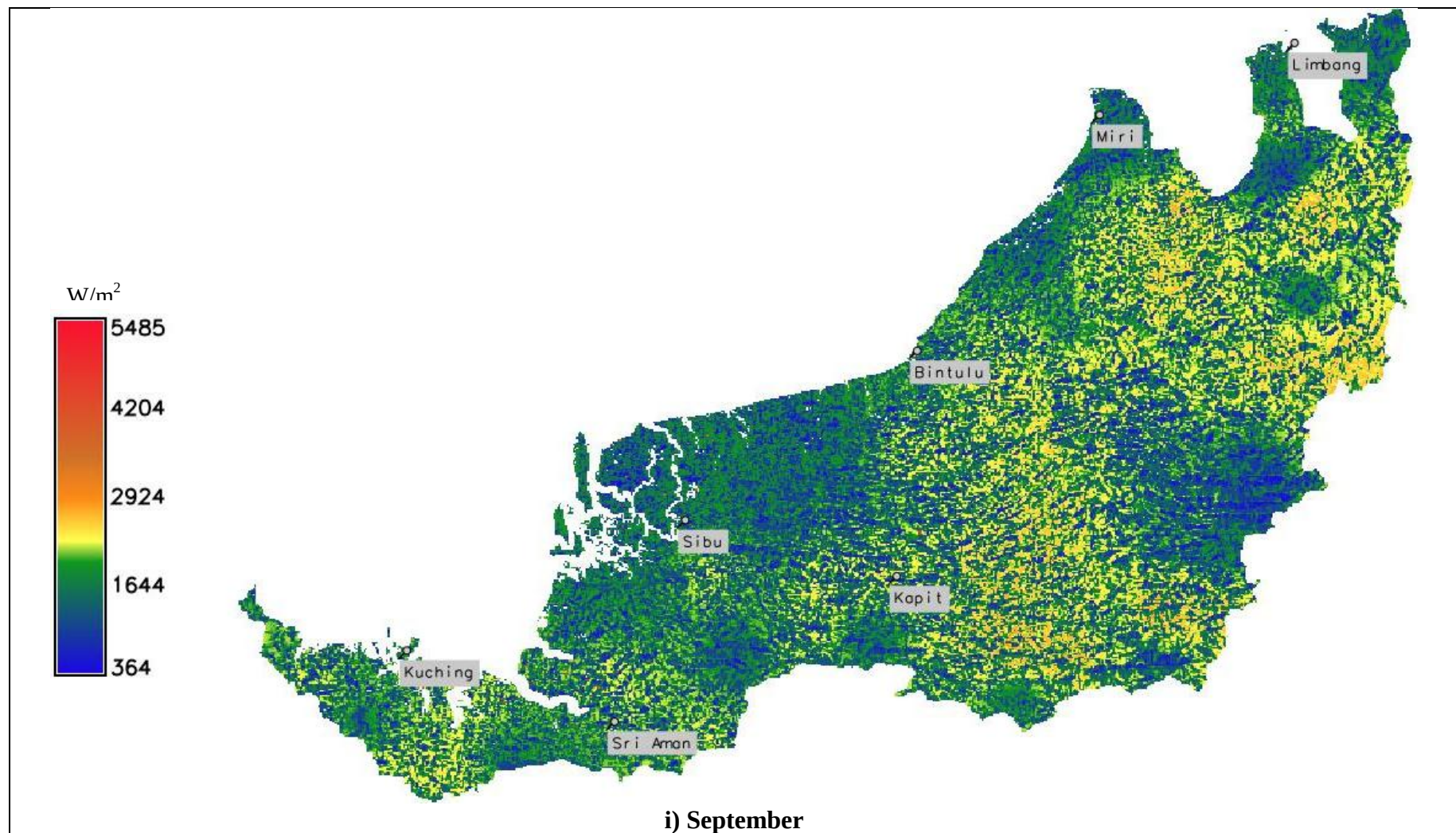


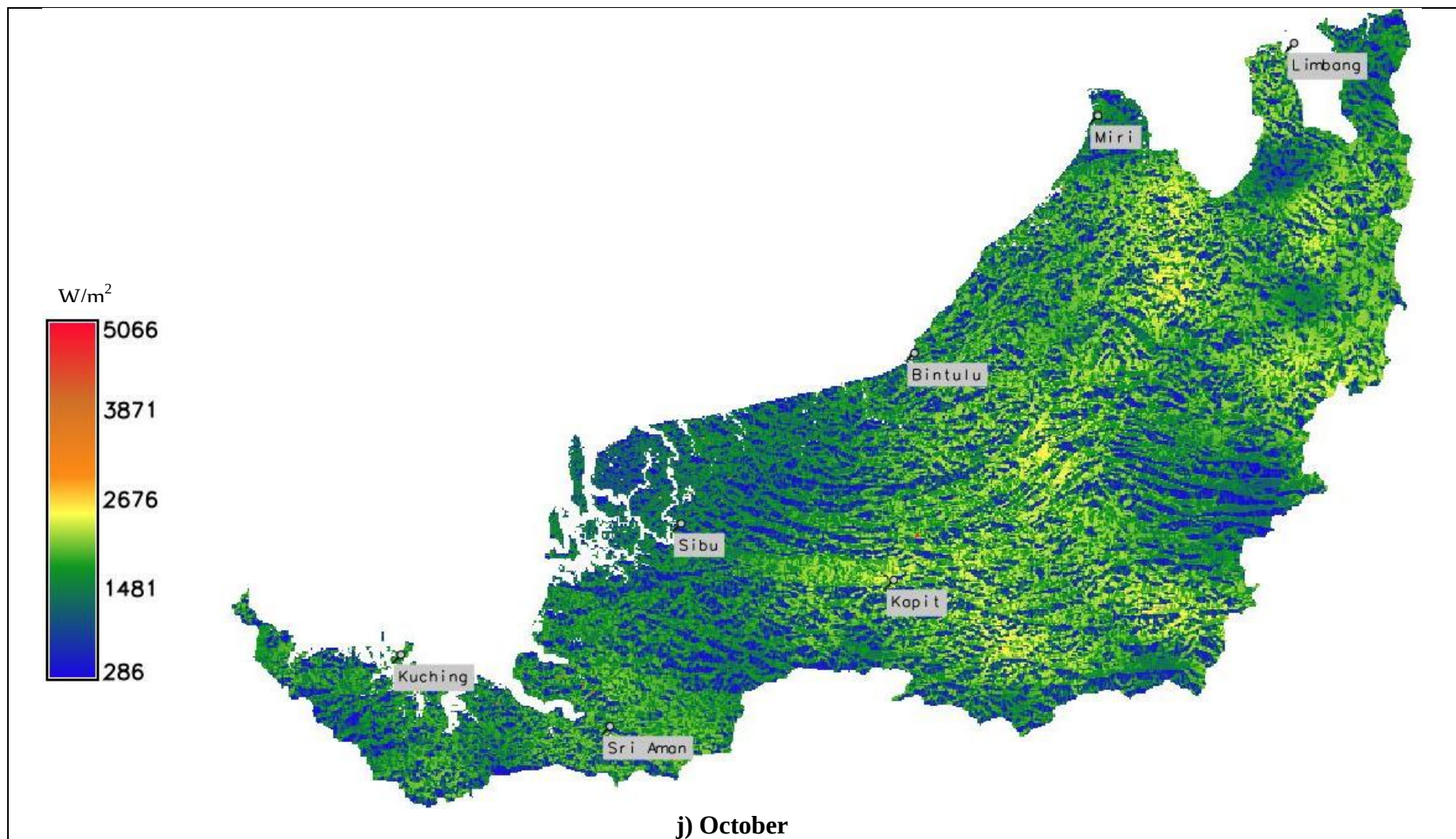


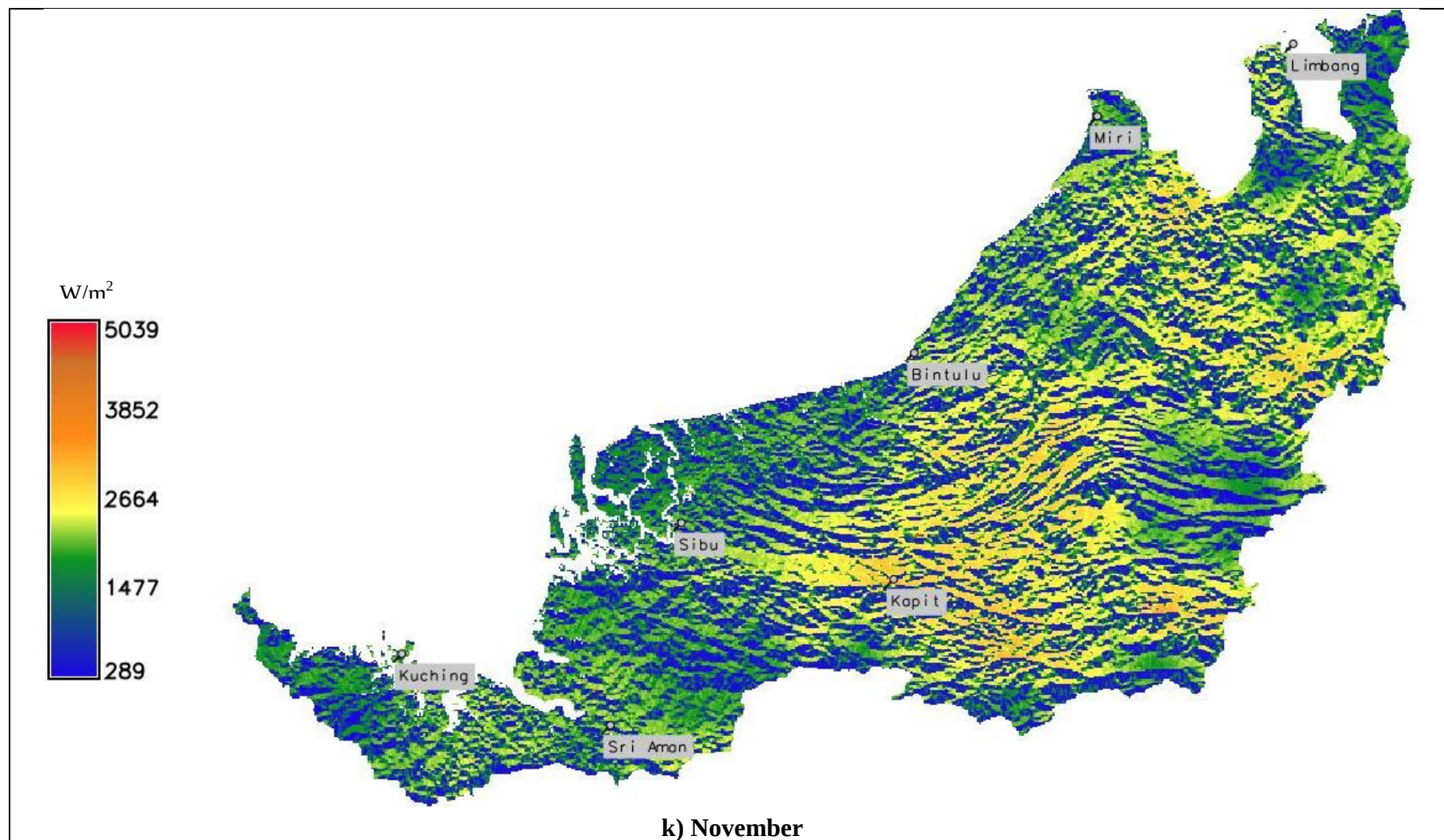


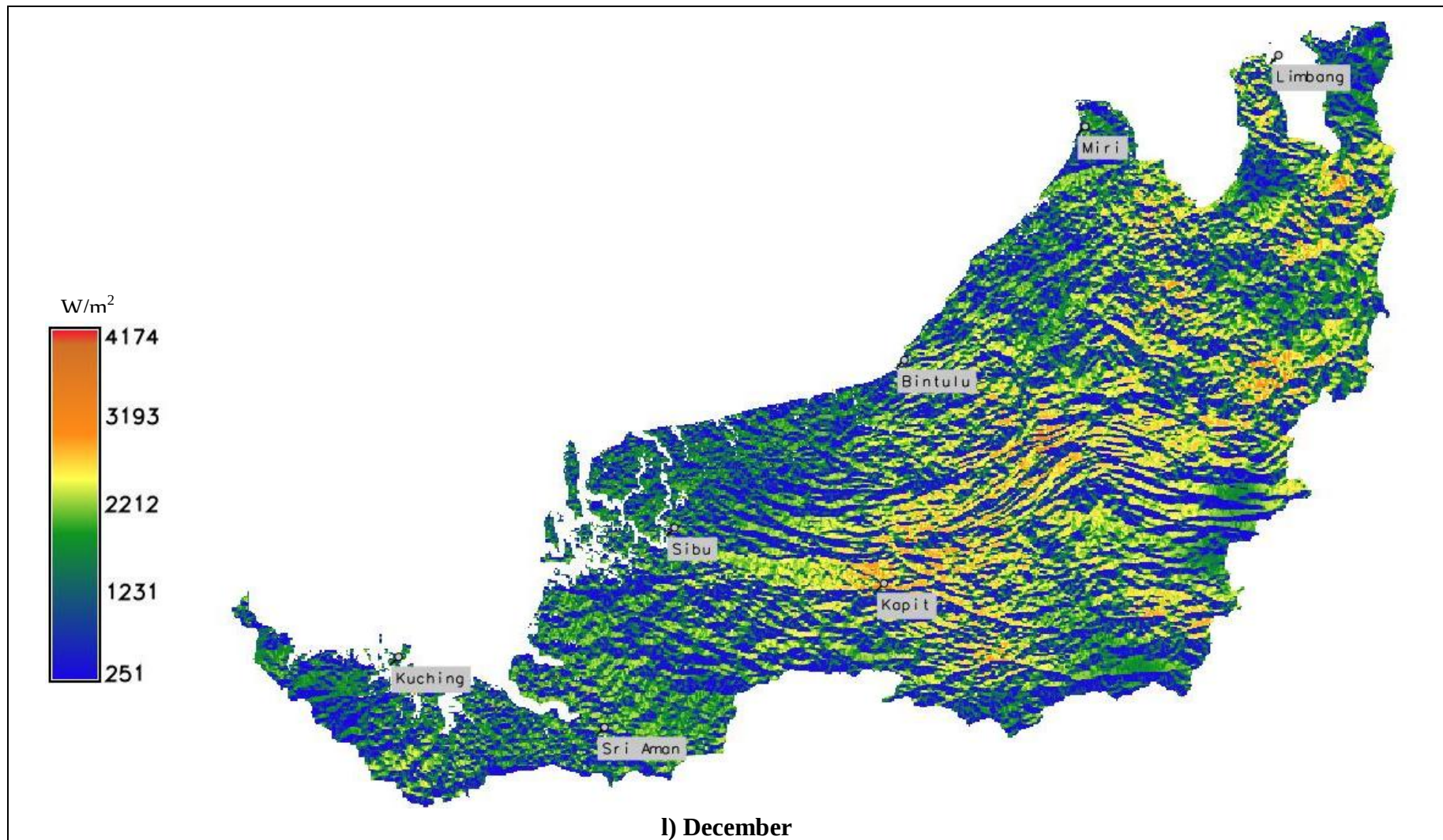












Appendix H: List of Publications

i. Journal Publication

Bandy, S., & Zainal, W.A.W. (2018). A General Solar Radiation Estimation Model using Ground Measured Meteorological Data in Sarawak, Malaysia. *Journal of Telecommunication, Electronic and Computer Engineering*, 10(1), 99–105.