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Evaluation of Solar and Meteorological Data Relevant to Solar Energy Technology Performance in Malaysia

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Abstract: Solar technology policy, development, and deployment require information related to meteorology and solar radiation to optimize technology selection and performance. As a tropical country, Malaysia has significant solar resources but a very limited radiation monitoring network. Meteorological data are available in more locations, but published analyses of these data are also limited. This paper presents an analysis of recent meteorological and radiation data in Malaysia as relevant to understanding solar technology performance. To compare differences between locations, yearly daily means of key meteorological parameters, global solar radiation (total radiation on the ground), and particulate air pollution were derived for 3-12 years, depending on the data availability. Annual mean global solar radiation values range from 3.73 to 5.11 kWh/(m^2d) in the eight cities with monitors. The analysis also used neural network techniques to evaluate the potential for using the key variables of temperature, humidity, wind speed, rainfall, cloud cover, latitude, longitude, and particle pollution to estimate global solar radiation at various locations and seasons. Prediction on a monthly basis indicated a slight under-prediction of the model during the rainy season and a slight over-prediction during the dryer months, confirming that global solar radiation values depended strongly on rainfall.

Key Words: Malaysia, meteorology, solar radiation.

1. Introduction

To evaluate solar technologies and optimize deployment of solar energy systems, it is important to have meteorological data relevant to a typical or standard year as well as a comprehensive understanding of the distribution and levels of the solar resource. Detailed knowledge of solar radiation and meteorology is required to select technologies, evaluate and model solar technology performance, design the size of the installations, and secure financing.

Malaysia is located between 2° and 7° north of the equator in Southeast Asia and consists of thirteen states and three Federal Territories. Kuala Lumpur is the capital city, although the administrative seat of government moved in 1999 to the newly designed Federal Territory of Putrajaya. The total Malaysian landmass is approximately 329,845 square kilometres with a population of over 28 million. The country has two geographical regions, Peninsular Malaysia connected to the Asian mainland and East Malaysia on the northern part of the island of Borneo (see Figure 1). These regions share a similar landscape including coastal plains that rise to densely forested hills and mountains. Mount Kinabalu, 4,095 metres, on the island of Borneo is the highest mountain in Southeast Asia. An estimated 59% of Malaysia remains forested to date [1]. The highest populated states in West (Peninsula) Malaysia based on population density are Kuala Lumpur, Pulau Pinang, and Putrajaya. In East (Borneo) Malaysia, the Federal Territory of Labuan has a substantially denser population than the much larger states of Sarawak (capital city Kuching) or Sabah (capital city Kota Kinabalu). The local is equatorial characterized by annual southeast (April to October) and northeast (October to February) monsoons.

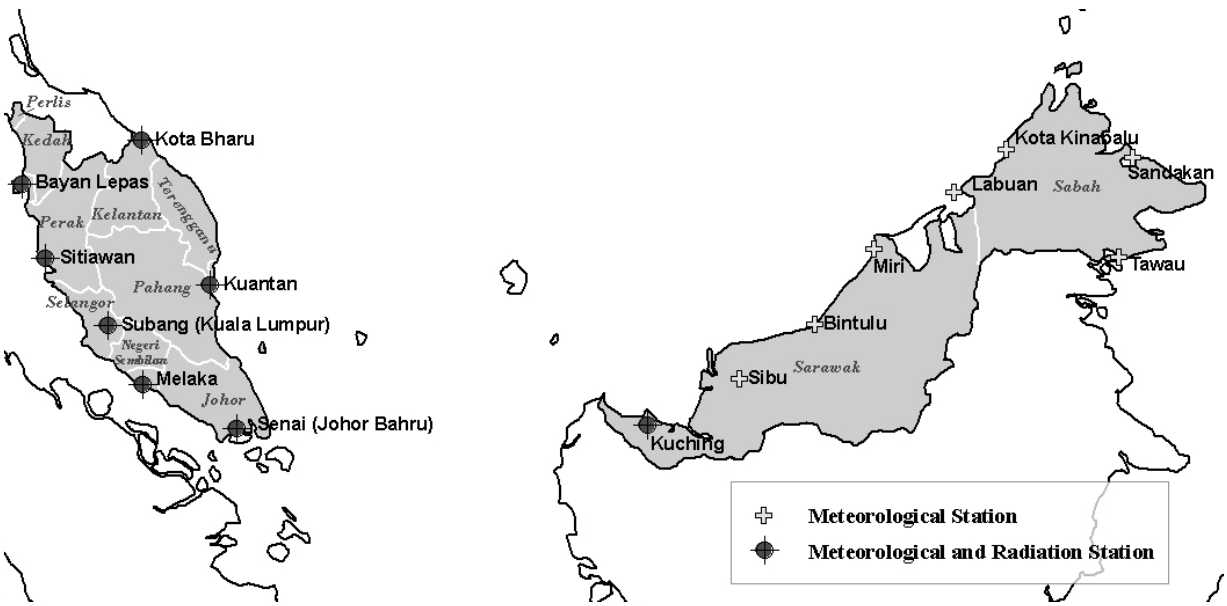

Figure 1. Location of meteorological data monitors and solar radiation monitors.

A limited number of studies have been conducted to evaluate typical meteorological data in Malaysia. The literature primarily presents information for Subang, the former airport near the center of Kuala Lumpur, as the site with one of the longest continuous datasets. Zain-Ahmed et al. [2] completed the most comprehensive study for Subang, creating a mean daily data for a model year based on the selection of typical months from 21 years of data. They found an annual mean dry bulb temperature of 27.6°C, relative humidity of 83%, cloud cover of 7 oktas, average wind speed of 1.2 m/s, and global solar radiation of 16.4 MJ/(m^{2}d) (4.56 kWh/(m^{2}d)). Other studies have focused on application of meteorological data for building design [3-4].

For solar radiation, early studies used four monitors in the peninsula as well as estimates of variations based on radiation at the top of the atmosphere and measurements of sunshine hours with regression analysis. For Peninsular Malaysia, Chuah and Lee [5] used sunshine duration data from 1961-1975 for 12 cities to estimate monthly average daily global solar radiation levels; they found levels between 3.5 and 6 kWh/(m^{2}d) at northern and east coast towns and between 4 and 5 kWh/(m^{2}d) at southern towns. Using linear regression to relate global solar radiation and sunshine duration, Hing Chong Hu and Joo Tick Lim [6] found similar seasonal values in the northwest peninsula ranging up to 6 kWh/(m^{2}d) in April to a low of 2.5 kWh/(m^{2}d) in the northeast in December. They also determined that the variation in global solar radiation most closely correlated with rainfall, which in turn is related to prevailing winds and local land/sea breezes, topography and convection. Kamaruzzaman and Mohd Yusof [7] were able to use an expanded network of global radiation monitors in eight cities, including east Malaysia, which allowed them to analyze directly monitored data. They found monthly average values for the eight cities between 3.3 kWh/(m^{2}d) for Kuching to 5.5 kWh/(m^2 d) for Bayan Lepas.

Ayu Wazira et al. [8-9] used cloud cover data from satellites and ground stations to estimate that Peninsula Malaysia receives about 4.9 kWh/(m^{2}d) of global solar radiation per year with a maximum radiation of 5.2 kWh/(m^{2}d), mostly in Northern region of Peninsular Malaysia. When comparing with previous studies, they found that the average global solar radiation had increased from 4.8 kWh/(m^{2}d) in 1982 to 4.965 kWh/(m^{2}d) in 2006. Modeling using satellite data has been done by Janjai et al. [10-11] for Thailand but not for other regions of Southeast Asia. Satellite-based results can have significant levels of uncertainty if not carefully ground-truthed, but are important to understanding spatial variability between monitoring stations. While all the studies summarized above yielded similar annual average results, the variability spatially and seasonally is significant and can have a major impact on the operations and economics of a solar power station.

Pollution is also a potential factor affecting solar radiation levels. Smoke and haze events have been documented to reduce ultraviolet and global solar radiation in the range of 16-23% [12]. For particulate matter less than 10 microns diameter (PM10), Liew et al. [13] used principal component analysis to identify four distinct regimes in Malaysia. Each regime exhibits a different seasonal pattern in PM10 concentrations: the southwest coastal region (Johor, Negeri Sembilan, Melaka, Selangor, Pahang) with peak concentrations during the summer monsoon; the northern region of the peninsula (Kedah, Penang, Perak, Kelantan, Terengganu) with two peaks, in late winter and summer monsoons; western Borneo (Sarawak) with a peak in August–September; and northern Borneo (Sabah) with no specific seasonal pattern. They associate the PM10 patterns with variation in rainfall.

The market for solar energy in Malaysia is complex and evolving. Electricity rates in Malaysia are subsidized and low, compared to many other countries and regions, with an average retail rate of RM0.28/kWh (US$0.08/kWh) [14]. Electricity reserve margins are large, 47% for Peninsular Malaysia and 16% for Sarawak [15]. However, several policies relevant to solar energy, such as a feed-in tariff, have been recently approved and may significantly change the power market in Malaysia. Thus, more monitoring data for solar radiation and meteorology and improved understanding of their relation to solar technology performance is essential in the near future. This paper presents an analysis of recent meteorology and radiation data in Malaysia as relevant to understanding solar technology performance.

2. Data and Methods

Meteorological, radiation, and environmental data were purchased from the Malaysian Meteorological Department, as summarized in Table 1. Meteorological data for seven relevant parameters were available for 15 stations (Figure 1). Data availability for Hourly Global Radiation (MJ/m^2) varied. Data were available for 2006-2009 for Bayan Lepas, Melaka, Subang (near Kuala Lumpur), Kuantan, and Kuching and for 2006-2008 only at Sitiawan and Kota Bharu. Global solar radiation only became available for Senai (near Johor Bahru) in 2009. We evaluated several types of environmental (air quality) parameters but focused on PM10 as the available pollutant parameter with the most significant potential effecting on solar radiation in Malaysia. Availability of the PM10 data also varied, with four sites having data available from 1998 to 2009 and three additional sites for 2008 to 2009; due to variability in pollutant loads, our analysis focused on more recent years from 2006-2009.

Table 1. Years of Meteorological and Environmental Data Acquired for Each Site.

Site	24 Hr Mean Dry Bulb Temp.	24 Hr Mean Relative Humidity	24 Hr Mean Wind Speed	Daily Rainfall Total 08-08 MST	24 Hour Mean Cloud Cover	PM10	Hourly Global Solar Radiation
Subang (Kuala Lumpur)	1997-2009	1997-2009	1997-2009	1997-2009	1997-2009	1998-2009	2006-2009
Kuantan	1997-2009	1997-2009	1997-2009	1997-2009	1997-2009	1998-2009	2006-2009
Sandakan	1997-2008	1997-2008	1997-2008	1997-2008	1997-2008	-	-
Kota Bharu	1997-2009	1997-2009	1997-2009	1997-2009	1997-2009	1998-2009	2006-2008
Bayan Lepas (Penang)	1997-2009	1997-2009	1997-2009	1997-2009	1997-2009	2008-2009	2006-2009
Sitiawan	1997-2009	1997-2009	1997-2009	1997-2009	1997-2009	1998-2009	2006-2008
Melaka	1997-2009	1997-2009	1997-2009	1997-2009	1997-2009	2008-2009	2006-2009
Senai (Johor Bahru)	2009	2009	1998-2009	2009	2009	2008-2009	-
Labuan	1997-2008	1997-2008	1997-2008	1997-2008	1997-2008	-	-
Kota Kinabalu	1997-2008	1997-2008	1997-2008	1997-2008	1997-2008	-	-
Bintulu	1997-2008	1997-2008	1997-2008	1997-2008	1997-2008	-	-
Miri	1997-2008	1997-2008	1997-2008	1997-2008	1997-2008	-	2006-2009
Sibu	1997-2008	1997-2008	1997-2008	1997-2008	1997-2008	-	
Tawau	1997-2008	1997-2008	1997-2008	1997-2008	1997-2008	-	
Kuching	1997-2009	1997-2009	1997-2009	1997-2009	1997-2009	-	

The above data were used to calculate a 12-year mean. A more in-depth analysis was also performed to gain an understanding of any significant differences between stations and to look at any trends which may have occurred from year to year, as may be relevant to understanding the variability of solar technology performance. To compare differences between locations, a yearly mean of each meteorological parameter was derived each year (1997-2008) for each station. This provided 12 data points for each station which were then compared via box plots, Student's t, and Tukey tests. The results are described in section 3. The next part of the analysis was to evaluate how meteorological data, PM10, location and season influenced global solar radiation at various sites. This was accomplished using neural network techniques. The results are presented in section 4.

3. Results and Discussion

For each of the meteorological parameters, except global solar radiation, a 12-year mean was calculated for each location. For trace amounts of rainfall, which were defined as <0.1 mm, a value of 0.05 mm was assigned. Global solar radiation was summed for each day and a mean daily value was calculated for the location's corresponding time period. For PM10, mean values for each site were calculated based on data available between 2006 and 2009. Records flagged as a defective reading were replaced with a blank. These mean values are listed in Table 2.

Zain-Ahmed *et al*. [2] calculated similar means for the Subang location using data from 1975-1998. When comparing the results in Table 2 to Zain-Ahmed *et al*. [2], some differences were expected, since they were averaged over a shorter time period than the 21-year dataset typical for calculating model years. The results were similar with the relative humidity decreasing and wind speed and global solar radiation increasing (see Table 3). These differences could be due to the use of fewer years to calculate the mean or equipment changes. The wind speed and humidity changes could be influenced by local land use changes (urbanization). The global solar radiation increases are proportionally consistent with a global trend showing a 'brightening' of solar radiation since 1990, which followed a 'dimming' that occurred from about 1950-1990 [16].

Various parameters were analyzed and assessed for their potential impact on global solar radiation. While Table 2 summarizes mean data for all the sites, a more in depth analysis was conducted for ambient meteorological, air pollution, and global solar radiation data.

3.1 Ambient Meteorological Data

The following sections discuss the key meteorology parameters, specifically dry bulb temperature, relative humidity, cloud cover, and daily rainfall. Table 2 contains the specific data discussed in each section.

3.1.1 Dry Bulb Temperature

As shown in Table 2, Labuan (27.9°C) and Bayan Lepas (27.8°C) had high Mean Yearly Temperatures while Kuching (26.4°C) had the lowest. Figure 2 illustrates the mean, median, and variability from year to year by sites. For this and similar following figures, the mean is represented by the line within the diamond with the 95% confidence limits reflected by the upper and lower points. The median is the line within the box. The upper and lower bounds of the box represent the 3rd (75%) and 1st (25%) quartile. The interquartile boundary is calculated by subtracting the 1st quartile from the 3rd. The whiskers are calculated by multiplying the interquartile range by 1.5 and adding this product to the 3rd quartile and subtracting this product from the 1st quartile. If no data points fall within these calculated values, then the whiskers are determined by the maximum and/or minimum data points.

Table 2. Mean Data for Meteorological and Environmental Data for Each Site.

Site	Area	Mean Daily Dry Bulb Temp. (°C)	Mean Daily Relative Humidity (%)	Mean Daily Average Wind Speed (m/s)	Mean Daily 24 Hour Cloud Cover (oktas)	Mean Daily Rainfall 08-08MST (mm)	Mean Total Daily PM10 (μg/m^3)	Mean Daily Global Solar Radiation (kWh/(m^2 d)
Subang (Kuala Lumpur)	Kuala Lumpur	27.7	78.6	1.62	6.99	7.65	38.8	4.86
Kuantan	East Coast	26.9	84.3	1.72	7.07	8.38	27.6	4.57
Sandakan	East Coast	27.5	82.7	N/A	6.87	8.77	N/A	N/A
Kota Bharu	East Coast	27.3	81.4	2.19	7.18	7.18	28.9	5.11
Bayan Lepas (Penang)	West Coast	27.8	79.4	1.84	6.94	6.50	28.9	5.10
Sitiawan	West Coast	27.2	83.8	1.03	6.95	4.86	34.5	4.62
Melaka	West Coast	27.5	80.6	1.55	6.90	5.42	41.4	4.50
Senai (Johor Bahru)	South	N/A	N/A	1.31	N/A	N/A	35.5	3.73
Labuan	East Malaysia	27.9	80.7	N/A	7.10	9.11	N/A	N/A
Kota Kinabalu	East Malaysia	27.4	81.0	N/A	7.11	7.51	N/A	N/A
Bintulu	East Malaysia	26.9	83.8	N/A	6.97	11.02	N/A	N/A
Miri	East Malaysia	27.1	83.9	N/A	6.90	7.75	N/A	N/A
Sibu	East Malaysia	26.6	84.3	N/A	6.89	9.61	N/A	N/A
Tawau	East Malaysia	26.7	83.0	N/A	6.35	5.33	N/A	N/A
Kuching	East Malaysia	26.4	85.1	1.32	6.95	11.68	N/A	4.19

Note: N/A = Not Available.

Table 3. Comparison of Subang station results with a previously published study.

Location/Time Range	Dry Bulb Temperature (°C)	Wet Bulb Temperature (°C)	Relative Humidity (%)	Cloud Cover (oktas)	Mean Wind Speed (m/s)	Global Solar Radiation (kWh/(m^{2}d))
Subang 1997-2009 (this analysis)	27.7	24.7*	79	7	1.6	4.86**
Subang 1975-1995 (Zain-Ahmed *et al*. [2])	27.6	24.2	83	7	1.2	4.56

*1997-2008; **2006-2009

Figure 3 shows the variation within the year based on location. They all show lower temperatures from roughly November through March, especially in regions like the east coast of Peninsular Malaysia which experience the strong northeast monsoon at that time. In the annual patterns shown in Figure 4, there were some atypically high values around 1998 in all areas which correspond with the El Nino pattern that year. It should be noted that these seasonal and regional variations of 2-3°C are relatively small compared to variations in non-tropical locations.

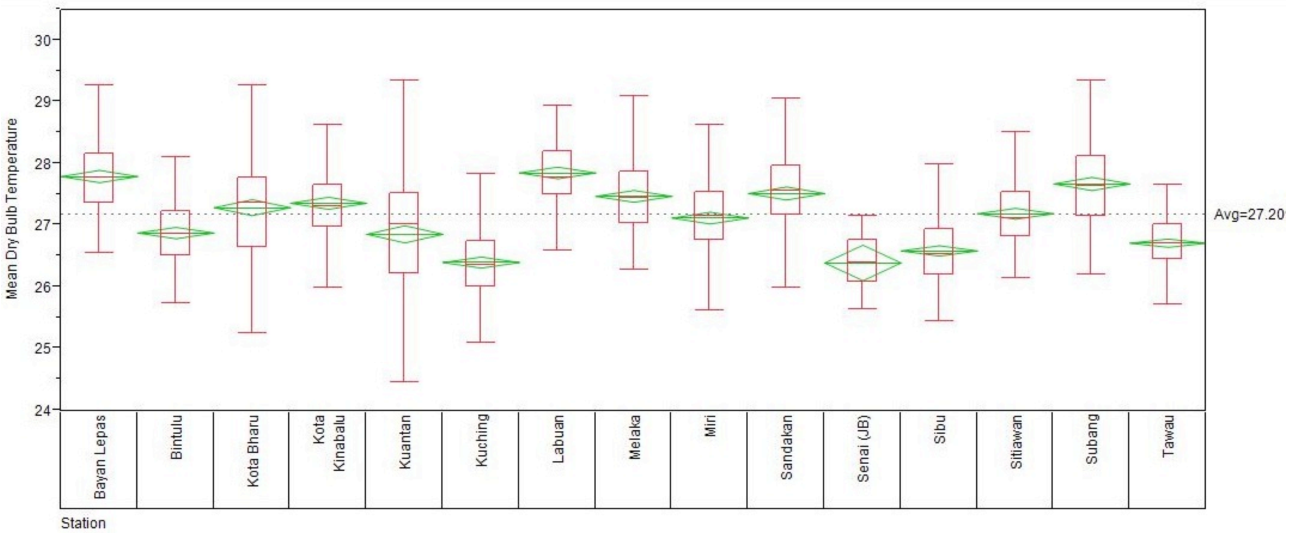

Figure 2. Yearly Mean Daily Dry Bulb Temperature Distributions by Station (1997-2008).

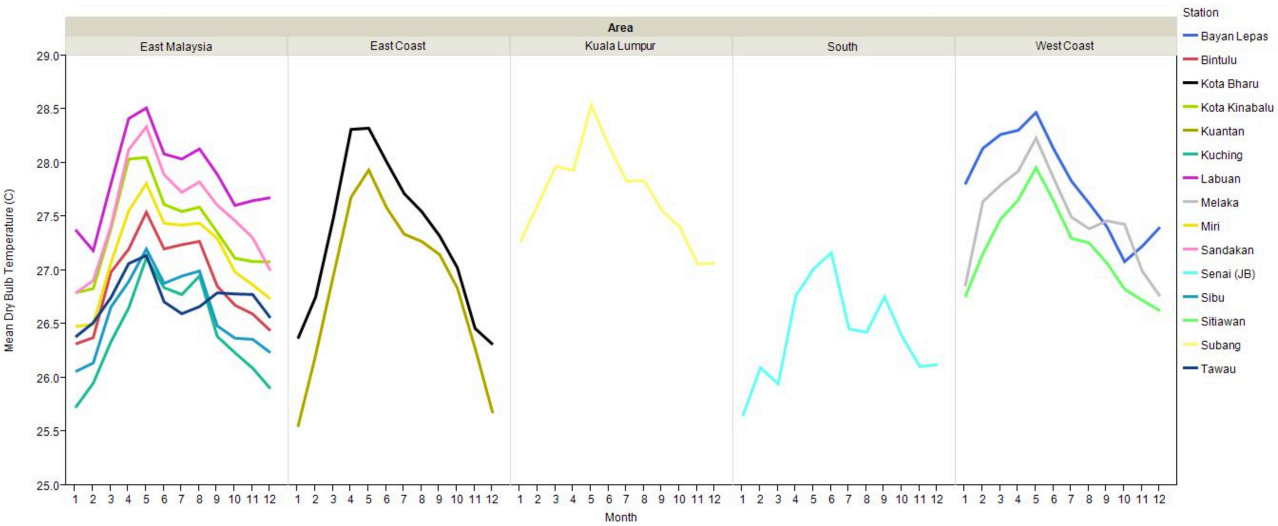

Figure 3. Monthly Mean Daily Dry Bulb Temperature by Area & Station.

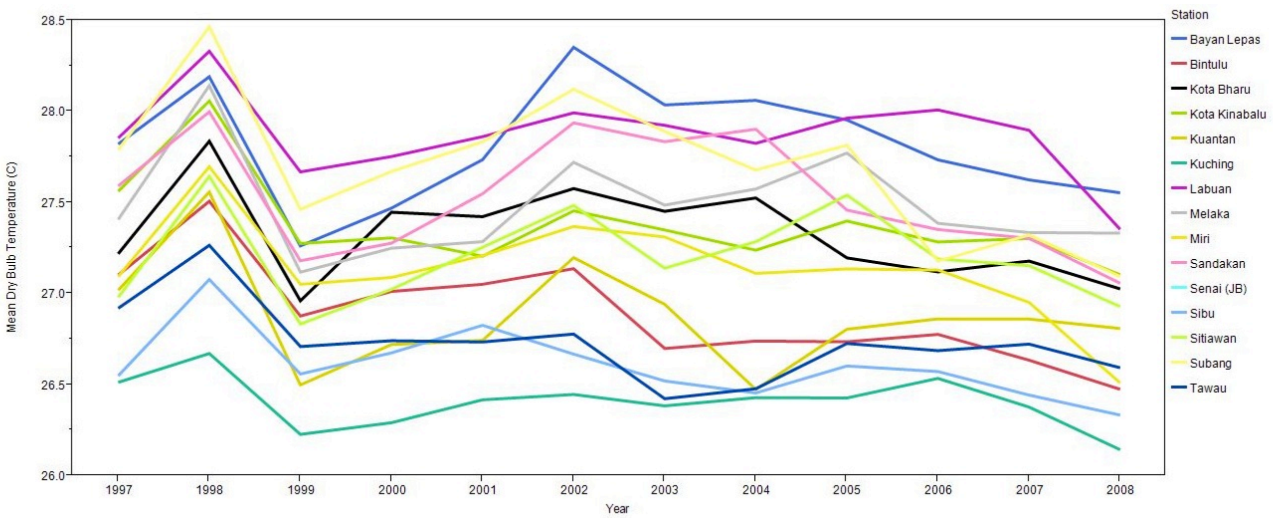

Figure 4. Yearly Mean Daily Dry Bulb Temperature by Station.

3.1.2 Relative Humidity

Relative humidity was low in Subang (78.6%) and Bayan Lepas (79.4%), as summarized in Table 2. The rest of the sites are divided into two basic groups, as seen in Figure 5. The higher relative humidity group contains Kuching (85.1%), Bintulu (83.8%), Kuantan (84.3%), Miri (83.9%), Sibu (84.3%), Sitiawan (83.8%), and Tawau (83.0%). A slightly lower humidity group contains Kota Bharu (81.4%), Kota Kinabalu (81.0%), Melaka (80.6%), and Labuan (80.7%). Sandakan (82.7%) lies between these two groups. Bayan Lepas overlaps with some of the stations in the lower humidity group while Subang has significantly lower humidity than the other stations. The annual patterns depicted in Figure 6 show significant variations, which are due to the varying northeast and southeast monsoon patterns that vary depending on region. Overall, the consistent and high humidity levels are typical of the tropical region.

3.1.3 Cloud Cover

Tawau (at 6.35 oktas) appears to have a significantly lower cloud cover than the other stations, according to data in Table 2 and as seen in Figure 7. It also appears to have more variation but values are still much lower than at other stations. Senai (Johor Bahru) also had very low cloud cover but this represented only one year, thus the annual variation is not represented. The stations with the highest cloud cover are Kota Bharu (7.18), Kota Kinabalu (7.11), Kuantan (7.07), and Labuan (7.10). Figure 7 presents a box plot of these data. Figure 8 indicates that cloud cover is generally high throughout the year, likely due to the persistence of near continuous high-level clouds, punctuated by strong rainstorms of relatively short duration. Many locations appear to have the lowest cloud cover values early in the year and the highest cloud cover values around October. The west coast locations appear to have the lowest values in January and February while the lowest cloud cover values appear a bit later in East Malaysia. Kuala Lumpur area appears to have less seasonal variation compared to other locations.

3.1.4 Rainfall

Sites with high average daily rainfall are Kuching (11.68 mm) and Bintulu (11.02 mm), both in Sarawak, the western part of East Malaysia (see Table 2). Sites with lower rainfall are Sitiawan (4.86 mm), Tawau (5.33 mm) and Melaka (5.42 mm). The remaining sites fall into a middle group, as seen in Figure 9. Some sites appear to vary more than others. Bintulu, Sandakan, and Kota Kinabalu have higher standard deviations than Melaka, Miri, Sitiawan and Subang. Figure 10 clearly shows the influence of the northeast monsoon on the east coast of Peninsular Malaysia and a slightly time shifted monsoon on East Malaysia. The other regions show a mild bimodal pattern reflecting the two rainy seasons.

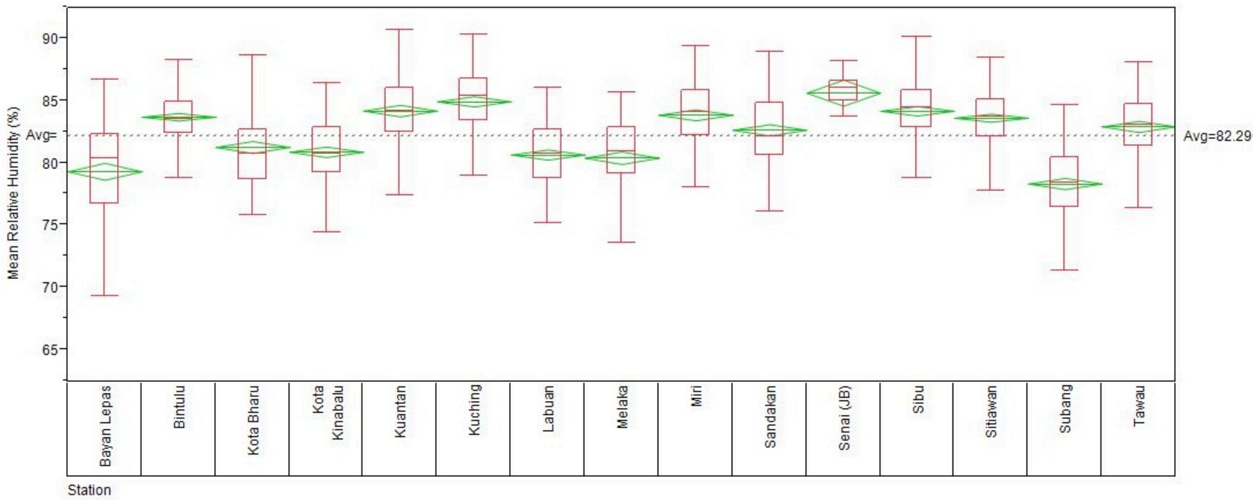

Figure 5. Yearly Mean Daily Relative Humidity Distributions by Station (1997-2008).

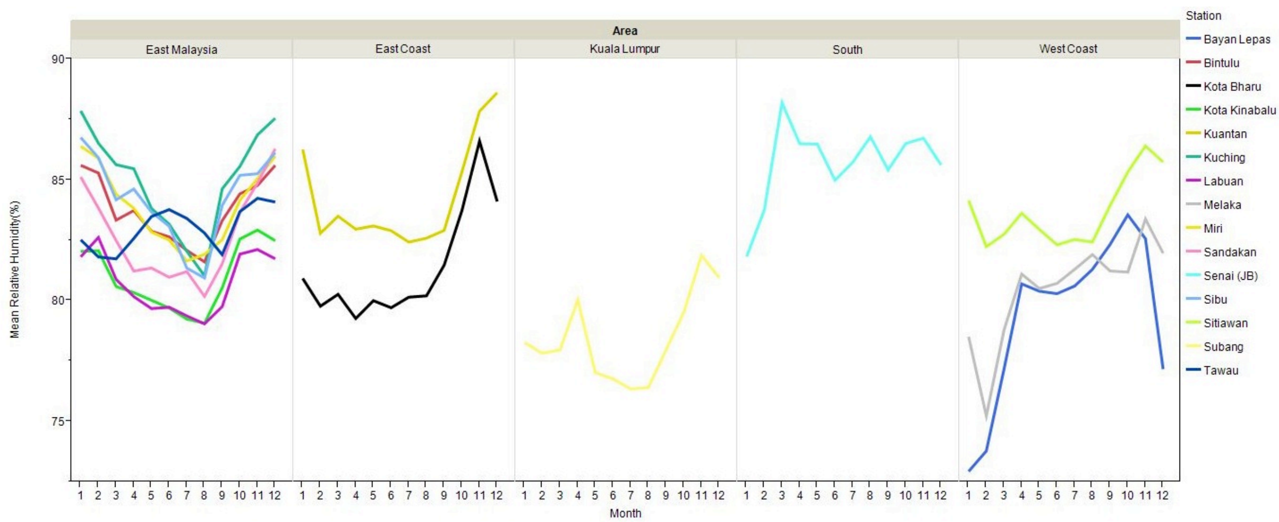

Figure 6. Monthly Mean Daily Relative Humidity by Area and Station.

3.1.5 Air Pollution Data

The PM10 monitoring program at most sites only took 24-hour average data once every 6 days. Thus, the dataset represents an overall average and may have missed daily or multi-day events. Table 2 summarizes the specific values of PM10 for each site where data were collected. Most of the sites studied have fairly close mean daily PM10 values, as seen in Figure 11, although Melaka (41.4 µg/m^3) and Subang (38.8 µg/m^3) appear to have a slightly higher mean daily PM10. Air pollution in Malaysia can be highly variable from year to year due to biomass burning; so Figure 12 shows the monthly averages for each station over 4 years. In 2006 and 2009, PM10 values appeared to be higher than normal, as well as 2009. Higher values appear to occur in June through October, which roughly corresponds to the dryer season and an increase in biomass burning.

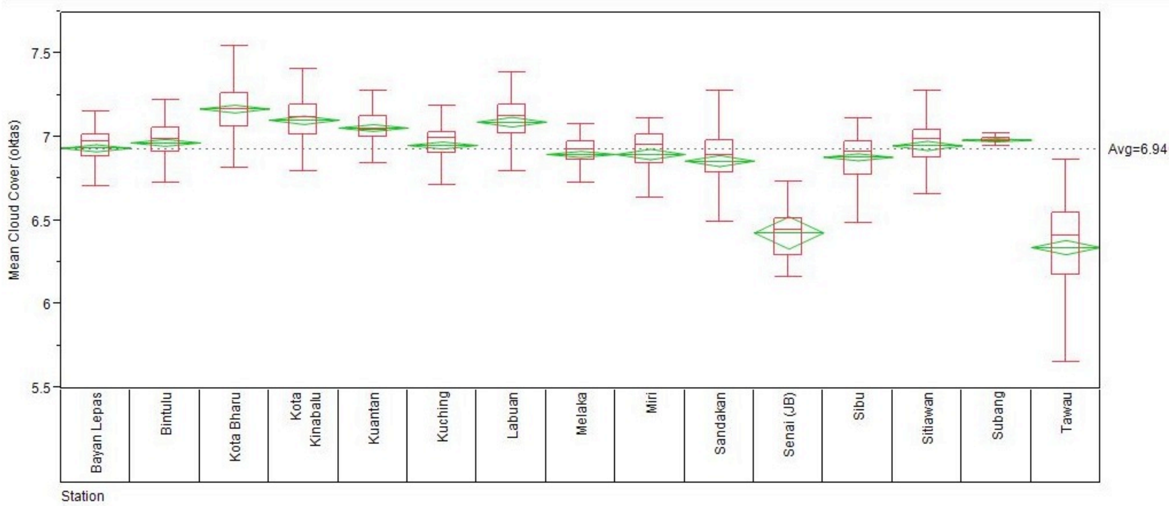

Figure 7. Yearly Mean Daily 24-hour Cloud Cover Distributions by Station (1997-2008).

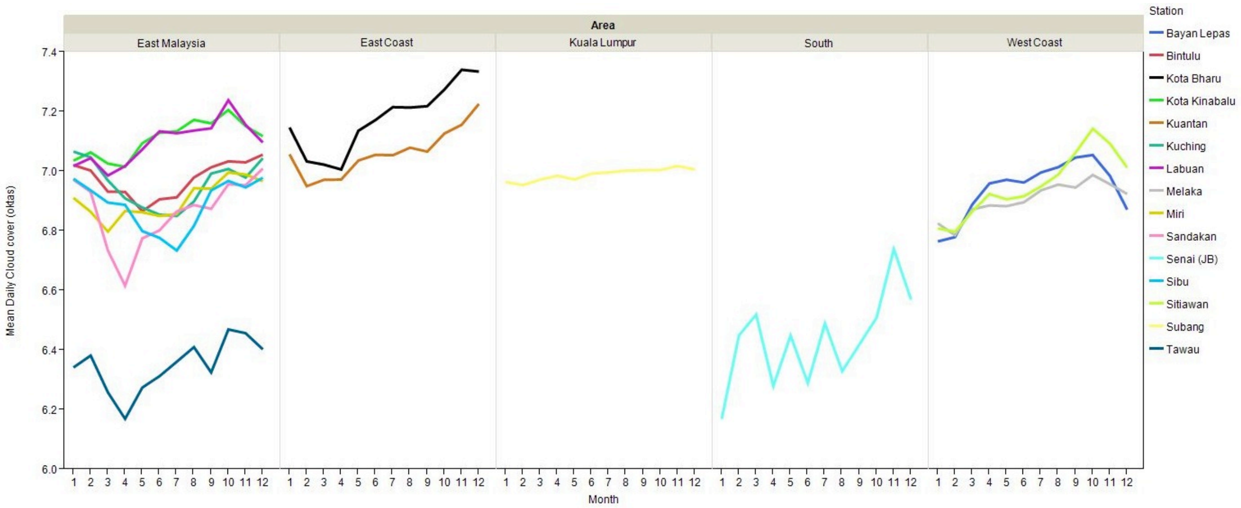

Figure 8. Monthly Mean Daily Cloud Cover by Area and Station.

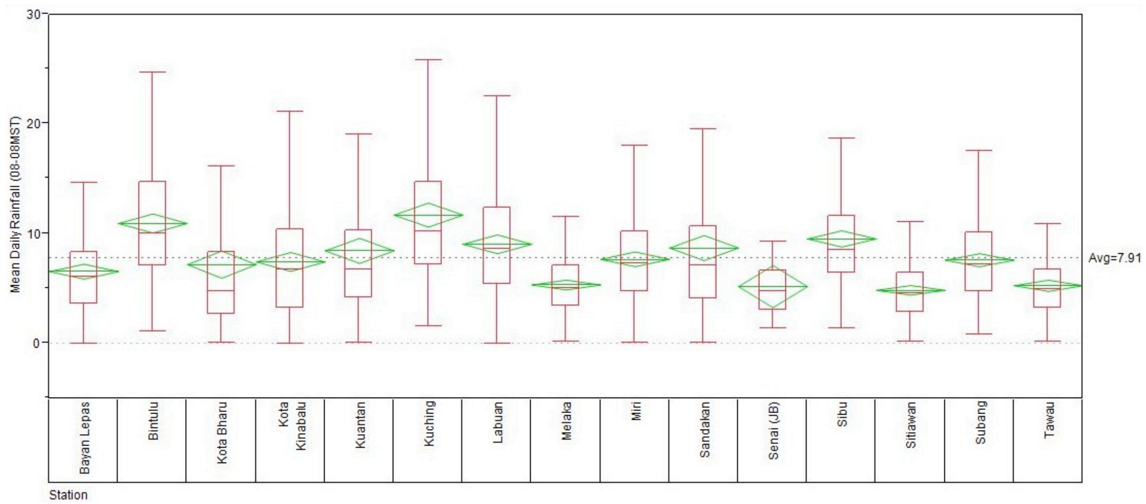

Figure 9. Yearly Mean Daily Rainfall Distributions by Station (1997-2008).

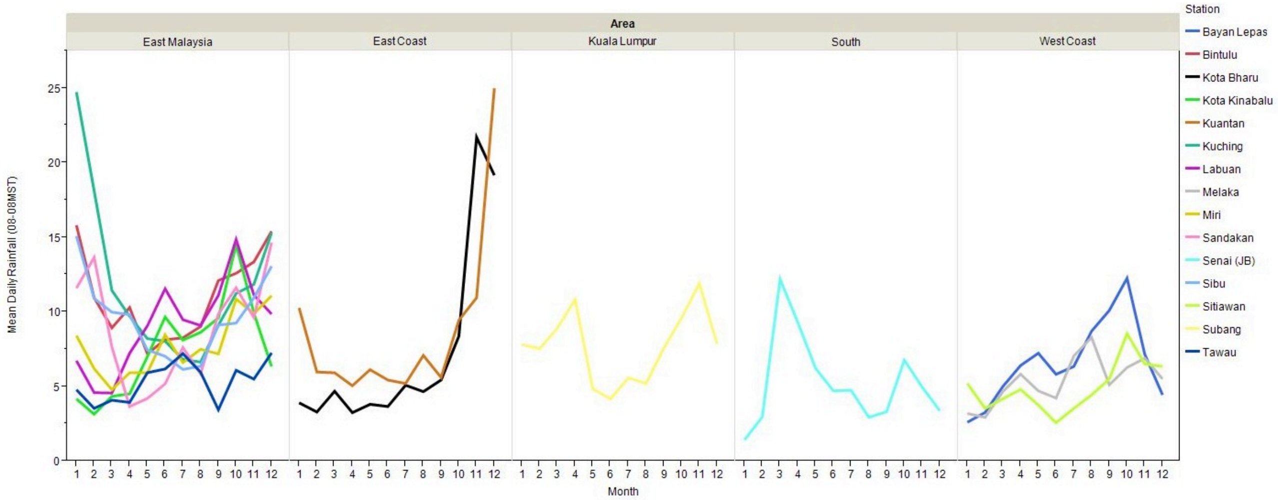

Figure 10. Monthly Mean Daily Rainfall by Area and Station.

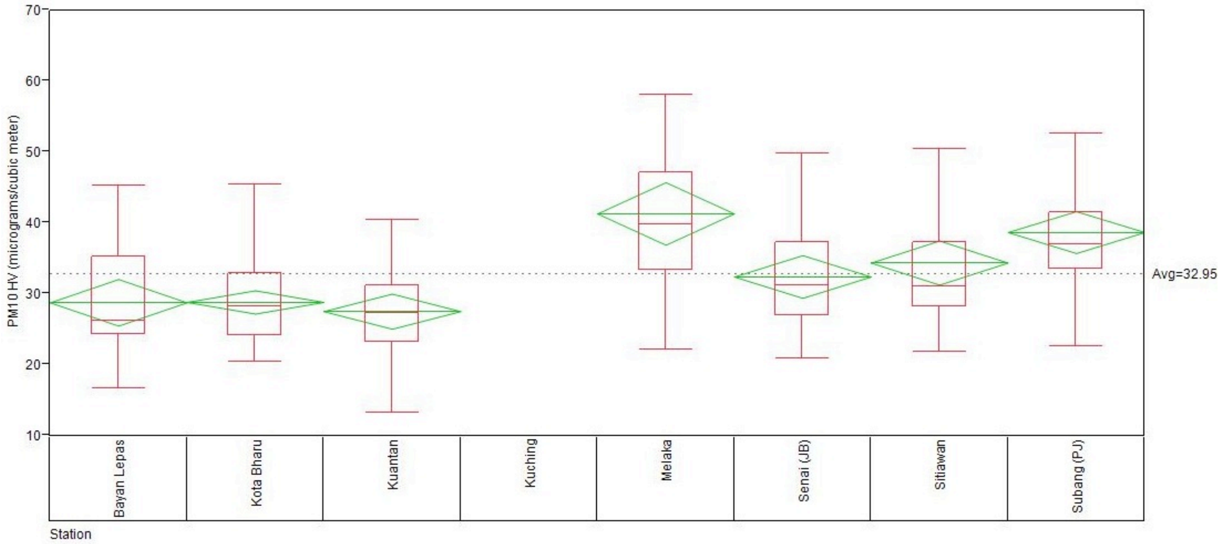

Figure 11. Yearly Mean PM10 Distributions by Station.

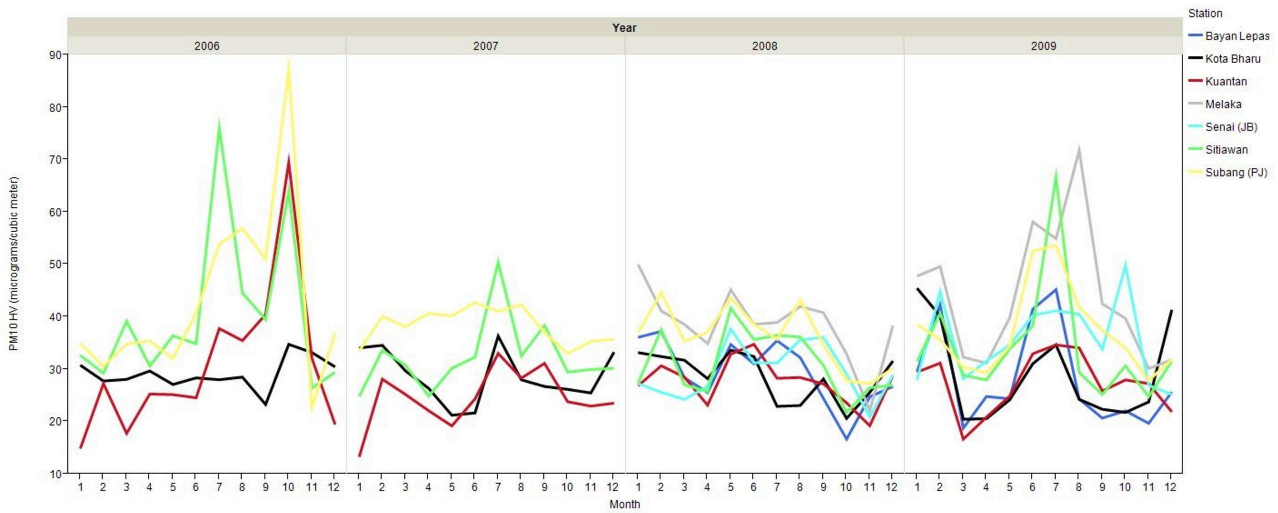

Figure 12. Monthly PM10 Values by Station and Year.

3.2 Global Solar Radiation Data

Bayan Lepas (5.10 kWh/(m^{2}d)) and Kota Bharu (5.11 kWh/(m^{2}d)), both in the northern part of Peninsular Malaysia, have the highest mean daily global solar radiation. Kuching (4.19 kWh/(m^{2}d)) has the lowest global solar radiation, as does Senai/Johor Bahru although this represents only one year of data. This is presented in Figure 13 and the data are summarized in Table 2. The monthly pattern varies considerably based on region, as seen in Figure 14, with the east coast of Peninsular Malaysia and East Malaysia showing a significant decline during the northeast monsoon and the other regions showing a less distinct pattern. When reviewing the data by station, it is difficult to detect consistent regional and seasonal patterns. There is considerable variation from year to year, as shown for the location with the most consistent data, Subang, in Figure 15.

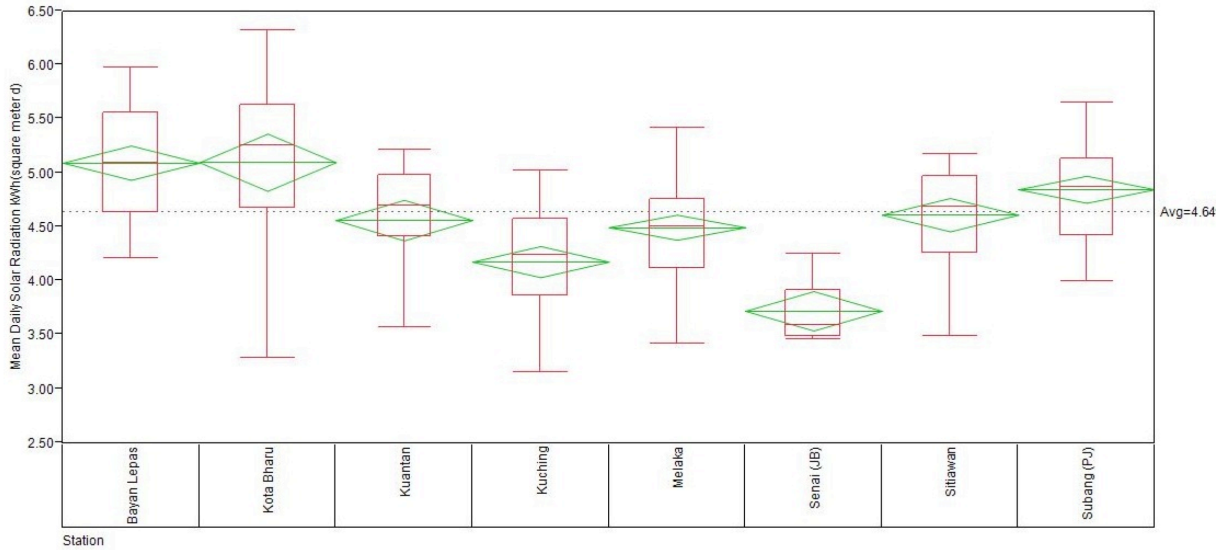

Figure 13. Yearly Mean Daily Solar Radiation Distributions by Station.

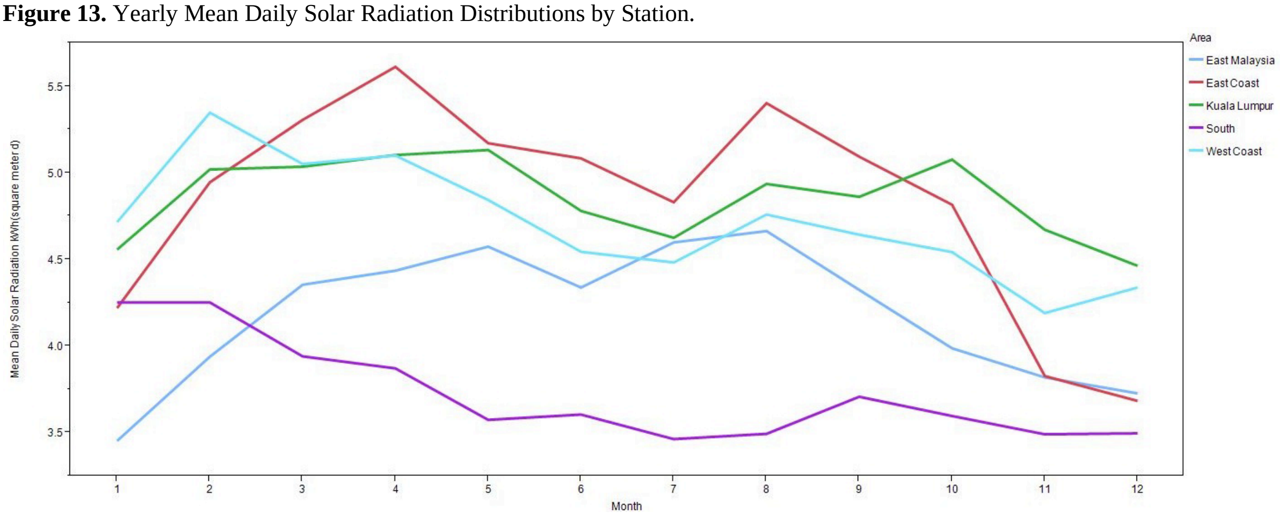

Figure 14. Monthly Mean Daily Solar Radiation by Area.

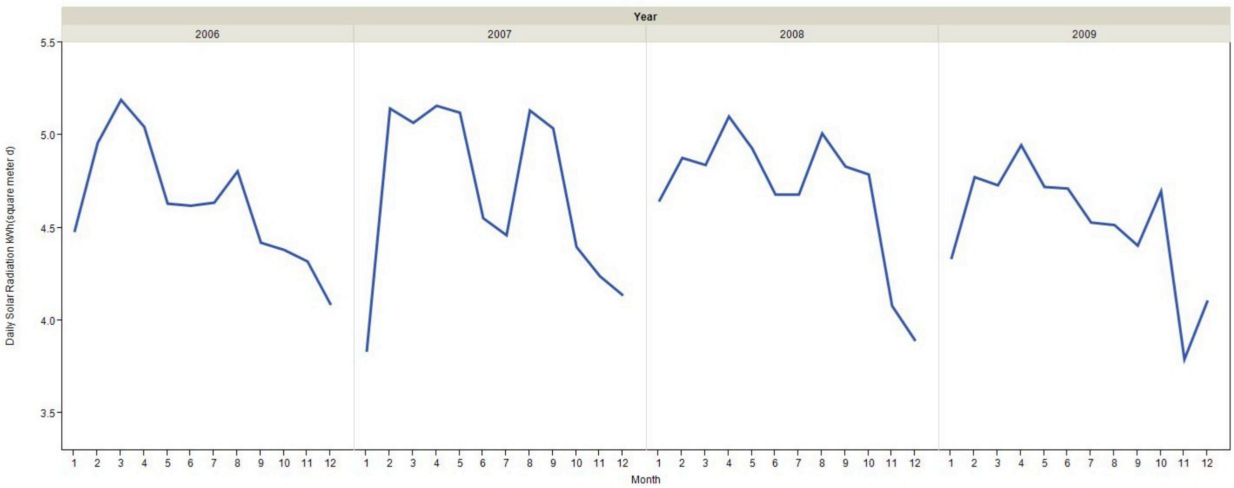

Figure 15. Monthly Mean Daily Solar Radiation for Subang by Year.

4. Key variables in predicting solar radiation

Malaysia has a very limited solar radiation monitoring network, with large spatial gaps particularly in East Malaysia (Borneo). Satellite data and satellite data-based models can provide some additional information. However, given the generally observed pattern between aspects of the meteorological data and the radiation levels and the more commonly available meteorological data, the next step in the analysis was to evaluate how the data could be used to predict solar radiation.

Through a series of statistical tests, the significant meteorological variables were determined to be: 24-Hour Mean Dry Bulb Temperature, 24-Hour Mean Humidity, 24-Hour Mean Wind Speed, Daily Rainfall Total 08-08 MST, 24-Hour Mean Cloud Cover, latitude, and longitude, with the response as daily global solar radiation. PM10 values were also tested as a variable, but due to the limited availability of PM10 data both spatially and temporally, the predictive formulas used in this study do not include PM10 as a variable. However, as additional data becomes available, this area warrants further investigation. The neural network methodology used was the Gauss-Newton model available in JMP [17]. This model is appropriate for models with less than forty regressors [18]. Five nodes were selected with an overfit penalty of 0.1. Forty tours were employed with the convergence criterion set at 0.00001 and the maximum iterations set at 75. K-Fold cross validation was performed with the number of cross validation groups set to 5. The model produced a coefficient of determination; R^2 = 0.81, and a root mean square error of 0.27 kWh/(m^2d).

When comparisons were grouped by station, as shown in Figure 16, the model appears to predict the differences in mean daily global solar radiation between the various stations. When comparisons were grouped by month, as shown in Figure 17, the variation in the predictive capability of the model is more distinct, indicating a slight under-prediction of the model during the rainy season and a slight over-prediction during the dryer months. This matches the findings of Hing Chong Hu and Joo Tick Lim [6] who found that the global solar radiation values are most dependent on rainfall. The model is limited by the amount of solar radiation data available. It is possible with the input of additional data that the models could be improved to predict monthly fluctuations in global solar radiation.

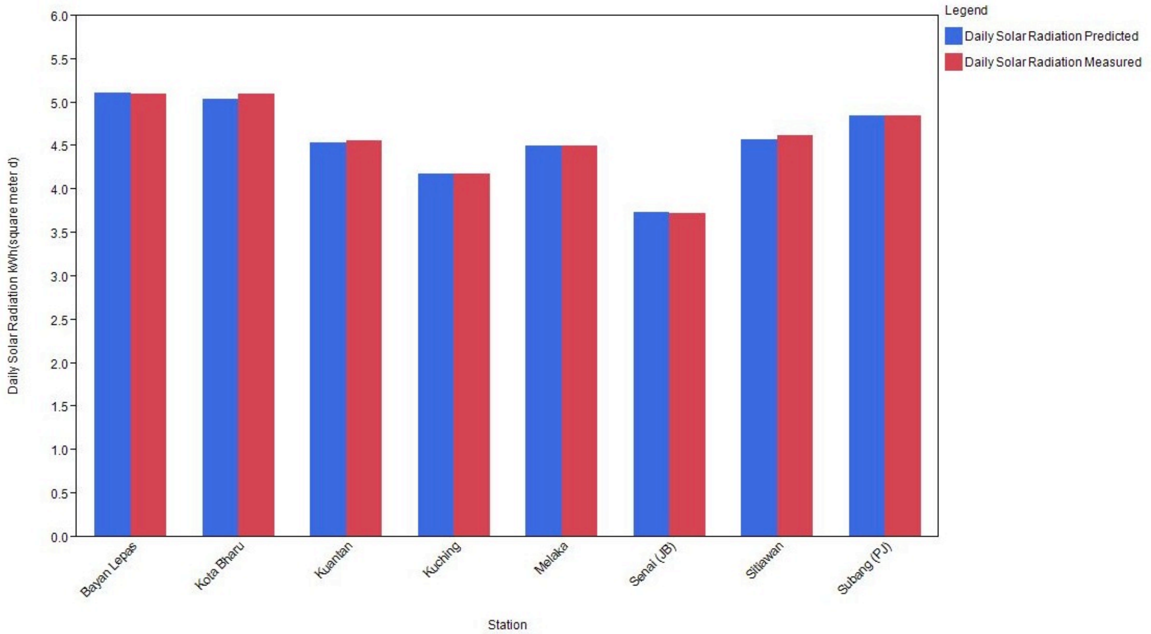

Figure 16. Mean Daily Solar Radiation Measured versus Modelled by Station.

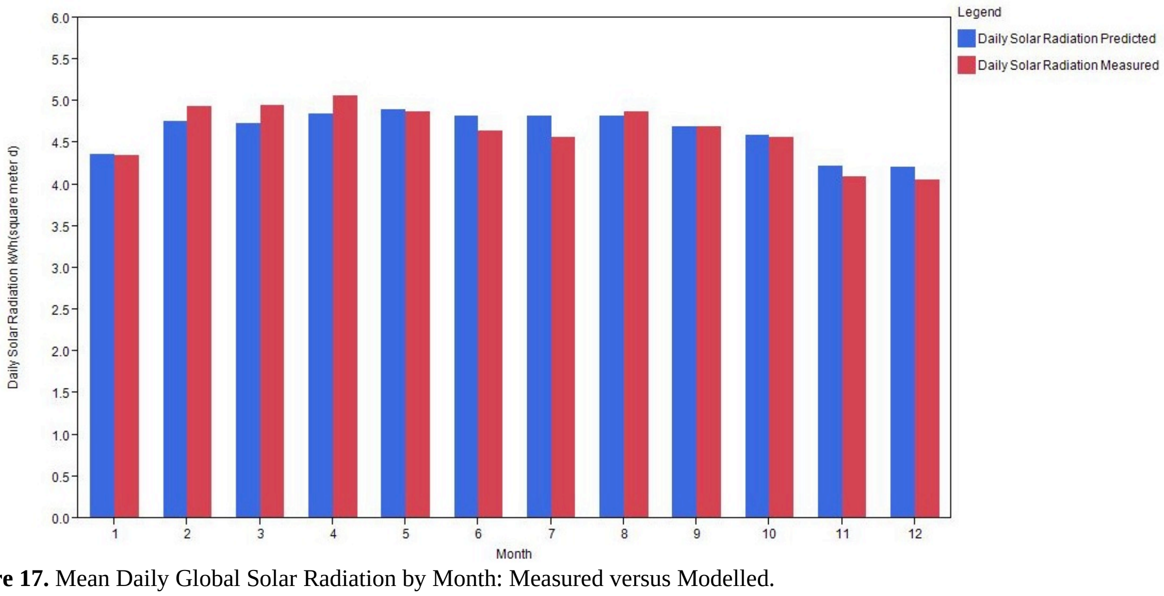

Figure 17. Mean Daily Global Solar Radiation by Month: Measured versus Modelled.

5. Applications of Results

Currently, the majority of the solar photovoltaic installations are located in the urban Klang Valley (Selangor, Kuala Lumpur, Putrajaya), with other locations in Johor and Melaka [19]. This small number of sites, many at residential locations, and the wide variety of technologies, installation configurations, and maintenance, did not allow for a meaningful analysis of technology performance based on variations in global solar radiation. The Malaysian government recently launched a feed-in tariff that may rapidly increase the deployment of solar technologies in more locations. The ability to estimate solar radiation using surrogate measures would provide better analysis of expected performance of technologies in locations outside of the Klang Valley. The validation of the average meteorological data for the region will also have applications when sizing and deploying solar technology systems.

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