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Sunshine-based Global Solar Radiation Modelling: Case Study of Putrajaya, Malaysia

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Abstract

Electricity demands are on the rise and with it, carbon dioxide emissions from many conventional power plants are increasing. In the efforts to mitigate such phenomena, the Malaysian government seeks to implement Building Integrated Photovoltaic (BIPV) projects. Early stage studies on Global Solar Radiation (GSR) have been carried out in several states in Malaysia including Penang, Kuala Lumpur and Kota Bharu. Afterward, data from the Malaysia Meteorological Department and the Malaysia National University have been used to estimate the monthly average daily global radiation in various locations in Malaysia. Putrajaya, a location which is implementing Malaysian Building Integrated Photovoltaic (MBIPV) is among the locations where a GSR study is currently absent. Conventional methods exist for GSR estimation with the aid of pyranometer. However, this method of GSR estimation is time consuming and not cost-effective practice. The main objective of this study is to estimate the GSR in Putrajaya. This is achieved in this study by utilizing sunshine-based data with calculated monthly average daily extraterrestrial radiation on a horizontal surface and monthly average maximum possible daily sunshine to plot a linearly fitted graph. Coefficients in the Angstrom-Prescott (A-P) model was generated from the plotted graph and was used for GSR estimation where $a = 0.5$ and $b = 0.11$. The mean percentage error (MPE) of the GSR estimation was found to be 3.4. Therefore, the estimation of GSR in Putrajaya have been successful for the first-time using sunshine-based data from dual locations method. The GSR estimation of Putrajaya in this study could benefit stakeholders in civil development sectors, policy and energy authorities.

Keywords: Angstrom-Prescott model; global solar radiation; Putrajaya

1.0 INTRODUCTION

Malaysia is a tropical country placed within the South East Asia region geographically and in terms of energy supply, it is heavily reliant on fossil fuel. 93% of its energy comes primarily from three major fossil fuel products which are coal, natural gas and crude oil and petroleum products and others. This leads to its power generation being heavily reliant on fossil fuel products like natural gas, fuel oil, coal and diesel. These products largely made up 92% of the fuel mix used in generating electricity in 2012 [1]. This heavy dependency on fossil fuel has caused the electricity cost to increase. Due to low supply of natural gas, the electricity tariff was increased by 7% in 2011 and 2014 [2]. Hence, it is facing the problem of rising cost in electricity which could have a negative impact on the economic development of the country. On top of rising electricity cost, the long-term increase in economic growth of Malaysia has caused increase in energy consumption and carbon dioxide (CO_2) emissions. In the published research paper, Ang 2008 examined the relationship between output, pollutant emission and energy consumption, specifically, in Malaysia during the time frame of 1971 to 1991 [3]. Malaysia was chosen as a case study because it was identified as one of the highest growth economies in the developing world. In addition to that, it had also experienced a significant increase in pollutant emissions and energy consumption. Ang 2008 concluded that CO_2 emissions and energy consumption were positively related to output in the long term. The results supported the argument that economic growth exerted a positive causal influence towards the growth of energy consumption in the short and long term [3]. This leads to more energy problems in terms of increasing electricity demand to continue its economic development and the need to mitigate CO_2 emissions.

The Malaysian government recognizes that the available energy resource is insufficient to assure supply beyond 2030. In addition to that, the forecast that electricity generation from oil would no longer be feasible due to dwindling national oil resources. Consequently, Malaysia is likely to become a net oil importer by 2030. The study from Oh et al. 2010 considered renewable energy to be the safest and cleanest of prospective energy sources in the long term [4]. Hence, the Malaysian government is interested to develop solar energy as one of the major sources of energy in the country. According to Mekhilef et al. 2012, the prospects of solar energy in Malaysia appears positive and a large provision has been dedicated to implement solar PV systems in the 9th Malaysia Plan [5]. As there is endorsement by policymakers and local government, this has led to attempts in implementing solar PV systems which include two Malaysian Building Integrated Photovoltaic (MBIPV) projects in Putrajaya. The first project is with bungalow houses in Precinct 16 and the second is with the Putrajaya Perdana Headquarters building [5]. For the government to further invest in the development of solar PV systems in Putrajaya, research on global solar radiation (GSR) at the location is crucial. Hence, this study aims to estimate the GSR in Putrajaya for the benefit of the various stakeholders who are interested in the development of solar PV systems in Putrajaya, like the government, local energy industry and the public.

In this paper, we intend to communicate the following: a brief literature review concerning GSR research, GSR models and the A-P model within the context of our research; a detailed account of the methodology; and results pertaining to achieving the estimate for GSR in Putrajaya. Alongside this, a different methodology is introduced which uses a dual location method and, ultimately, estimates of GSR will be obtained for a new location, i.e. Putrajaya, in Malaysia. There were studies related to the estimation of the GSR in Penang, Kuala Lumpur and Kota Bharu in 1981 [6]. Later, in 1992, data from the Malaysian Meteorological Department (MET) and the Malaysian National University were used to estimate the monthly average daily global radiation in a greater number of locations within Malaysia. These locations included Kuala Lumpur, Petaling Jaya, Bandar Baru Bangi, Kota Baru, Senai, Bayan Lepas, Kuching and Kota Kinabalu [7]. Currently, the GSR in Putrajaya, a location identified for implementing solar PV systems, has yet to be estimated. Thus, there is a need to estimate GSR in Putrajaya to maximize the potential use of solar PV systems there.

The ideal method to obtain the amount of GSR at a location is to install a measuring device like a pyranometer at the site to observe and document its day-to-day recordings. However, this can be a time-consuming and costly practice. Hence, models are commonly used to estimate GSR to avoid this. These models are usually based on astronomical factors like hour angle, solar declination, the solar constant and sun to earth distance; geographical factors like longitude, latitude and elevation; geometrical factors like azimuth angle, surface tilt angle, sun azimuth angle and sun elevation angle; physical factors like water vapor content, scattering of air molecules and scattering of dust and other elements in the atmosphere like O_2, CO_2, N_2, etc.; and meteorological factors like extraterrestrial solar radiation, temperature, sunshine duration, precipitation, effects of cloudiness, relative humidity, evaporation, soil temperature, etc. [8].

2.0 METHODOLOGY

There are numerous models used to predict GSR based on the meteorological parameters. The models were categorized base on sunshine, cloud, temperature and other meteorological parameters, as shown in Table 1 [8]. Additionally, the global solar energy models were grouped by modelling techniques such as linear, nonlinear, artificial intelligence and fuzzy logic modelling techniques in a review. The reviewers discovered the models used to estimate GSR in published works were mostly correlated to sunshine duration, air temperature, relative humidity and geographical parameters like latitude, longitude and altitude [9].

Table 1 Models based on meteorological parameters found in [8].

Models	Quantity
Sunshine-based	35
Cloud-based	6
Temperature-based	16
Other meteorological parameter-based	21

Various studies on global solar radiation had been carried out at different locations in the world. Table 2 presents sunshine based model regression equation classifications. For Malaysia context, several models were proposed and used to estimate monthly average global solar radiation in selective areas including Penang, Kuala Lumpur, Kota Bharu at the earlier stage and followed by Petaling Jaya, Bandar Baru Bangi, Kota Baru, Senai, Bayan Lepas, Kuching and Kota Kinabalu excluded Putrajaya. Thus, this paper presents the global solar radiation at Putrajaya using sunshine based empirical models. The conventional approach to measure global solar radiation at a specific location relies on pyranometer or manual recording method on daily basis. These methods required high precision of measuring devices, big data storage capabilities which are time-consuming and costly. The contribution of this paper is to exhibit a reference of global solar radiation at Putrajaya for a braid range of beneficiaries including energy policy maker, local authority, urban planner and energy investor etc.

Table 2 Sunshine based model regression equation classifications [10]-[16].

Regression Equation	
Linear	**Quadratic**
$\frac{H}{H_O} = a+b\log(\frac{n}{N})$ $\frac{H_g}{H_g} = 0.29 + 0.52(S)$ $\frac{H_O}{H_g} = 0.32 + 0.42(S)$ $\frac{H_g}{H_g} = 0.29COS\varphi + 0.52(S)$ $\frac{H_g}{H_o} = 0.18 + 0.62(S)$	$\frac{H_g}{H_o} = 0.145 + 0.845(S) - 0.280(S)^2$ **Cubic** $\frac{H_g}{H_o} = a + b(\frac{s}{s_o}) + c(\frac{s}{s_o})^2 + d(\frac{s}{s_o})^3$

In comparison to other models, the Angstrom-Prescott (A-P) model is most widely used to estimate GSR at a location. This is mainly because, firstly, there is readily available meteorological data for the sunshine-based model. That means that MET can provide solar radiation data like the daily hourly GSR and the average daily sunshine duration to be used for computation in the A-P model. Secondly, the linear models derived from the A-P model are ranked high in global performance indicator (GPI). A review and statistical analysis were conducted on the various models used to predict GSR found that the linear models performed better than other models. The review categorized the various types of GSR models as linear, polynomial, logarithmic, exponential, power and hybrids. Using ten statistical indicators, they introduced a global performance indicator (GPI) to rank the performance of the different models. Out of 101 models, their results showed that the linear model took first and third place while the polynomial model took second place. Within the top ten, 6 were linear models [17]. Thirdly, the A-P model is preferred due to its simplicity as a linear model and its reliability as a tool to estimate the GSR for practical applications like solar PV systems [18]. Monthly average daily extraterrestrial radiation, H_0 and average maximum possible daily sunshine duration within a month, S_0 can be calculated using equation (1) and (2) as shown below.

$$H_0 = \frac{24\times3600}{\pi} I_{sc}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right]\left[\cos\varphi\cos\delta\sin\omega_s + \frac{\pi}{180}\omega_s\sin\varphi\sin\delta\right]. \quad (1)$$

$$S_0 = \frac{2}{15}\omega_s. \quad (2)$$

In equation (1) and (2), I_{sc} is the solar constant with a value of 1367 W m^{-2}, n is the number of day in the year beginning at first of January, φ is the latitude of the location measured in °, δ is the solar declination measured in degree and ω_s is the sunset hour angle measured in degree. Furthermore, both, δ and ω_s, from equation (1) can be calculated using equations (3) and (4) as shown below.

$$\delta = 23.45\sin\left(\frac{360}{365}[284 + n]\right). \quad (3)$$

$$\omega_s = \cos^{-1}(-\tan\varphi\tan\delta). \quad (4)$$

First, determining the average daily global radiation on a horizontal surface within a month (H). The first step was to compute the average daily GSR data from the hourly GSR data provided by MET. This was done in two stages; the first stage was to compute the daily GSR from the hourly GSR and the second stage was to compute the average daily GSR in a month from the daily GSR. In the first stage, the daily GSR data was computed by summing the hourly GSR for a given day as shown in equation (5) below.

$$H_{daily} = \sum_{i=1}^{i=d} H_{i,h}. \quad (5)$$

Here, H_{daily} is the daily GSR, $H_{i,h}$ is the hourly GSR and d is the number of hours with solar radiation in a day. In the second stage, the average daily global radiation in a month was obtained by using equation (6).

$$H = \frac{1}{m}\sum_{i=1}^{i=m} H_{daily_i}. \tag{6}$$

Whereby, H is the daily average GSR in a month, H_{daily_i} is the daily GSR and m is the number of days in a month. The daily average was computed for each month in a year from January to December and used in the A-P model for the linear regression [19]. In this study, the average daily values in a month was chosen to be used for computation instead of the daily values because of 4 main reasons. Firstly, the model was originally intended to be used with the monthly average daily data [20]. Secondly and more importantly, a study conducted in 2009 to compare the different timescales on the A-P model and found that although there were large effects on the coefficients, a and b, there were no significant impact on the estimation accuracy of the GSR [21]. This was due to the little change in $(a + b)$ values for the different timescales. Thirdly, in the same study, it was also mentioned that the sunshine-based methods, particularly the A-P model performed the best generally. Finally, from a pragmatic point of view, there would be less computation required in using the average daily values in a month compared to the daily values. This was supported by a review article on solar radiation models as it was concluded that the linear, termed as first-order Angstrom type, correlation surpasses the second and third order, both, in the accuracy of the estimated values of the average daily global radiation on a horizontal surface in a month and in requiring less computational work [22].

Second, determining the average daily bright sunshine duration within a month (S). Since the daily sunshine duration data obtained from MET came with the average daily sunshine duration for a given month, no computation was required.

Third, determining the monthly average daily extraterrestrial radiation on a horizontal surface (H_0). The monthly average daily extraterrestrial radiation on a horizontal surface was computed using equation (1). Due to the complex appearance of equation (1), it was simplified into equation (7) for ease of computation.

$$H_0 = A \times B \times (C + D). \tag{7}$$

In equation (7), $A = \frac{24\times3600}{\pi} I_{sc}$, $B = 1 + 0.033\cos\left(\frac{360n}{365}\right)$, $C = \cos\varphi\cos\delta\sin\omega_s$ and $D = \frac{\pi}{180}\omega_s\sin\varphi\sin\delta$. In addition to that, recommended values of n that were used in the computation. These values were corresponding to the following dates: 17th of January, 16th of February, 16th of March, 15th of April, 15th of May, 11th of June, 17th of July, 16th of August, 15th of September, 15th of October, 14th of November and 10th of December [17]. Table 3 shows these dates and their corresponding n values.

Table 3 Recommended values of n used in computation and their corresponding dates.

Month	Date	n
January	17	17
February	16	47
March	16	75
April	15	105
May	15	135
June	11	162
July	17	198
August	16	228
September	15	258
October	16	288
November	14	318
December	10	344

Fourth, determining the monthly average maximum possible daily sunshine (S_0). The computation was done according to equation (2).

Fifth, determining the coefficients in the linear A-P Model. To achieve this, a scatter plot diagram of the ratio $\frac{H}{H_0}$ against the ratio $\frac{S}{S_0}$ was created. The values of $\frac{H}{H_0}$ and $\frac{S}{S_0}$ covered the duration of 2011 to 2014. Subsequently, the scatter plot was linearly fitted and the linear equation was obtained. The coefficients a and b in the linear A-P model were observed from the linear equation.

Sixth, validating the model using MBE, MAE, RMSE and MPE according to equations (8), (9), (10) and (11) through computation.

$$RMSE = \sqrt[2]{\frac{1}{n}\sum_{i=1}^{i=n}\left(\bar{H}_{i,m} - \bar{H}_{i,c}\right)^2}. \quad (8)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{i=n}\left(\bar{H}_{i,m} - \bar{H}_{i,c}\right). \quad (9)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{i=n}\left|\bar{H}_{i,m} - \bar{H}_{i,c}\right|. \quad (10)$$

$$MPE = \frac{100}{n}\sum_{i=1}^{i=n}\left(\frac{\bar{H}_{i,m} - \bar{H}_{i,c}}{\bar{H}_{i,m}}\right). \quad (11)$$

In equations (8), (9), (10) and (11), $\bar{H}_{i,m}$ and $\bar{H}_{i,c}$ are the measured and estimated monthly average daily GSR respectively and n is the number of observations. The computation was done with data of the measured monthly average daily GSR data and the estimated monthly average daily GSR at KLIA (latitude 2.7333°) since there were no available measured GSR data at Putrajaya. The estimated monthly average daily GSR at KLIA was computed according to equation (12) using the latitude of KLIA. Here, equation (12) is the rearranged form of equation (1).

$$H = (H_0)\left[a + b\left(\frac{S}{S_0}\right)\right]. \quad (12)$$

Seventh, and finally, estimating the monthly average daily GSR on a horizontal surface in Putrajaya (latitude 2.9264°). To do this, computation was done according to equation (12) using the latitude of Putrajaya. Figure 1 indicates the overall workflow and the main functional blocks involved in each methodological stage.

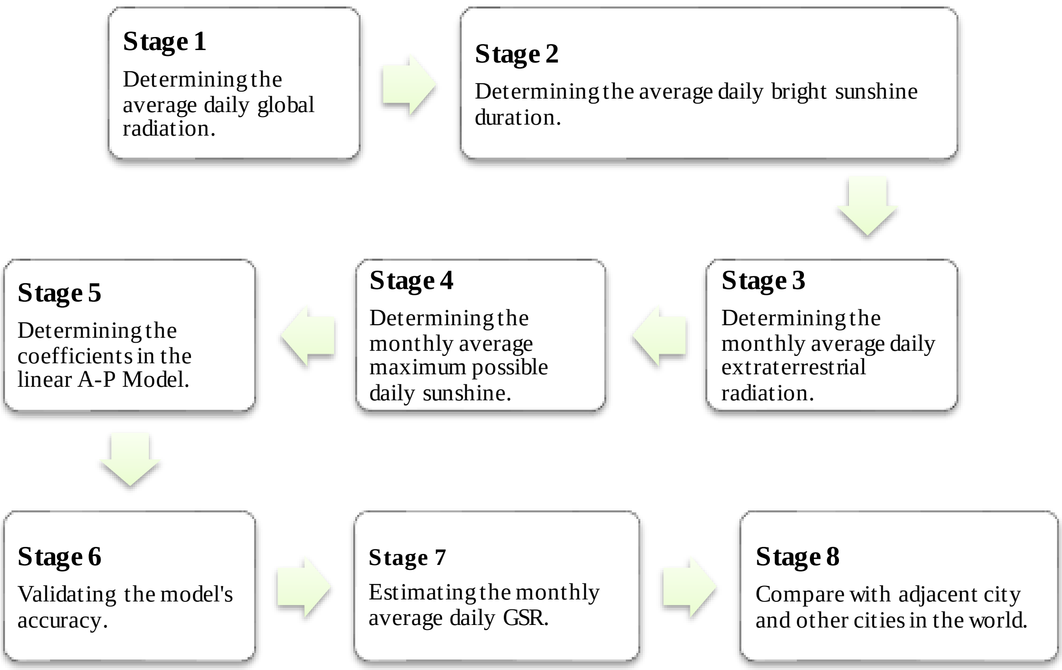

Figure 1 Overall workflow and its functional block at each stage.

3.0 RESULTS AND DISCUSSION

This section will cover the results of monthly average daily extraterrestrial radiation and average maximum possible daily sunshine duration within a month. The data from MET and computational values will be compared. This is followed by the results of linear fitting plot. Comparison with selected countries in various geographical locations in the world will be presented. Finally, the results of the estimated and measured GSR will be demonstrated.

3.1 Results of S_0 and H_0

The results from Table 4 were attained through computation based on the latitude of KLIA (2.7333°) and MARDI (2.9833°), values of n, δ, ω, S_0 and H_0 in accordance to equations (1), (2), (3) and (4). The S_0 and H_0 results from Table 4 is further used to compute the data required for the A-P model.

Table 4 Results of computed monthly data of δ, ω_s, S_0 and H_0.

Month	n	δ (°)	ω_s (°)	S_0 (h)	H_0 (MJ/m^2 day)
January	*17*	*-20.92*	*88.86*	*11.85*	*35.15*
February	*47*	*-12.95*	*89.31*	*11.91*	*36.79*
March	*75*	*-2.42*	*89.87*	*11.98*	*37.74*
April	*105*	*9.41*	*90.50*	*12.07*	*37.22*
May	*135*	*18.79*	*91.02*	*12.14*	*35.64*
June	*162*	*23.09*	*91.27*	*12.17*	*34.55*
July	*198*	*21.18*	*91.16*	*12.15*	*34.89*
August	*228*	*13.45*	*90.71*	*12.10*	*36.31*
September	*258*	*2.22*	*90.12*	*12.02*	*37.30*
October	*288*	*-9.60*	*89.49*	*11.93*	*36.85*
November	*318*	*-18.9*	*88.98*	*11.86*	*35.41*
December	*344*	*-23.05*	*88.73*	*11.83*	*34.49*

3.2 Results of $\frac{H}{H_0}$ and $\frac{S}{S_0}$

The data of H and S from MET and S_0 and H_0 from Table 3 was used to compute the ratios of $\frac{H}{H_0}$ and $\frac{S}{S_0}$ are shown in Table 4. The results in Table 5 shows both computable data of $\frac{H}{H_0}$ and $\frac{S}{S_0}$. All data of $\frac{H}{H_0}$ and $\frac{S}{S_0}$ were computable for the months of September, October and November. All data of $\frac{H}{H_0}$ and $\frac{S}{S_0}$ were incomputable for the month of December. Some data of $\frac{H}{H_0}$ and $\frac{S}{S_0}$ were computable for January, February, March, April, May, June, July and August.

Table 5 Results of computed $\frac{H}{H_0}$ and $\frac{S}{S_0}$

Month	H/H_0				S/S_0			
	Set 1	Set 2	Set 3	Set 4	Set 1	Set 2	Set 3	Set 4
January	-	-	-	-	-	-	-	-
February	-	0.4840	0.4733	-	-	0.5363	0.3063	-
March	-	0.4649	0.6288	-	-	0.3722	0.5644	-
April	-	0.5989	-	-	-	0.5468	-	-
May	-	0.5787	0.6117	-	-	0.5382	0.5561	-
June	-	0.6124	0.6162	-	-	0.5212	0.5351	-
July	-	0.5994	0.5691	-	-	0.4504	0.4579	-
August	-	0.5779	0.5871	-	-	0.3832	0.4507	-
September	0.4815	0.5803	0.5530	0.5615	0.4874	0.4608	0.4299	0.03360
October	0.4380	0.5580	0.6074	0.5463	0.4252	0.4650	0.4405	0.03431

November	0.4278	0.4917	0.5552	0.5167	0.3456	0.4111	0.3523	0.03290
December	-	-	-	-	-	-	-	-

3.3. Results of Linear Fitting of $\frac{H}{H_0}$ against $\frac{S}{S_0}$ Plot

The result of the linear fitting of the scatter diagram is given by equation (13).

$$\frac{H}{H_0} = 0.5 + 0.11\left(\frac{S}{S_0}\right). \tag{13}$$

Equation (13) reveals that $a = 0.5$, $b = 0.11$ and $a + b = 0.61$. Further analysis was performed by comparing between the results of a, b and $a + b$ from this study with that of Sopian et al. 1992 in their respective locations of Putrajaya and Kuala Lumpur as shown in Table 6 [7].

Table 6 Results of a, b and $a + b$ from Putrajaya and Kuala Lumpur [7].

Location	a	b	$a + b$
Putrajaya	0.5	0.11	0.61
Kuala Lumpur	0.27	0.35	0.62

Table 6 shows that there is variation in the values of a and b for geographical locations of Putrajaya and Kuala Lumpur. However, the value of $a + b$ is approximately the same. Table 7 presents a comparison with selected countries in various geographical locations in the world using with different regression equations and coefficients.

Table 7 Comparison with selected countries in various geographical locations in the world [23]-[26].

Country	Region	Regression Equation	Reference
Turkey	Middle East	$\frac{H}{H_o} = 0.2786+0.4160(\frac{S}{S_o})$	[23]
India	South Asia	$\frac{H}{H_o} = 0.34+0.32(\frac{S}{S_o})$	[24]
Zambia	East Africa	$\frac{H}{H_o} = 0.240+0.513(\frac{S}{S_o})$	[25]
Oman	Middle East	$\frac{H}{H_o} = 0.9428\text{-}1.2027\left(\frac{S}{S_o}\right) + 0.9336\left(\frac{S}{S_o}\right)^2$	[26]
Malaysia (Putrajaya)	Southeast Asia	$\frac{H}{H_o} = 0.5+0.11(\frac{S}{S_o})$	-

3.4. Results of Estimated and Measured GSR

The coefficients a and b obtained through linear fitting is used to estimate the GSR using the latitude of Putrajaya and equation (12). Both estimated and measured GSR results were compared using a linked plot diagram as shown in Figure 2.

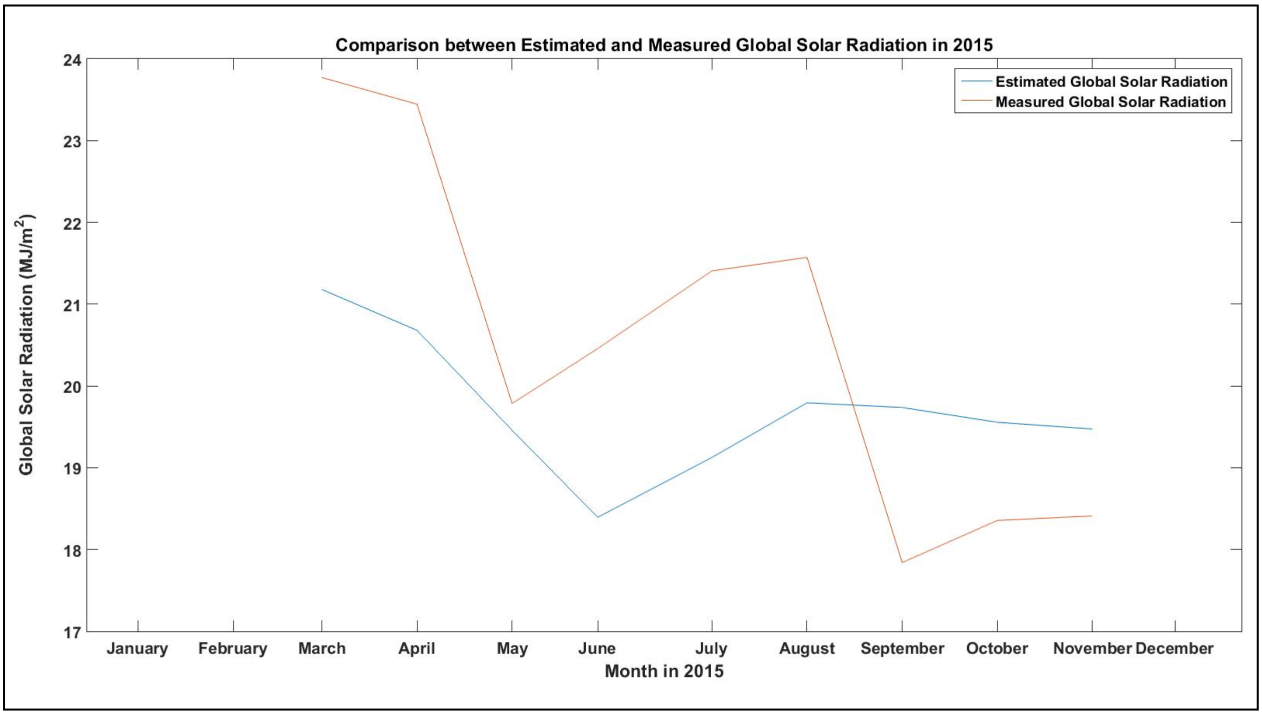

Figure 2 Results of the linked plot diagram of estimated and measured monthly average daily GSR.

The linked plot diagram from Figure 2 shows that out of 12 months, this study was able to estimate the monthly average daily GSR for 9 months while not being able to estimate the monthly average daily GSR for 3 months which was January, February and December. Figure 2 also shows that out of the 9 available estimates, 6 were underestimated and 3 were overestimated. The months of March to August showed overestimation while the months of September to November showed underestimation. The results obtained and shown in Table 4 support the choice of using the sunshine-based linear A-P model in this study. They were easily computed due to the readily available sunshine-based data and the relative simple to compute due to the linear characteristics of the A-P model as was mentioned stated by (Paulescu, et al. 2016) [18]. These results can function as a reference for future researches on GSR in Putrajaya as they reusable without having to be computed again. The substantial quantity of missing data amounting to 47.9% in Table 5 is mainly due to the defective data owing to the pyranometer malfunctioning and the screening process practiced in the methodology to ensure the remaining data was reliable as discussed in [19]-[21]. This work chosen a four-year window data based on several reviews on GSR models using available sunshine duration and GSR data around the world [17]. Our study used four years which fell within that range. Results from Table 6 show the of the A-P coefficients obtained in this study at Putrajaya in comparison to a previous study at Kuala Lumpur. The difference in the coefficients, a and b, is not uncommon as it is usually associated with difference in location [19]. More importantly, the sum of $a + b$ represents the overall atmospheric transmittance of a cloudless sky. In the case whereby there are no clouds in the sky, $\frac{S}{S_0} = 1$ which makes $a + b = \frac{H}{H_0}$. From Table 6, the sum of $a + b$ in Putrajaya and Kuala Lumpur showed similar values. The absence of estimates for the months of January, February and December as evident in Figure 2 is mainly due to missing data from MET. The coefficients, a and b, can be used along with sunshine-based data can be used to estimate GSR at a location with the application of equation (12).

4.0 CONCLUSION

This study has shown that by using data from dual nearby locations, estimates of the GSR in Putrajaya has be obtained for the first time. Coefficients in the Angstrom-Prescott (A-P) model was generated from the plotted graph and was used for GSR estimation where a = 0.5 and b = 0.11. The mean percentage error (MPE) of the GSR estimation was found to be 3.4 and the value of (a + b) is close to the value obtained at Kuala Lumpur which is 0.61 and 0.62 respectively. Thus, the finding of this paper provides an indication of global solar radiation at Putrajaya (hub of administration) which can be useful to the stakeholders including renewable energy policy maker, sustainable energy development authority, energy commission and renewable energy project investors and developers. The outcome of this work can also serve as reference model for several locations adjacent to Putrajaya via comparative studies. Based on this study, suggestions for further work including estimating the global solar radiation in Putrajaya using other models and different time scales; standardizing statistical tools in evaluating results or validating models; investigating the effects of regional haze on global solar radiation in Putrajaya; investigating the effects of monsoon weather on global solar radiation and setting up a pyranometer at a location in Putrajaya to collect long term global solar radiation data. Other recommendations for future work of the proposed work including the adoption of smart model to improve the estimation [27], consider both direct and diffuse solar radiation [28]&[30], climatic parameters [29], adoption of genetic algorithm [31] and influence of environmental pollution [32].

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