Solar irradiance uncertainty management based on Monte Carlo-beta probability density function: case in Malaysian tropical climate

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Article Info	ABSTRACT
	In recent years, solar PV power generation has seen a rapid growth due to environmental benefits and zero fuel costs. In Malaysia, due to its location near the equator, makes solar energy the most utilized renewable energy resources. Unlike conventional power generation, solar energy is considered as uncertain generation sources which will cause unstable energy supplied. The uncertainty of solar resource needs to be managed for the planning of the PV system to produce its maximum power. The statistical method is the most prominent to manage and model the solar irradiance uncertainty patterns. Based on one-minute time interval meteorological data taken in Pekan, Pahang, West Malaysia, the Monte Carlo-Beta probability density function (Beta PDF) is performed to model continuous random variable of solar irradiance. The uncertainty studies are needed to optimally plan the photovoltaic system for the development of solar PV technologies in generating electricity and enhance the utilization of renewable energy; especially in tropical climate region.

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1. INTRODUCTION

Malaysia is comprising of the Peninsular Malaysia; which known as West Malaysia and the state of Sabah and Sarawak; known as East Malaysia. Malaysia is located on South China Sea between 1° and 7° in North latitude and 100° and 120° in East longitude on the equatorial zone which being hot and humid throughout the year. Hence, solar energy is abundance and can be harnessed all year round. Solar energy has become the most popular renewable energy resources in Malaysia due to its availability, an environmentally friendly to generate electricity [1-4]. The grid maps of annual solar irradiation for Peninsular (West Malaysia) and state of Sabah and Sarawak (East Malaysia) are depicted in Figure 1 and Figure 2 respectively [5].

The ambient temperature in Malaysia ranges between 22°C to 33°C with average of daily temperature measured at approximately 26.5°C [2]. With elevated level of temperature and humidity, the annual average daily solar irradiations for Malaysia is measured between the ranged of 4.21kWh/m^2 to 5.56 kWh/m^2 [6]. The average of solar irradiation in Malaysia per year is approximately 1643kWh/m^2 [7]. Since the solar radiation is not applicable at night, the solar energy could be harvest from 8 am to 7 pm throughout the year [8]. The map of Malaysia on the equatorial zone which being hot and humid, is an advantage for the country in moving towards solar energy sources to reduce dependency in fossil oil [9]. The tropical climate

condition in Malaysia makes it possible for the development of solar PV technologies to generate electricity and enhance the utilization of RES for sustainable development in national electricity supply [7, 10].
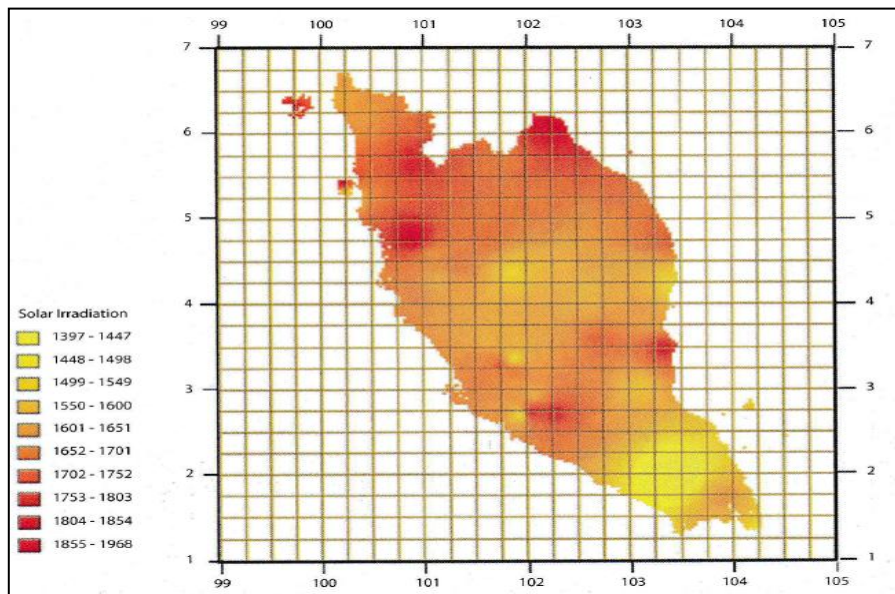

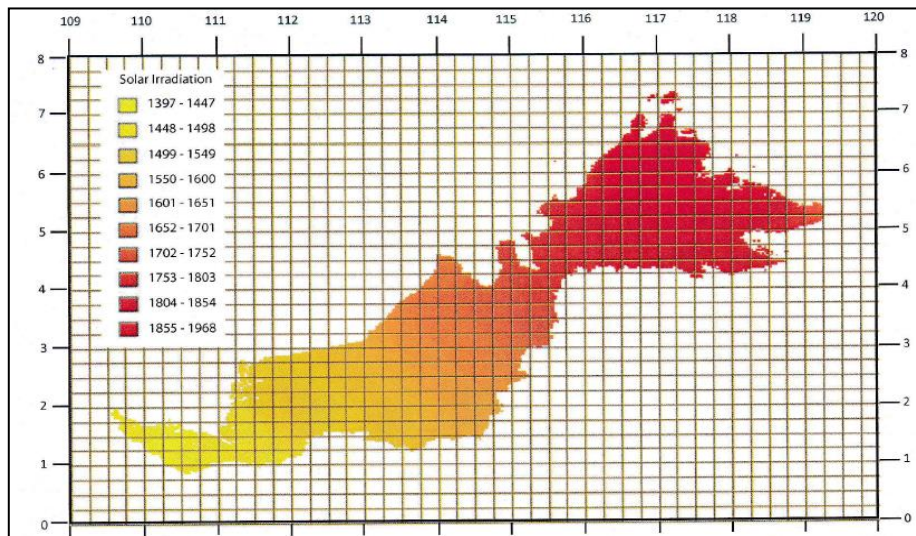Figure 1. Grid map of peninsular Malaysia (West Malaysia)

Figure 2. Grid map of East Malaysia (Sabah and Sarawak)

However, solar radiation in tropical climate has a high degree of uncertainty which depends on the environmental and meteorological conditions [11, 12]. The conditions such as cloud cover, haze, fog, shadow conditions, rapid change in ambient temperature and irradiance will contribute to solar radiation uncertainty, which will cause the energy supplied by photovoltaic systems become unstable and cause negative impacts on the utility grid stability [13, 14]. To optimally plan and integrate PVs in grid connected system, the modelling, control and optimization studies of power system considering uncertainties are needed [3, 15–20]. Thus, this paper will explore the solar irradiance uncertainty for case study in Pekan, Pahang, Malaysia. The paper comprises of five sections. Section 1 is introduction. Section 2 discussed on solar irradiance meteorological data. Section 3 discussed on statistical model of solar irradiance patterns based on Monte

Carlo-Beta PDF. The results, discussions and conclusions are presented in Section 4 and Section 5 respectively.

2. METEOROLOGICAL DATA COLLECTION

The stochastic data preparation for uncertainty components of distributed solar generation is based on meteorological solar irradiance and ambient temperature taken at Renewable Energy laboratory, Faculty of Electrical & Electronics, Universiti Malaysia Pahang, at GPS coordinate latitude 3°32', longitude 103°26'. The one reference year historical data with one-minute time intervals is used to develop the data set of solar generation uncertainty as described below:

$$60 \; minute \; \times (24 \; hours/day) \times (30 \; days/month) \times (12 \; month/year)$$
$$= 518,400 \; minutes/year$$

3. MONTE-CARLO-BETA PDF METHOD

The solar irradiance is assumed as a random variable property; hence the behavior can be mapped to a probabilistic distribution [21]. The interpretation of this probability distribution varies with regards to the nature of variable which fall into continuous variable [22]. For modeling the uncertainty in solar radiation, the Monte Carlo-Beta PDF is employed. The flowchart of non-sequential Monte Carlo is demonstrated in Figure 3. The statistical mean, μ and standard deviation, σ, is calculated based on the historical data set as following [22, 23];

$$\mu = \frac{1}{N_d} \sum_{j=1}^{N_d} d_j \tag{1}$$

$$\sigma = \sqrt{\frac{1}{N_d} \sum_{j=1}^{N_d} \left(d_j - \mu \right)^2} \tag{2}$$

The probabilistic distribution of solar irradiance is based on Beta PDF, as expressed in (3) to (6) [24, 25];

$$f(s) = \begin{cases} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \cdot s^{(\alpha-1)} \cdot (1-s)^{(\beta-1)}, for \;\; 0 \le s \le 1, \, \alpha \ge 0, \beta \ge 0 \\ 0 \qquad\qquad\qquad\qquad , otherwise \end{cases} \tag{3}$$

$$\beta = (1 - \mu) \cdot \left(\frac{\mu(1+\mu)}{\sigma^2} - 1 \right) \tag{4}$$

$$\alpha = \frac{\mu\beta}{1-\mu} \tag{5}$$

$$P[S = s_i] = \int_{s_{i,min}}^{s_{i,max}} f(s) ds \tag{6}$$

Where s is the solar irradiance in kW/m^2, *f(s)* is probability density function as Beta PDF, α and β are the shape parameters for the Beta PDF. The statistical model is sampled based on one-minute interval for one reference year data which is segmented into twelve months. For each month which has been segmented, there will be multiple data points for the same minutes over a month by considering data for every single day. The data sets involved in each segment for all the days over a year are divided into 288 segments (24 hours x 12 months). There are 1440 data (60 minutes x 24 hours) for each 24 segments.

The variance of the data sets is calculated to determine the maximum iterations needed for Monte Carlo simulation to perform. Based on Figure 4, the variance for solar irradiance data became stable after 3000 iterations. Thus, the Monte Carlo is performed for 3000 iterations to sample continuous random variables of the solar irradiance. Then, the average output from the simulation is calculated.
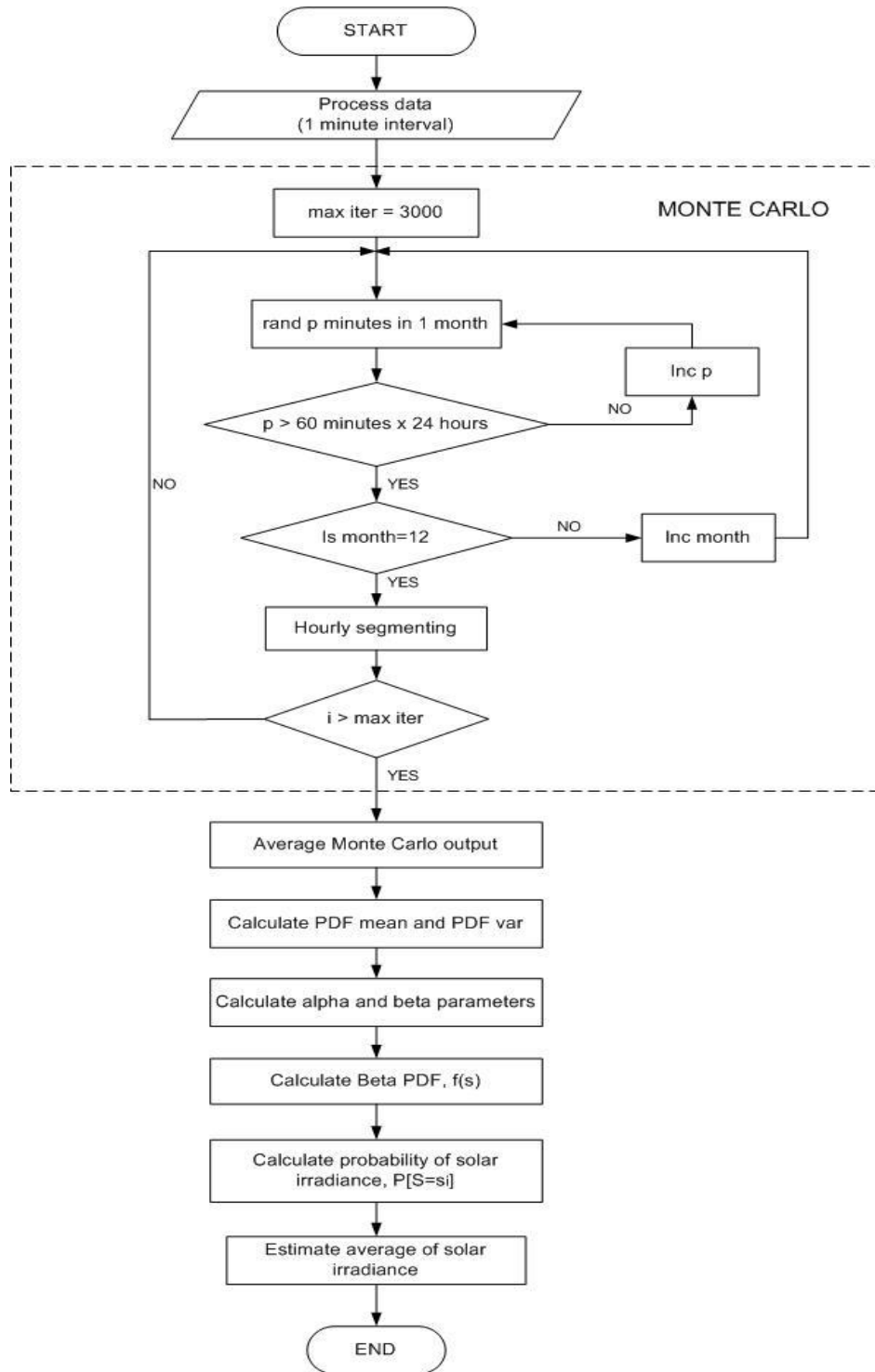
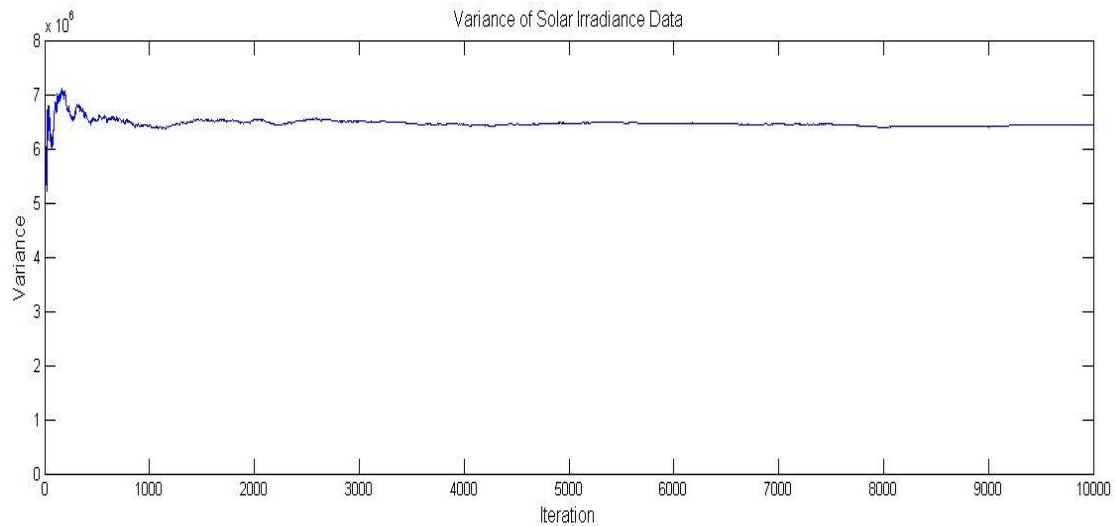Figure 3. Flowchart of Monte Carlo-beta PDF procedures

Figure 4. Variance for solar irradiance data to determine maximum iteration for Monte Carlo method

4. RESULTS AND ANALYSIS
4.1. Solar irradiance pattern in Pekan, Pahang, West Malaysia

The one-minute interval meteorological data are obtained to factorize and segmented for modeling purposes of solar irradiance uncertainty. Figure 5 demonstrates the variation in solar irradiance measurements for 1-hour sample data in Pekan, Pahang, Malaysia. It consisted of 60 data points for 1-hour sample data with 1-minute time interval which clearly show that uncertainties are apparent. The data also shows uniformly incline irradiance data which indicate that the sun is rising.
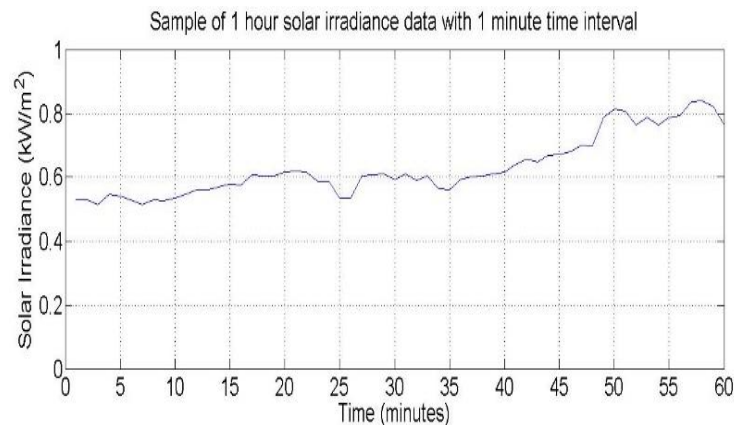

Figure 5. Sample of 1-hour solar irradiance uncertainty data with 1-minute time interval

The average hourly data of solar irradiance for one reference year were analyzed and illustrated in Figure 6. These data sets are used as baseline in the corresponding probabilistic modeling studies of solar irradiance uncertainty. The data are divided into a specified number of segments representing the Beta probability distribution patterns of time-varying solar radiation. Set of factorized curves representing the solar irradiance for 288 segments based on Monte Carlo simulation is depicted in Figure 7. The probabilistic of solar irradiance patterns for 288-time segments are depicted in Figure 8. Figure 9 shows the curve representing the average total daily solar irradiance for one typical year.

The results obtained is compared with official ground data supplied by SEDA Malaysia, for location GPS coordinate latitude $3^{o}29'$ and longitude $103^{o}20'$ for Pekan Pahang site [5]. The results of average total daily solar irradiation obtained from Renewable Energy Laboratory of UMP Pekan, and SEDA for Pekan site can be seen in Figure 10. These data are plotted for every month based for one reference year. The solar radiation data by NASA are satellite data which can be used for validity of results obtained by Renewable Energy Laboratory.
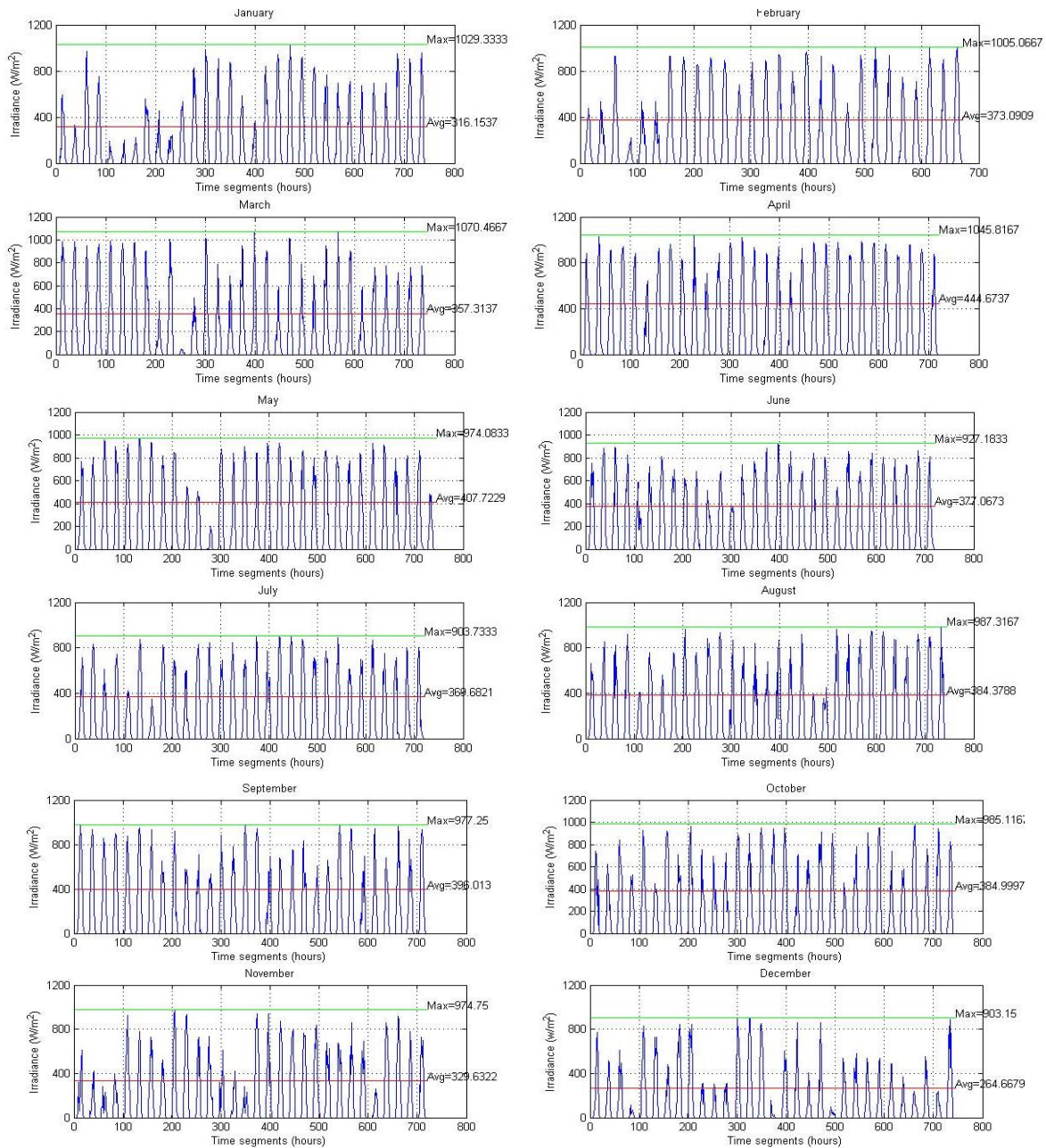
Figure 6. Average hourly data of solar irradiance for one reference year in Pekan Pahang, Malaysia
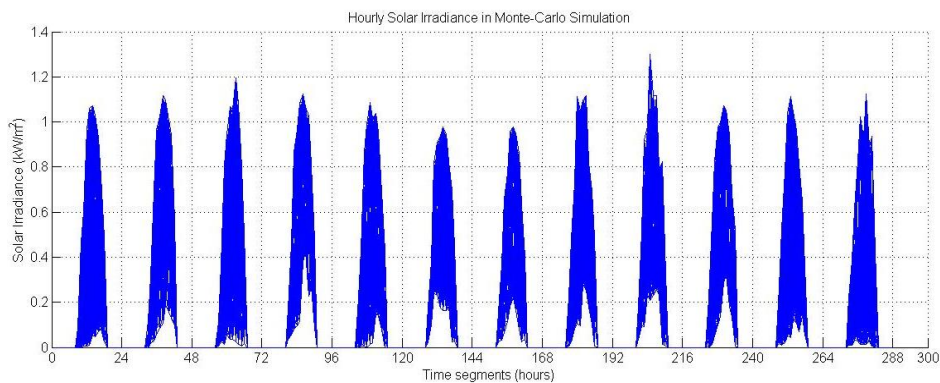

Figure 7. Solar Irradiance for 288-time segments using Monte-Carlo simulation
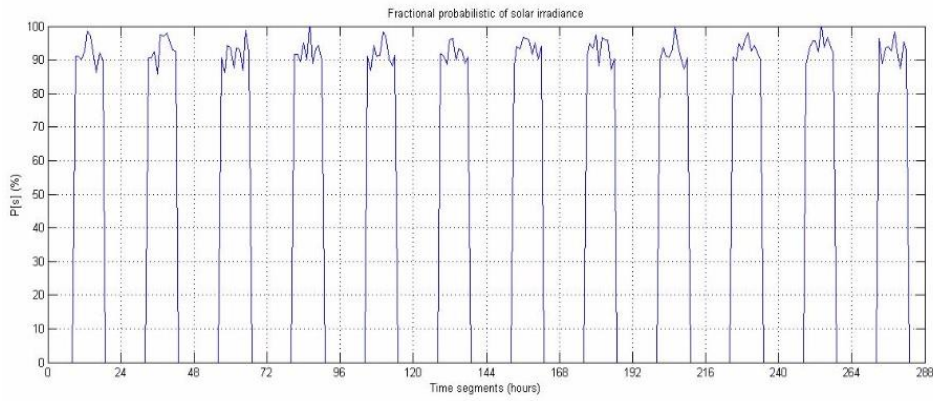
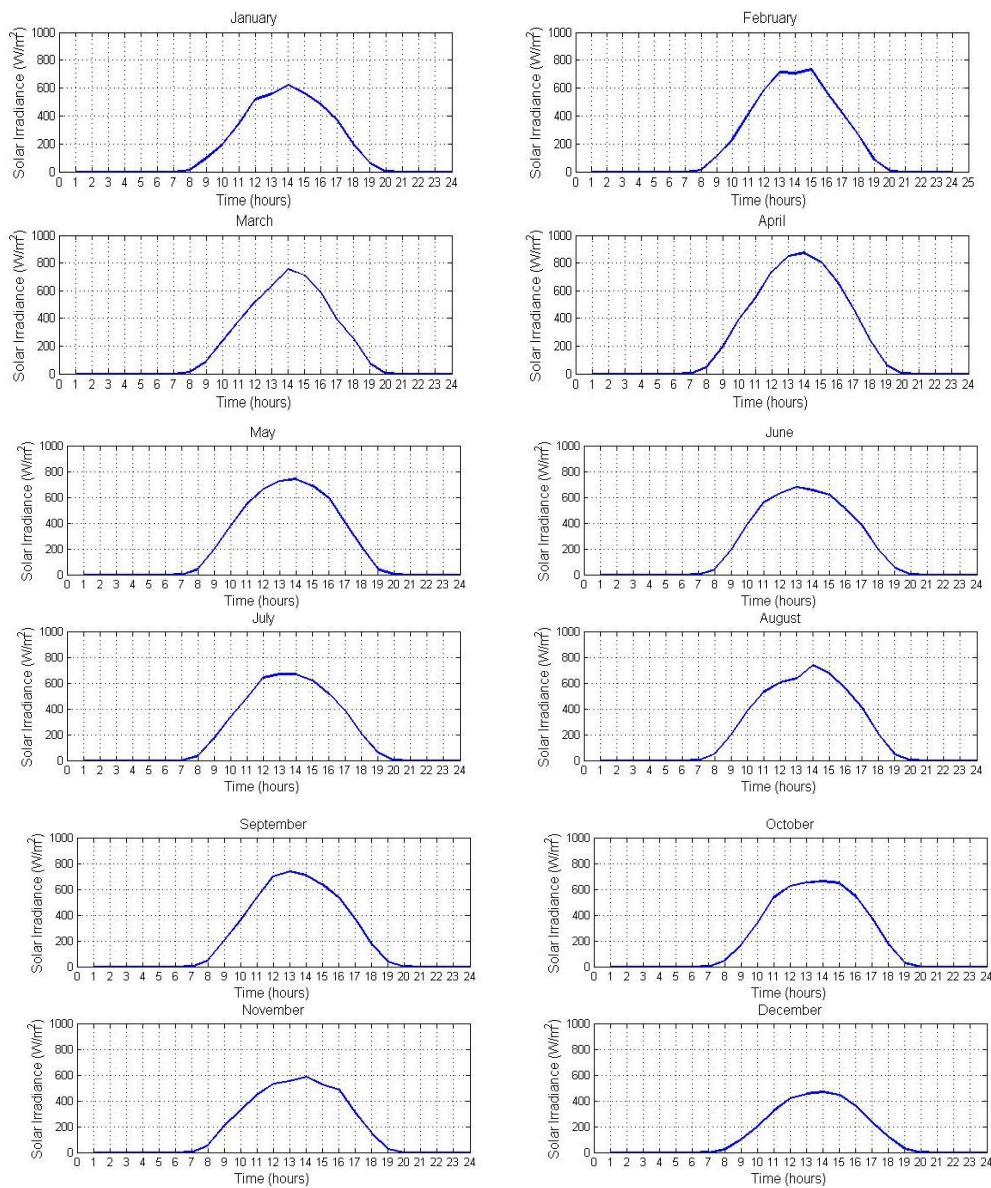Figure 8. Fractional probabilistic of solar irradiance for 288 segments

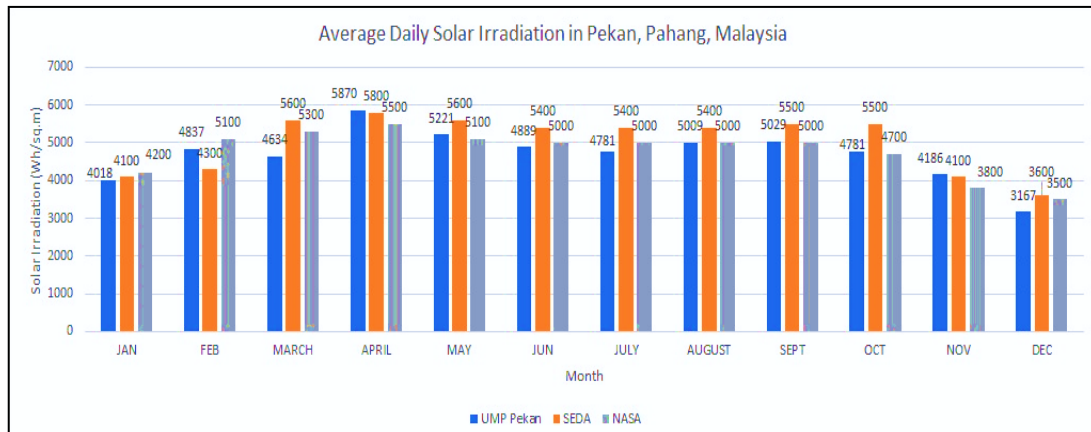Figure 9. Average daily solar irradiance pattern

Figure 10. Average total daily solar irradiation

4.2. Analysis of results

The solar irradiance output peak in any typical day can be estimated to occur between the hours of 11a.m. to 4p.m. in any typical day as depicted in Figure 9. It has been observed that the highest peaks in average daily solar irradiance can be seen during April with the irradiance value of about $874W/m^2$. The lowest peaks of average daily solar irradiance are occurred in December with the value of $469.2W/m^2$, followed by November and January with the peak value of average daily solar irradiance at $584.6W/m^2$ and $622.3W/m^2$ respectively.

The average daily solar irradiances are low during November, December and January due to the Northeast Monsoon which brings in more rainfall compared to the Southwest Monsoon. The rainfall season during November to December creates greater temperature variations, large amount of cloud cover and humidity levels which produce cooler and wetter weather thus affected the solar radiation pattern. March and October which are the transitions between the two monsoons; Northeast Monsoon and Southwest Monsoon recorded the output peak of average daily solar irradiance at $755.9W/m^2$ and $660.7W/m^2$ respectively. The duration of solar resources availability can be approximated to occur between the hours of 7a.m to 7p.m. for entire year.

In terms of solar irradiations; which is the solar irradiance integrated over time, the results of average total daily solar irradiation obtained from Renewable Energy Laboratory of UMP Pekan, indicate almost similar patterns with acceptable percentage deviation as compared to SEDA and NASA data for Pekan site as illustrated in Figure 10. The highest total average daily solar irradiation in UMP Pekan is occurred in April at $5870Wh/m^2$. The lowest total average daily solar irradiation is occurred during rainfalls season in December with the value of $3167Wh/m^2$, followed by January and November at $4018\ Wh/m^2$ and $4186Wh/m^2$ respectively. As depicted in Figure 10, the percentage deviation of data obtained by Renewable Energy Laboratory as compared to data released by SEDA and NASA are less than 15%.

5. CONCLUSION

This paper has presented the necessity of managing the solar irradiance uncertainty based on tropical climate condition for utilization of solar photovoltaics technology and development in Malaysia. Since solar irradiance has uncertain output which can be classified as continuous random, it is difficult to precisely controlled and predict the output of PVDG for integration to grid system. Hence, the Monte-Carlo-Beta PDF is exploited to model the continuous random variable for uncertainty management of solar irradiance pattern in Malaysian Tropical Climate. The results show almost similar patterns with less than 15% deviation as compared to data by SEDA and NASA. For future direction, the optimization technique will be utilized to handle the randomness and stochasticity of solar PV for optimally planning and operation of PVDG integration in power system network in Malaysia.

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