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Enhanced Insolation and Global Irradiance in Near-Tropic Region

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Abstract

Knowledge of peak solar irradiance levels and radiation is required to perform holistic photovoltaic system design for a particular location. In order to quantify solar energy input, c-Si reference cells were installed in three locations representing the North, middle-East and South of Mauritius. Global horizontal solar irradiance was measured at high frequency distribution intervals of 30-seconds since March 2012. The high resolution data was used in order to evaluate the enhanced irradiance levels and to compute average irradiance, radiation and the sky clearness. The latter were used to develop contour plots representing distribution of radiation and clearness for the whole year across the island. Enhanced irradiance levels of above solar constant (1367 W/m^2) were recorded in the summer months. The frequency of occurrence of those values was from a few to as many as 70 times and they lasted for up to 2 minutes. Enhanced irradiance levels of above 1500 W/m^2 were also recorded at least twice in all the three locations. Average daily global radiation was calculated to be 3.91 kWh/m^2, 5.09 kWh/m^2 and 3.97 kWh/m^2 in the East, North and South respectively, but even 7.79 kWh/m^2 was recorded. Low clearness values, between 0.3 – 0.61 were obtained. They reflect a higher level of cloud coverage over the island which subsequently increase Mie scattering and justify the enhanced irradiance levels that were measured. All solar data were compared to countries of the African continent with the same latitude as Mauritius.

Key words: *Enhanced irradiance, Enhanced global horizontal radiation, Near-tropic African region*

1. Introduction

Solar energy is considered as one of the promising renewable energy sources and its quantification is of utmost importance for the realisation of renewable energy projects. Photovoltaic (PV) engineers and contractors require reliable and valid locally measured solar data to perform system sizing and yield evaluation. Solar data comprises of solar irradiance, solar radiation as well as information on sky clearness or cloud coverage. As described by Ransone and Funtan (2005), measurement frequencies higher than 5 minutes are vital for system evaluation. But in order to perform holistic system sizing, in addition to site-specific solar energy knowledge of peak level of solar power is required. Numerous works have been performed for the quantification of solar resource and development of solar maps. Suri et al. (2007) developed a solar radiation database using solar radiation model and climatic data integrated with Photovoltaic Geographic Information System (PVGIS). The database provides information on solar radiation for PV potential in 25 European Union member states and 5 candidate countries. Journee et at. (2012) characterised solar radiation in Benelux countries using a dataset of daily global horizontal radiation based on on-site observations as well as long-term satellite based data. Solar radiation climatic zones within the Benelux were also defined. Solar resource have been assessed in US by Gueymard and Wilcox (2011), in South American countries by Ortega et al. (2010), African countries by Taele et al. (2007), Aksas and Gama (2011), Zawislka and Brooks (2011), Okoro and Madume (2004), Bugaje (2006) and Munzhedi and Sebitosi (2009), as well as Asian countries by Li et al. (2011). Information provided by numerous researchers around the globe on solar radiation data has played a very significant role for increasing the deployment of photovoltaic projects. Currently, the minimum installed capacity of PV systems around the globe is estimated by IEA (2014) to be around 134 GW. At least 36.9 GW of PV systems have been installed and connected to

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the grid in the world last year. Being among Africa's most rapidly developing countries, Mauritius is boosting the integration of PV systems in the grid through Independent Power Producers (IPPs) and Small Scale Distributed Generators (SSDGs). The installed capacity has increased from 2 MW to 3 MW in 2012 and Medium Scale Systems (>50kW PV systems) will be implemented in the near future. As information on solar resource in the Far East side of Africa is not available, Ramgolam et al. (2013) have evaluated the potential of PV system of a site in the east of Mauritius and have proposed the optimum design configurations for enhancing the yield of a PV system at the given location by 6% annually. Being in the tropical region, Mauritius is well located to efficiently harvest solar energy. But, effects of local climatic conditions of the tropical zone, such as high level of humidity and high cloud cover must be carefully assessed prior to PV system design.

The energy reaching the Earth's surface is involved in several complex processes such as scattering and absorption through the atmosphere. The latter, generally, lead to an attenuation of the solar irradiance to levels lower than the solar constant. But in certain circumstances, due to a combination of forward scattering and reflection at the border of clouds, global horizontal irradiance (G) may be enhanced. Several researchers have reported solar irradiance values greater than the solar constant. Yordanov et al. (2013) stated that irradiance enhancements may be attributed to forward Mie scattering of light. Tapakis et al. (2014) mentioned that diffuse irradiance may be enhanced due to reflection from the base of clouds and through scattering of direct irradiance due to cloud particles and reported enhanced global horizontal irradiance (EGHI) values (>1500 W/m^2). Design of PV systems cannot be based only on electrical data given in data sheets as they correspond to standard test conditions (STC) with irradiance levels of 1 sun. For proper, inverter and balance of system (BoS) component sizing the peak irradiance levels at the site of installation must be known. This will lead to reduction of power wastage from PV panels. The power output from PV panels is linearly proportional to the input irradiance whereas the ouput from inverter is limited to its power rating. Louma et al. (2012) studied a PV array and an inverter system installed in San Diego, California, in order to determine the energy losses due to inverter saturation. Emphasis was laid on the importance of cloud enhancement which extends beyond energy losses to issues such as inverter tripping and blown fuses at large solar PV plants. Results show that increasing the inverter sizing ratio to R = 1.22 for the studied system would lead to the greatest yearly energy output. In addition to energy losses due to saturation of inverter, Tapakis et al. (2014) discussed that regardless of the ability of the inverter to regulate the input power, there are limits that cannot be overcomed. If the DC input power to the inverter exceeds the maximum DC power threshold of the inverter, then it may cause irreparable damage to the inverter.

Mauritius is an island which is surrounded by the sea. Therefore the level of humidity and cloud cover is higher and therefore enhancement of irradiance levels is highly probable. The objective of this study was to quantify the occurrence of enhanced solar irradiance with high accuracy across the island. For the purpose three locations that provide a good coverage of Mauritius were selectively chosen to install c-Si reference cells. Global horizontal irradiance was measured at the three sites in Mauritius at a frequency interval of 30-seconds. Such high measurement frequency provides an opportunity to consider all minute changes in irradiance and allows researchers and engineers to better evaluate incident solar energy. In addition the high resolution data, compiled since 2012, was used to assess the average daily, monthly and yearly radiation and hence provided an opportunity for comparison of local solar data with African countries having the same latitude as Mauritius.

2. Methodology

2.1. Location and overview of climate

Mauritius is an island which lies between latitudes 19º58.8' and 20º31.7' South and longitudes 57º18.0' and 57º46.5' East (Monthly Bulletin of climatological summaries, 2008) nearly 2000 km in the south east of the African continent. Mauritius is 45 km in width and 65 km in length (Discover Mauritius). Being in the tropical zone, Mauritius has two seasons: a warm humid summer extending from November to April and a relatively cool dry winter from June to September. Mean summer temperature is 24.7 ºC and mean winter temperature is 20.4 ºC. The warmest months are January and February with average day maximum temperature reaching 29.2 ºC and the coolest months are July and August when average night minimum temperatures drops down to 16.4 ºC (Climate of Mauritius, 2014). The long term mean of humidity varies between 75% in winter and 84% in summer, but lowest and highest noted values are 36% and 100% respectively (Environment, 2012).

2.2. Equipment details

In order to evaluate the solar resource locally, 80spc Soldata reference cells were installed in three different locations. They provide a good coverage of the island and represent the middle-East, North and South of Mauritius. The reference cells have an accuracy of 3%. 12-bit resolution U12 4-channel outdoor HOBO data loggers were connected to the reference cells. The logger use direct USB interface for launching and data readout which were performed on a weekly basis. More details of the sites and the reference cells are provided in Tab. 1.

Tab. 1: Details of measurement sites and pyranometers

Location of reference cells	Calibration factor, $mVkW^{-1}m^{-2}$	Altitude	Latitude, L	Longitude
Brisee Verdiere: middle-East	144.5	200 m	-20.18	57.66
Cottage: North	156	100 m	-20.06	57.63
Mare Tabac: South	160	200 m	-20.44	57.59

2.3. Solar data

Ground-based measurement provided very accurate G data. The latter is used to assess G and quantify enhanced solar irradiance (EG), daily irradiation (*H*) and sky clearness index. Global horizontal irradiance represents the total amount of incident irradiance that comes directly from the Sun and is incident on a surface that is perpendicular to the direction of Sun rays. The reference cells were mounted on adjustable tilt kits and their inclination was set to 0 degrees using a digital clinometer. G data, measured at intervals of 30-seconds was warehoused and used to detect enhanced solar irradiance and quantify their frequency of occurrence. EG values represent global irradiance which exceeds the solar constant, I_0, the intensity of solar irradiance which is incident to the Earth's atmosphere. Average daily irradiation (*H*) was computed for each month of measurement using the high frequency measurement data. Monthly averaged and yearly *H* for each region of Mauritius was hence defined. Solar energy availability for PV applications is characterised by the sky clearness index, K_T. It provides a useful metric for global radiation at the given location. It is obtained by dividing *H* at the surface by the extraterrestrial irradiation (H_0), on the same time scale. The extraterrestrial irradiation is measured in kW/m^2 and is given by:

$$H_0(n) = \frac{24 I_0}{\pi}\left(1 + 0.03344 \cdot \cos\left(\frac{360 \cdot n}{365}\right)\right)\left(\cos(L)\cos(\delta_s(n))\sin(\omega_s) + \frac{\pi \cdot \omega_s}{180}\sin(L)\sin(\delta_s(n))\right) \text{(eqn. 1)}$$

where I_0 is the solar constant (1367 W/m^2) and $\omega_s(n)$ is the sunset hour angle which is given by:

$$\omega_s(n) = cos^{-1}(-\tan(L)\tan(\delta_s(n))) \qquad \text{(eqn. 2)}$$

n – day number with 1st January as day 1, L – the latitude angle and $\delta_s(n)$ - solar declination.

3. Results and Discussion

3.1. Global horizontal irradiation and Sky Clearness Index

The high frequency resolution solar data from the three sites was used to compute daily *H* and hence monthly averaged *H*. The monthly averaged *H* distribution throughout a year in Mauritius is represented in Fig. 1 as colour filled contour map. The solar map reflects the climatic changes that occur in Mauritius, with the high *H* levels recorded in summer with lower values in winter. It can be easily noticed that the north receives the highest amount of daily *H* from January to November. But in December the southern part receives higher *H* with values of 6.25 kWh/m^2 compared to 5.99 kWh/m^2 in the north. This is attributed to the location of Mauritius and the sun path in the summer season. During most part of the year, the sun is directed from the north, whereas during peak summer, the sun is directed from south for the most of December. The middle-East part receives almost the same amount of solar energy as the southern part in the winter months, but during summer the southern part receives higher level of *H*. Minimum registered monthly averaged *H* values were 3.67, 2.75 and 2.26 kWh/m^2 in the north, middle-East and South respectively.

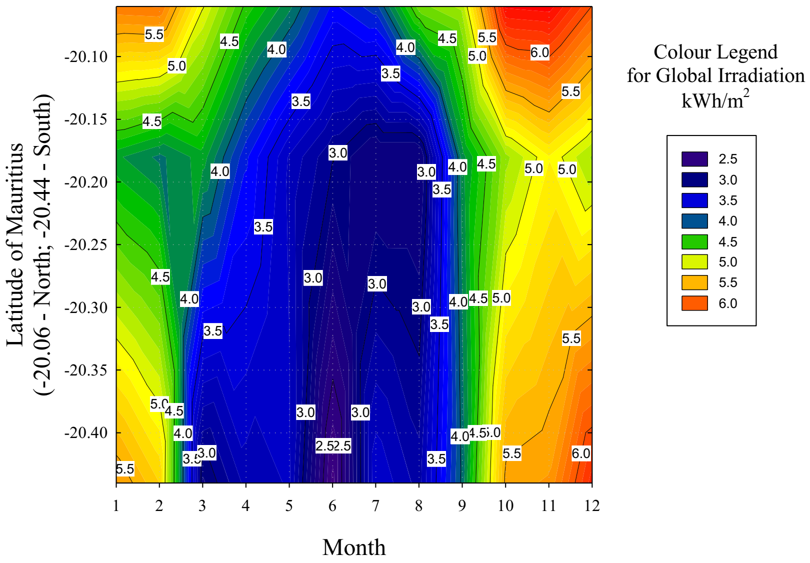

Fig. 1: Distribution of monthly averaged global horizontal irradiation over Mauritius

The yearly averaged daily measured H was 3.91 kWh/m^2, 5.09 kWh/m^2, and 3.97 kWh/m^2 daily in the middle-East, North and South, but even enhanced H over 7 kWh/m^2 were recorded in the summer months. Maximum registered H levels were identified for each region and used to create a contour map (Fig. 2) which shows the distribution of peak H throughout a year in Mauritius. Peak enhanced H values, 7.1 - 7.71 kWh/m^2, were recorded in the north during the months of October to March. Whereas, the east registered 7.01 – 7.44 kWh/m^2 during November to February and the south registered between 7.21 – 7.79 kWh/m^2 during the same months. It must be noted that in December and January, enhanced H values which were recorded in the south (7.75 and 7.79 kWh/m^2) were higher than those recorded in the north (7.54 and 7.57 kWh/m^2).

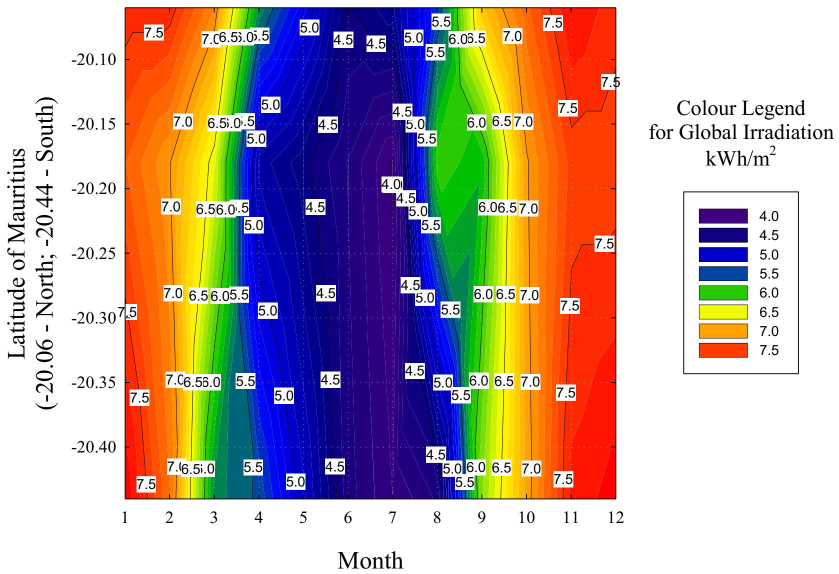

Fig. 2: Distribution of maximum measured global horizontal irradiation over Mauritius

On a yearly basis the average radiation that can be yielded is 1428 kWh/m^2 in the middle-East and 1450 kWh/m^2 in the South whereas the North receives 1803 kWh/m^2. For a better analysis and understanding of solar energy available in Mauritius, NASA SSE solar data were downloaded for sites located in Namibia, Zimbabwe, Botswana, Mozambique and Madagascar which have the same latitude as Mauritius. The result has been presented in Fig. 3 as distribution of global horizontal radiation across sites in Africa having latitude -20.3° for a whole year. It must be noted that NASA SSE data represent monthly average amount of the total solar radiation incident on a horizontal surface at the surface of the earth for a given month, averaged for that month over the 22-year period. Each monthly averaged value is evaluated as the numerical average of 3-hourly values for the given month. In addition PV GIS (2012) data were extracted from solar map of Africa for the same countries and compared to annual average H derived from measurement data for Mauritius. The PV GIS map contains 2 km x 2 km grid resolution of annual mean of daily sum of global irradiation for horizontal plane.

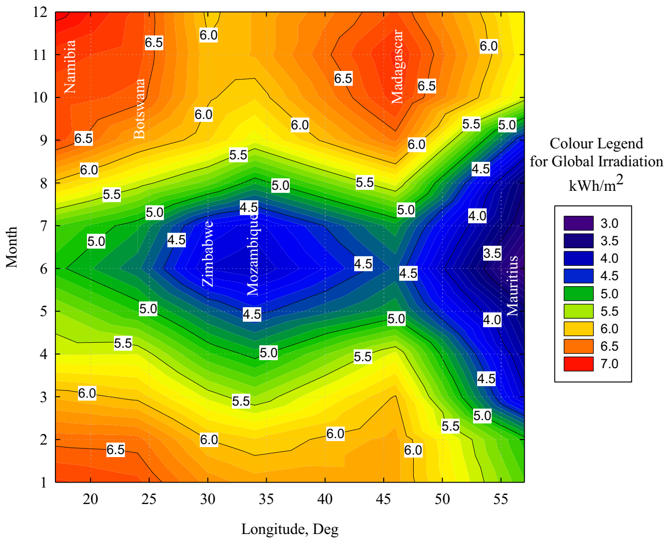

Fig. 3: Comparison of monthly averaged global horizontal irradiation over Mauritius and African countries with latitude -20.3°

Tab. 2: Comparison of global horizontal irradiation data extracted from PV GIS solar map for Africa with solar data from measurement in Mauritius

Country	Annual Global Irradiation kWh/m^2			
	PV GIS		Measured	
	Min	Max	Min	Max
Namibia	2200	2800	NA	NA
Botswana	2200	2400	NA	NA
Zimbabwe	2000	2400	NA	NA
Mozambique	2000	2400	NA	NA
Madagascar	1800	2600	NA	NA
Mauritius	2400		1425	2340

From Fig. 3, it can be easily concluded that, Mauritius receives lower global horizontal radiation across the year than the other countries of the African continent having the same latitude. It is also clearly noticed that countries near the sea such as Mozambique, Madagascar and Mauritius receive lower H levels during the winter months compared to the other countries. The geographical location of Mauritius, surrounded by the sea, has indeed an impact on the annual solar energy input. This is further confirmed by solar data from PV GIS. Compared to all the other countries, given in Tab. 2, Mauritius receives the least annual H with a minimum of 1425 kWh/m^2 in the middle-east and a maximum of 2340 kWh/m^2 in the north of the island. The sky clearness index, which is a better metric for assessing solar energy and cloud coverage, was computed for the different sites and a monthly average was defined for Mauritius. The latter is compared to insolation clearness index obtained from NASA SSE for the countries in African continent having the same latitude as Mauritius. The result is shown in Fig. 4 and Tab. 3.

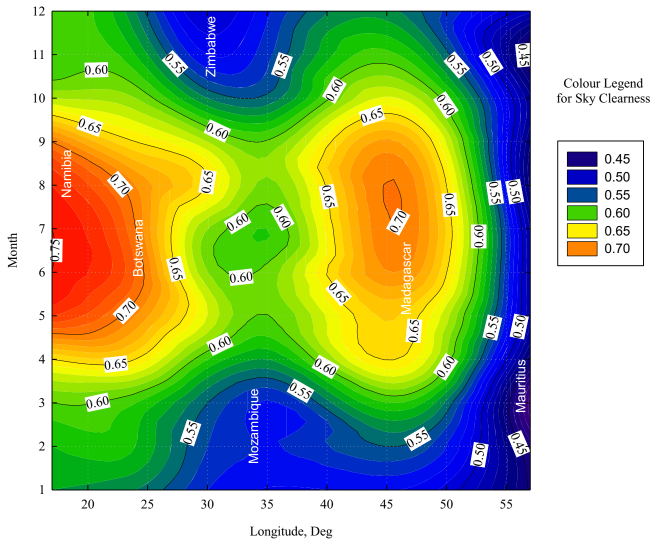

Fig. 4: Comparison of monthly averaged sky clearness over Mauritius and African countries with latitude -20.3°

Tab. 3: Sky clearness index in the three sites of Mauritius

Month	Sky Clearness Index		
	North	Mid-East	South
1	0.50	0.36	0.48
2	0.52	0.37	0.41
3	0.49	0.42	0.30
4	0.53	0.45	0.38
5	0.57	0.43	0.44
6	0.55	0.46	0.43
7	0.55	0.40	0.49
8	0.61	0.34	0.42
9	0.49	0.44	0.46
10	0.48	0.44	0.49
11	0.42	0.44	0.45
12	0.53	0.39	0.56
Average	**0.52**	**0.41**	**0.44**

As seen in Fig. 4 and Tab. 3, during the winter season the cloud cover is lower. The average yearly clearness index value was found to be 0.41, 0.44 and 0.52 for the middle-East, South and North respectively. It must also be noted that regions near or surrounded by the sea have lower sky clearness index compared to inland regions. Compared to the other countries, low monthly clearness values, between 0.3 – 0.61 were obtained for any location in Mauritius. They reflect a higher level of cloud coverage over the island, which on one side decreases daily H and on the other side may subsequently increases Mie scattering as well as reflection at the edges of clouds.

3.2. Irradiance and Enhanced Irradiance

Fluctuations in the level of irradiance has a direct impact on the maximum power point of solar modules. As irradiance increases, the short circuit current increases proportionally and hence maximum power point voltage. On the other hand, temperature has an inverse impact on open circuit voltage or maximum power point voltage. As temperature decreases, maximum power point voltage in increases. During cloudy conditions, temperature decreases. But in the other hand, as described by Piacentini et al. (2011) thick clouds may scatter solar rays and increase diffuse irradiance. Besides, multiple reflections and even forward Mie scattering may increase the global irradiance. Instantaneous enhancement of global irradiance has a direct impact on the power output of solar modules. In case, PV system engineers are not aware of peak irradiance levels in a site, improper sizing of inverters may lead to energy losses or inverter saturation or even damage due to over voltage. These enhanced irradiance levels occur during short intervals and only high-frequency of measurement may detect them. The 30-second interval G data measured in the different sites in Mauritius was carefully analysed to detect variations in G that occurs and identify the frequency of occurence of enhanced G. The results are shown in Fig. 5 to 7.

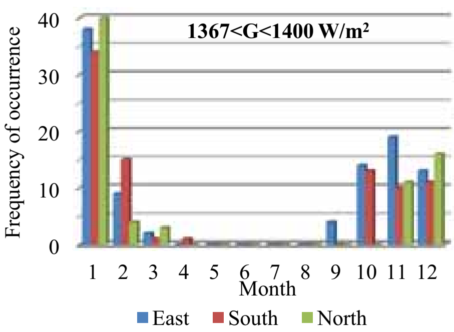

Fig. 5: Frequency of occurrence of G within 1367<G<1400 W/m^2

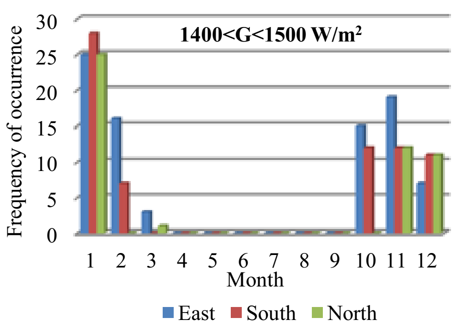

Fig. 6: Frequency of occurrence of G within 1400<G<1500 W/m^2

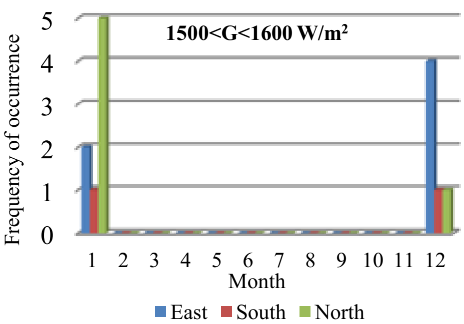

Fig. 7: Frequency of occurrence of G within 1500<G<1600 W/m^2

Following thorough analysis of G data, it was noticed that the southern part of Mauritius received the least irradiance levels in the winter months, but it increased in summer. Peak irradiance exceeded the standard 1 kW/m^2 for most of the months in all the sites of measurements across the island, but especially in summer enhanced G values were noted. As seen in Fig. 5 - 6, the frequency of occurrence of G > 1367 W/m^2 was from a few to up to 70 during a month. It was also noticed that near solar constant values lasted for up to 2 minutes. Between 1 to 5 enhanced values of G (> 1500W/m^2) were noted in all the three locations and that was only in December and January. The peak G recorded were between 1510 W/m^2 and 1532 W/m^2. During the summer months firstly the elevation of the Sun at solar noon locally is 90 ± 5 degrees and the distance between the Tropic and the Sun is minimal. This implies that the direct irradiance component has the maximum value. Mauritius is an island which is surrounded by the sea. As observed by the sky clearness values provided in Tab. 3 and Fig. 4, the level of cloud cover is higher compared to any inland country. Hence, Mie scattering, scattering and multiple reflection due to clouds tend to increase the diffuse irradiance. Hence, the global irradiance values are enhanced.

4. Conclusion

Instantaneous variations in the level of irradiance has a direct impact on the maximum power point of solar modules. Cloud cover may cause irreperable damage to a PV system's components, such as inverter and fuses, if the proper condition of temperature decrease and enhanced solar irradiance which is due to forward Mie scattering and multiple reflections occur simultaneously. Therefore, for holistic PV system design engineers must know not only daily, monthly or seasonal variations in solar energy, but also the peak irradiance values that may be incident on a PV module. Only high-frequency measurement of solar data can provide highly reliable information on solar energy input and detect any enhanced solar irradiance as the latter has short durations. During the study, high frequency resolution solar data from three sites which provide a good coverage of Mauritius were used to compute daily *H,* hence monthly averaged *H* and identify enhanced *H*. They have been represented in the form of solar maps with distribution throughout a year in Mauritius. The yearly averaged daily measured *H* was 3.91 kWh/m^2, 5.09 kWh/m^2, and 3.97 kWh/m^2 daily in the middle-East, North and South, but even enhanced *H* over 7 kWh/m^2 were recorded in the summer months. In December and January, the southern part of the island recorded enhanced *H* values (7.75 and 7.79 kWh/m^2) which were higher than those recorded in the north (7.54 and 7.57 kWh/m^2). Following a comparative analysis of *H* in Mauritius and other near-tropic countries in Africa, it was noticed that Mauritius receives lower global horizontal radiation across the year than the other countries of the African continent located in the same latitude. The latter is attributed to the geographic position of Mauritius. Regions near or surrounded by the sea have lower sky clearness index compared to inland regions. Compared to the other countries, low monthly clearness values, between 0.3 – 0.61 were obtained for any location in Mauritius. Peak irradiance exceeded the standard 1 kW/m^2 for most of the months in all the sites of measurements across the island, but in summer enhanced G values were noted. The frequency of occurrence of G > 1367 W/m^2 was from a few to up to 70 during a month. It was also noticed that near solar constant values lasted for up to 2 minutes. Between 1 to 5 enhanced values of G (> 1500W/m^2) were noted in all the three locations and that was only in December and January. This is attributed to high solar elevation accompanied by high level of cloud cover during these months.

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