Modeling of a Photovoltaic Module Considering the Solar Energy Available from Horizontal Surfaces over Kuwait Area

F. Q. Al-Enezi and J. K. Sykulski

***Abstract*—The paper identifies and analyzes the geographical and temporal variability of solar energy in Kuwait. The fundamental solar trigonometric model has been modified to estimate daily and hourly solar radiation on horizontal surfaces on the basis of the more readily available meteorological data. The results demonstrate that Kuwait has an abundance of solar energy capability. An overview of the production and consumption of electrical energy, installed capacity, and peak loads in Kuwait is also presented. Finally, it is shown how the power produced from the photovoltaic (PV) cells depends on the solar radiation. The proposed PV module is made up of a combination of series and parallel cells to increase power, while the *I-V* characteristic and output power of the module each month may be obtained from the model.**

***Index Terms*—Extra-terrestrial insolation, hour angle, meteorological data, peak load, photovoltaic module, solar radiation, solar time.**

1. Introduction

Solar energy is clean, quiet, abundant, and renewable energy source, which produces no pollution to the environment[1]. Therefore, solar energy as renewable energy source occupies one of the most prominent places among alternative energy sources and is increasingly adapted in many applications[2].

Accurate knowledge of solar radiation (SR) availability at a particular geographical location is of vital importance for the development of solar energy systems and for the estimation of their efficiencies and outputs[3]. The knowledge of SR data is a prerequisite for the modeling and design of all photovoltaic (PV) systems[4],[5]. Familiarity with SR data is valuable to architects, agriculturalists, air conditioning engineers, and energy designers as an aid to proper design and operation of engineering projects. The information about SR is also useful for the atmospheric energy-balance, climatology, and pollution studies[6]–[8]. There are hundreds models with different techniques available which correlate the global SR to other climatic parameters such as sunshine hours (solar time), maximum temperature, and relative humidity.

The basic and fundamental empirical model was proposed by Angstrom in 1924[9]. Many authors have modified this model for estimating SR data at their places of interest. For example, some researchers have proposed trigonometric models, others suggested linear logarithmic or quadratic models. The Angstrom model was widely used for measurements of SR until 1970 when the National Oceanic and Atmospheric Administration (NOAA) in United States and later the National Renewable Energy Laboratory (NREL) established the first SR data-base for 239 sites in the United States[10]. In 1973, during the oil crisis, many oil importing countries and those with limited fossil fuel resources started in-depth research into SR to guarantee their national energy security.

2. Simple Model for Global Solar Radiation on Horizontal Surfaces

The prime objective of this section is to derive a simple model for daily global solar radiation intensity on horizontal surfaces at the earth's surface. This model incorporates improvements in methodology as well as the algorithm to calculate the SR based on the model by Duffie and Beckman[11]. Their approach will be modified and adjusted to be applicable to Kuwait taking into consideration the country's geographical parameters and climate conditions.

The declination angle of the sun can be approximated using Cooper's equation as

$$\delta = 23.45\sin\left(\frac{360(n+284)}{365}\right) \quad (1)$$

where δ is the declination angle of the sun in degrees, and n is the day number (from 1 to 365).

The solar time, which is the most commonly used

Manuscript received February 17, 2012; revised March 15, 2012.

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Digital Object Identifier: 10.3969/j.issn.1674-862X.2012.02.015

parameter for estimating global SR[12], is determined from the movement of the sun. For trigonometric calculations in the following, the solar time t in hours is expressed as an hour angle H, in degree:

$$H = 15^{\circ}(t-12)\ . \tag{2}$$

The standard convention used is that H is taken as positive after and negative before the solar noon. The solar altitude angle depends on the latitude angle of the site, day number and, most importantly, the time of day [13]. Hence it may be expressed as

$$\sin\beta = \cos L\cos\delta\cos H + \sin L\sin\delta \tag{3}$$

where β is the solar altitude angle in degrees and L is the latitude angle of the site (L=29.33° in Kuwait area).

A straightforward calculation of sunrise time and sunset time may be based on a simple manipulation of (3). It follows that the sunrise or sunset hour angle H_{SR} is given by

$$H_{\mathrm{SR}} = \cos^{-1}(-\tan L\tan\delta)\ . \tag{4}$$

The solar insolation which passes perpendicular through an imaginary surface just outside of the earth's atmosphere is called the extra-terrestrial (ET) insolation. The ET insolation depends on the distance between the earth and the sun, which varies with the time of year. It also depends on the intensity of the sun, which rises and falls with a fairly predictable cycle. The ET insolation really consists of the three components of SR (beam, diffuse and reflect) in a clear sky and Kuwait's climate for almost nine months (from 1st of March to 30th of November) means cloudless atmosphere. Moreover, this approach is suitable for dry conditions and temperatures typical for the Kuwait region.

The starting point for a clear sky daily global SR calculation is with an estimate of the ET insolation, S_{ET}, in W/m^2. One expression that is used to describe the day-to-day variation in ET solar insolation is

$$S_{\mathrm{ET}} = S_0\left[1+0.034\cos\left(\frac{360n}{365}\right)\right] \tag{5}$$

where the solar constant, S_0, is an estimate of the average annual ET insolation and the accepted value of S_0 is 1377 W/m^2. Now, the average daily ET solar insolation on a horizontal surface, $\overline{S}_{\mathrm{ET}}$, in Wh/m^2-day can be calculated by

$$\overline{S}_{\mathrm{ET}} = \frac{24}{\pi}S_0\left[1+0.034\cos\left(\frac{360n}{365}\right)\right]\times \left(\cos L\cos\delta\sin H_{\mathrm{SR}} + \frac{\pi}{180}H_{\mathrm{SR}}\sin L\sin\delta\right) \tag{6}$$

or

Table 1: Monthly averaged clearness index in Kuwait area

Latitude 29.33° Longitude 47.5°	22-Year average K_t
January	0.52
February	0.57
March	0.56
April	0.56
May	0.62
June	0.69
July	0.68
August	0.67
September	0.65
October	0.60
November	0.50
December	0.47
Annual average	0.59

$$\overline{S}_{\mathrm{ET}} = \frac{33048}{\pi}\left[1+0.034\cos\left(\frac{360n}{365}\right)\right]\times \left(\cos L\cos\delta\sin H_{\mathrm{SR}} + \frac{\pi}{180}H_{\mathrm{SR}}\sin L\sin\delta\right). \tag{7}$$

In clear sky atmosphere calculations, the clearness index K_t is defined as the ratio of the horizontal insolation S_H at the site to the ET insolation $\overline{S}_{\mathrm{ET}}$ on a horizontal surface above the site and just outside the atmosphere and is given by

$$K_t = \frac{S_H}{\overline{S}_{\mathrm{ET}}}\ . \tag{8}$$

A high clearness index ($K_t > 0.5$) corresponds to clear skies, where most of the SR will be direct beam, while a low one ($K_t < 0.5$) indicates overcast conditions with diffuse SR. A monthly averaged clearness index for the site of Kuwait can be obtained from National Aeronautics and Space Administration (NASA) website for Kuwait area over 22 years (1983 – 2005)[14], as given in Table 1.

From the best curve fitting for the values of K_t in Table 1, the clearness index can be expressed to a good accuracy as a function of day number n, as

$$K_t = -3.807\times10^{-6}n^2 + 0.001124n + 0.6139\ . \tag{9}$$

According to (8), the daily global SR on horizontal surfaces, S_H, in Wh/m^2, can be found from

$$S_H = K_t\overline{S}_{\mathrm{ET}}\ . \tag{10}$$

The hour by hour SR data is essential if the radiation on the horizontal surfaces is to be estimated. We can follow the same procedure as for the daily radiation except for expressing the hour angle in terms of solar time in hours (local apparent time, LAT) as in (2) and letting the solar time t vary between sunrise time and sunset time according to the longitude of site. For the Kuwait area with a longitude of 47.5°, the standard sunrise and sunset times are 6:00 am and 18:00 pm, respectively, and $\overline{S}_{\mathrm{ET}}$ may be obtained from Kuwait Metrological Centre as

$$\bar{S}_{\mathrm{ET}}=\frac{33048}{\pi}\left[1+0.034\cos\left(\frac{360n}{365}\right)\right]\times$$
$$\left(\cos L\cos\delta\cos H+\sin L\sin\delta\right). \qquad (11)$$

From (11) and substituting $\bar{S}_{\mathrm{ET}}$ into (10), the hourly global SR on horizontal surfaces can be readily estimated.

3. Availability of SR in Kuwait

Kuwait tries to provide support for development to stay in line with the growing demand for electric utility, especially in light of the natural growth of population and expansion of development projects at all levels. Energy demand in Kuwait is rapidly increasing; during the past half century the electrical demand has in fact quintupled. Thus inevitably there is high cost incurred by the state budget to keep providing this service to all consumers without interruption, especially in the light of the dependence on oil and its derivatives in the operation of electric power stations. Due to the increasing global demand for oil, and because it represents the main income for Kuwait, it is becoming paramount to stop the wasteful consumption of electricity and reduce the amount of fuel used for electricity generation.

The primary source of electrical energy in Kuwait is the chemical energy contained in natural gas and liquid oil products. The electrical utility in Kuwait mainly employs thermal power stations for the generation of power needed to satisfy demand. However, gas turbines (GTs) are also used which make up around 28.7% of total installed capacity. These GTs are usually used in emergencies and during the time of peak loads[15], in spite of their high operational cost and low thermal efficiency. Power generating plants use different types of fossil fuel available in Kuwait, such as natural gas, heavy fuel oil, crude oil, and gas, depending on the boiler design with priority given to natural gas within the limits of the available quantities. Older plants can burn natural gas and gas oil in case of emergency while newer ones are capable of burning the four types of fuel. Fig. 1 illustrates the Kuwait installed capacity and peak loads for selected years.

Kuwait faces a dangerous predicament because of the insufficient electrical energy capabilities and load peaking, regarded as an unacceptable situation. The consumption of electrical energy in Kuwait indicates that almost one half of the generated energy in Kuwait is consumed for domestic purposes because both the government and the citizens are still establishing more and more residential areas every year[16]. At the same time, most of the load in residential, industrial, and commercial areas is due to air conditioning (A/C) systems.

According to the maximum and minimum load distributions shown in Fig. 2 for the year 2010, Kuwait electrical load is characterized by high load in summer and low load in winter depending on the increase and decrease in the values of temperatures and relative humidity. Based on the foregoing, during the past years and through government foundations and academic centres, Kuwait has not overlooked to provide campaigns and practical solutions to reduce waste and excessive consumption of electricity, which has one of the highest rates in the world[1], in the hope that general consumers would take rational and moderate approach to life.

The contribution of this paper is to find solutions to the rationing of energy use with the aim to preserve Kuwait's oil wealth and to prioritise future needs during the gradual shift towards the use of alternative and renewable energy in power generation, with emphasis on solar energy and PV generation. Solar energy as a renewable energy resource will play a major role in Kuwait's future energy supply. Kuwait has an abundance of solar energy capability. Unfortunately, SR measurements for Kuwait are not easily available because of the country not being able to afford the necessary measuring equipment and techniques involved. Instead, the model developed above will be used to estimate and identify the SR on horizontal surfaces on the basis of the more readily available meteorological data.

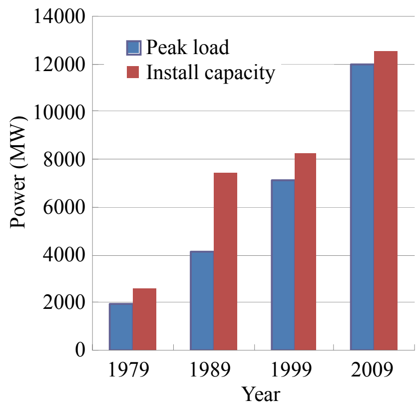

Fig. 1. Kuwait installed capacity and peak load for selected years.

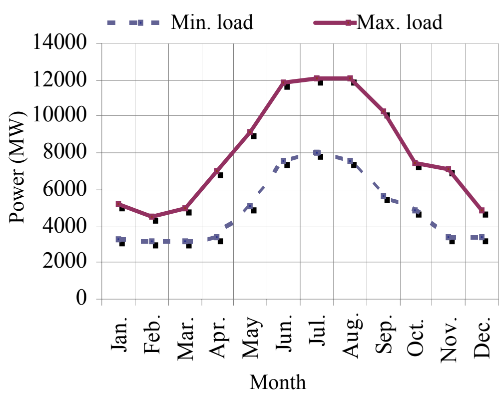

Fig. 2. Maximum and minimum loads during 2010.

The meteorological data for Kuwait, latitude angle (L = 29.33°), longitude angle ($\gamma = 47.5^{\circ}$), clearness index K_t (almost cloudless atmosphere for nine months), solar time t (varying from 6:00 to 18:00), and the corresponding hour angle H, has been used in the model and the intensity of daily and hourly global SR on horizontal surfaces S_H in Kuwait area has been obtained as a function of both day number n (with a day number increment of one day) and time (with a time increment of one hour). These results can be obtained for any day of the year and for any hour of the day.

4. Modeling of the Photovoltaic Module

Solar Radiation (SR) has been called the fuel of photovoltaics and its characteristics form the basis of the PV system design, from array construction to the reliability of electrical supply[17]. Moreover, the electrical power produced from the PV depends on the value of SR. The PV modules can be wired in series to increase the voltage, V, or in parallel to increase the DC current, I. Our PV module is made up of a combination of series and parallel modules to increase power, as shown in Fig. 3. Each module contains a number of PV cells. The I-V characteristic equation of the PV cell may be described by the well-known Shockley equation as

$$I = I_{\rm ph} - I_0\left[\exp\left(\frac{qV}{BT}\right) - 1\right] \tag{12}$$

where $I_{\rm ph}$ is the photogenerated current which equals to the short circuit current ($V = 0$), I_0 is the reverse saturation current, $q = 1.602\times10^{-19}$ is the electron charge, B=1.381×10^{-23} J/K is the Boltzmann's constant, and T is the junction (cell) temperature.

When the PV cell is left open (I = 0), we can solve (12) for the open-circuit voltage, $V_{\rm oc}$, and we obtain

$$V_{\rm oc} = \frac{BT}{q}\ln\left(1 - \frac{I_{\rm ph}}{I_0}\right). \tag{13}$$

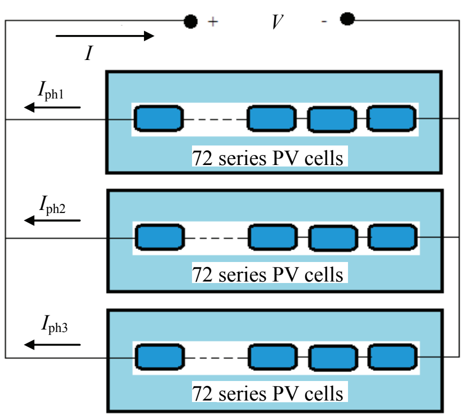

Fig. 3. One SMC-PV module with the proposed wiring.

Since the current $I_{\rm ph}$ is much greater than the current I_0 ($I_{\rm ph}$ >> I_0), we find

$$I_0 = I_{\rm ph}\exp\left(-\frac{qV_{\rm oc}}{\rm BT}\right). \tag{14}$$

In (12), (13), and (14), the photogenerated current, $I_{\rm ph}$, is directly proportional to SR on the PV cell surface. Thus the value of $I_{\rm ph}$ at any other insolation, S_H, is given by

$$I_{\rm ph}(S_H) = \frac{S_H}{S_S} I_{\rm ph}(S_S) \tag{15}$$

where $I_{\rm ph}(S_S)$ is known under the standard test conditions (STC) of S_s=1000 W/m^2 at 1.5 air mass ratio and 25 °C cell temperature. Manufacturers always provide the performance data of PV cells under these operating conditions. There are many types of such cells in the international market, the best of which is the silicon mono-crystalline (SMC) PV type. This type is a 63 V module and has 216 field-wired cells connected in three parallel strings, having 72 series cells in each. The maximum power of this module is 300 W and its efficiency is no less than 17%. Therefore, SMC-PV module has been chosen for this research work. From catalogues of typical SMC-PV modules, the electrical data for $I_{\rm ph}(S_S)$ of 6.5 A and $V_{\rm oc}$ of 63.2 V has been assumed. However, we can calculate V and I produced by the PV cell at different operating conditions. The output power P_c of the cell is expressed by

$$P_c = IV. \tag{16}$$

By solving (12) to (16), the output DC current, voltage and power from the PV module or array can be obtained as a function of day time, n.

5. Results and Discussions

The simulation results of the daily SR on horizontal surfaces in the Kuwait area now are graphically presented by using the model developed. As shown in Fig. 4, it is observed that the daily SR on horizontal surface in Kuwait increases rapidly from 3786.5 Wh/m^2 on 15th of January to 7984.9 Wh/m^2 on 15th of June and then decreases very rapidly to 3691.6 Wh/m^2 on 15th of November. It reaches its peak values during months from April to August (for n from 91 to 244) and the maximum daily SR occurs exactly in June as shown in Fig. 5. These results indicate very good agreement between the calculated data and the climatic conditions, because during hot months in Kuwait (April–August), the solar altitude angle β reaches its highest values from 64.69° on 1st of April to 83.85° on 30th of June and again to 68.77° on 31st of August (Fig. 6) and this explains the high temperatures in Kuwait during these months. This is also in conformity with the clear sky atmospheres and high clearness index K_t values for these months with average K_t varying between 0.56 in April and 0.67 in August (see Table 1). Even for the remaining months of the year (September–March), we have high values for daily or averaged monthly SR on horizontal surfaces with a minimum value of not less than 2902 Wh/m^2 occurring in December, which is still high if we compare it to the daily or monthly SR in some cities in Europe; for example, London has monthly averaged SR on horizontal surfaces of no more than 2800 Wh/m^2 in June.

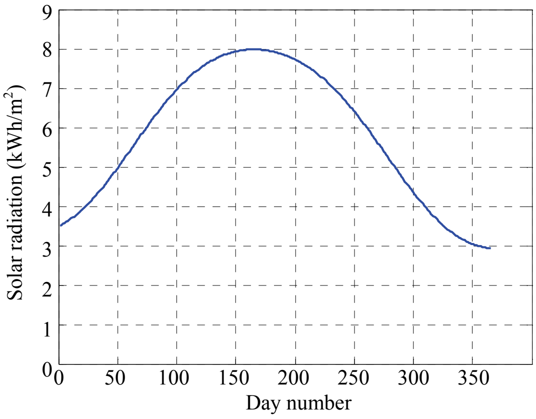

Fig. 4. Daily global SR intensity on horizontal surfaces in Kuwait area (Wh/m^2 –day).

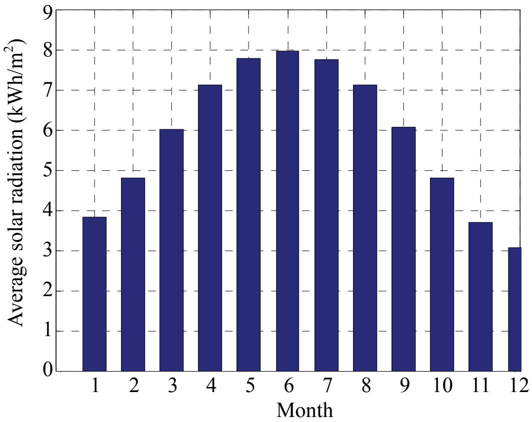

Fig. 5. Monthly averaged SR intensity on horizontal surfaces (Wh/m^2 –day).

Table 2: Monthly averaged insolation incident on horizontal surface in Kuwait area (kWh/m^2/day)

Latitude 29.33º Longitude 47.5º	22-year average S_H
January	3.89
February	4.96
March	6.09
April	6.91
May	7.80
June	8.16
July	7.76
August	7.29
September	6.28
October	5.05
November	3.82
December	3.26
Annual average	5.94

In general, for a daily SR on horizontal surfaces, the maximum value (on the summer solstice of 21 June) is 7959 Wh/m^2, and the minimum value (on the winter solstice of 21 December) is 2902 Wh/m^2, while for the equinoxes (21 March and September) it is 6210 Wh/m^2 per day and 5909 Wh/m^2, respectively. The monthly averaged global SR intensity on a horizontal surface in Kuwait area is also given and plotted in Fig. 5. Table 2 shows the results for monthly averaged SR intensity on a horizontal surface in Kuwait area as a 22-year average obtained from NASA website. The closeness of the computed results and those from NASA is evident, which provides some validation for the developed mathematical model.

The results obtained for the hourly SR on horizontal surfaces are shown in Fig. 7 to Fig. 9 for selected days in specific months of the year. The hourly SR is calculated every hour with a range according to the solar time t in hours from sunrise to sunset. It is clear that the hourly SR is increased from the sunrise hour H and reaches its peak at solar noon and then decreases until the sunset hour. It can be easily noticed that the peak hourly SR always occurs at solar noon (according to the longitude where γ equals 47.5º in Kuwait area) where the sun at its highest altitude in sky during its daily path.

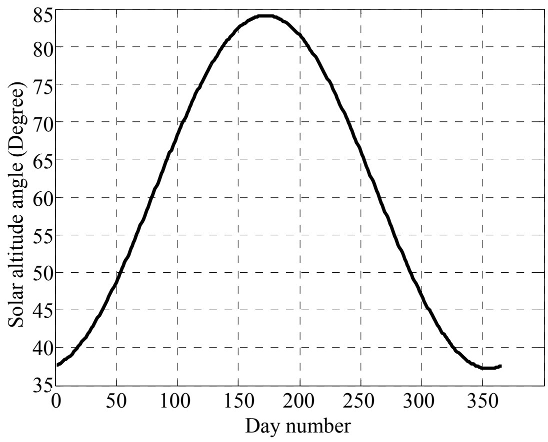

Fig. 6. Daily solar altitude angle in degrees at solar noon in Kuwait area.

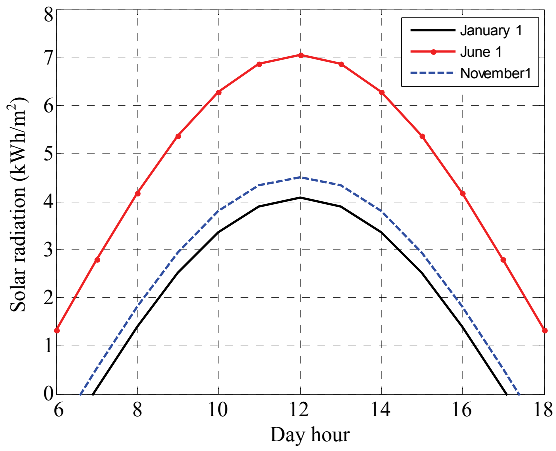

Fig. 7. Hourly global SR intensity on horizontal surfaces in Kuwait area on 1st of Jan., June and November.

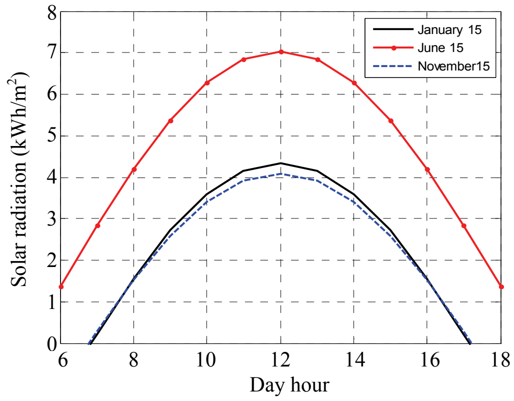

Fig. 8. Hourly global SR intensity on horizontal surface in Kuwait area on 15th of January, June, and November.

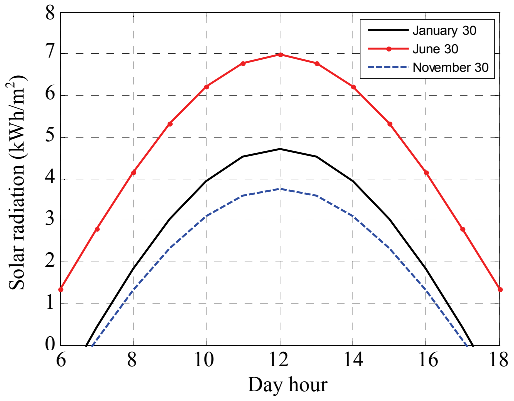

Fig. 9. Hourly global SR intensity on horizontal surface in Kuwait area on 30th of January, June, and November.

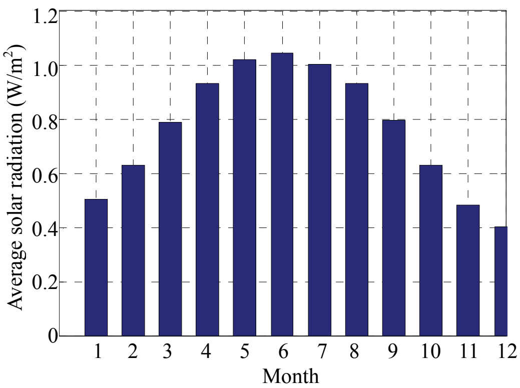

Fig. 10. Monthly averaged clear sky SR incident on horizontal surfaces in Kuwait area in (W/m^2).

The average monthly power generated from the insolation which is expected to strike horizontal surfaces in Kuwait area is obtained by dividing (10) by solar time during sun rise or sun set. This yields the solar power received per unit area at horizontal surfaces in W/m^2 that can be delivered to the photovoltaic cells at cloudless weather, as shown in Fig. 10 and Table 3.

Moreover, Fig. 2, Fig. 5, and Fig. 10 show that the peak load matches the maximum incident SR and its relative averaged electrical power, and these results are very promising in terms of the capability for Kuwait to use solar energy in electrical power generation.

Table 3: Monthly averaged SR incident on horizontal surfaces in Kuwait Area (W/m^2/day)

Month	S_H (W/m^2)
January	501.90
February	628.17
March	787.80
April	931.71
May	1017.63
June	1042.70
July	1000.61
August	930.86
September	794.48
October	628.84
November	483.63
December	401.02

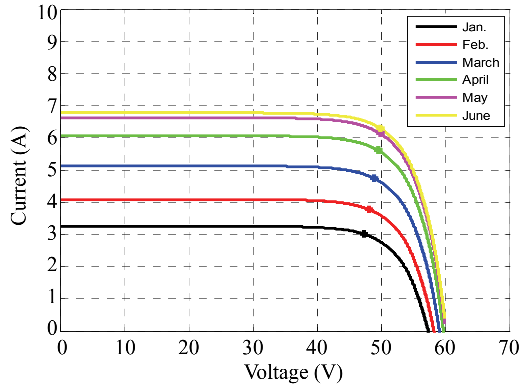

Fig. 11. *I*-*V* characteristics of a typical silicon mono-crystalline PV module at different SR intensity from January to June.

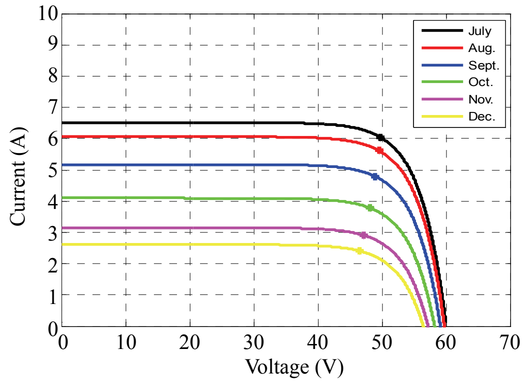

Fig. 12. *I*-*V* characteristics of a typical silicon mono-crystalline PV module at different SR intensity from July to December.

The electrical data of the selected SMC-PV module and the results obtained from the proposed SR model are used as input data to solve the governing equations for the PV module. Equations (12) to (16) are solved to predict the performance of a typical SMC-PV cell or module. Results are shown in Fig. 11 and Fig. 12 as the *I*-*V* characteristics of the selected module at different monthly averaged SR intensity over Kuwait area. It is easy to notice that the open-circuit voltage of the module ranges between 56 V and 61 V (actual value is 63.2 V at STC) and these differences are related to the differences in SR for each month. Moreover, the value of the short-circuit current of the PV module ranges from 2.8 A to 6.8 A (actual value is 6.5 A at STC). The dotted points in these curves show the maximum power point which is the operating point of the module at each month, and this signifies the importance of the *I-V* curve of the PV module. These curves show the behavior of the PV system from January to December under all load conditions from open circuit to short circuit. Thus the maximum output current of this PV module of 6.8 A occurs in June and the minimum current of 2.8 A occurs in December, while the maximum output voltage of the module for the whole year does not exceed 63.2 V. The *I-V* curves can be taken for any portion of an array provided there is electrical access.

The *I-V* curve of an entire module or array will give the peak power rating of the PV system. Substituting the values of *I* (module current) for each month into (16) and letting *V* (module voltage) vary between 0 and 70 V yield the output power rating of the module for different months, as illustrated in both Fig. 13 and Fig. 14. It is obvious that the rated power of the module is directly proportional to the SR intensity. Therefore, the rated power of the module in June has the highest value (320 W) due to the peak SR intensity occurs in June. Moreover, the maximum output power of the module ranges from 120 W in December to 320 W in June. We can choose a reasonable area in square meter and calculate the number of modules, *N*, to build the desired PV array (the module's area is 2.427 m^2) after making the required wiring to the PV modules. Then the total current and voltage of the whole PV system can be obtained with the desired electrical power.

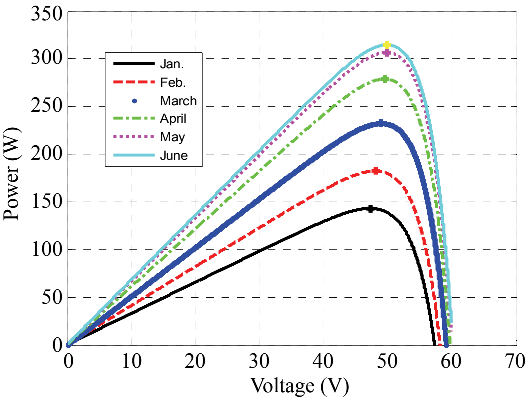

Fig. 13. Output power of a typical silicon mono-crystalline PV module at different SR intensities from January to June.

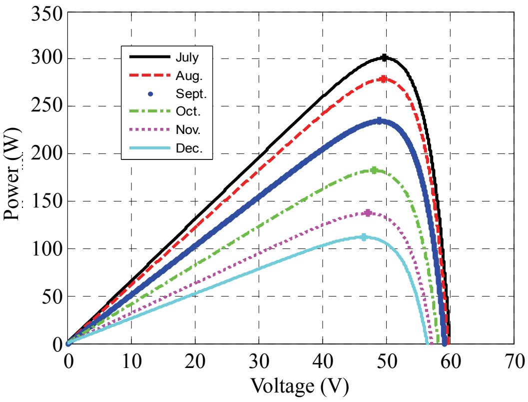

Fig. 14. Output power of a typical silicon mono-crystalline PV module at different SR intensities from July to December.

6. Conclusions

Being motivated by insufficient power supply capabilities and high peak loadings in Kuwait, the solar energy availability in Kuwait area as a potential renewable energy resource has been investigated and estimated. A trigonometric SR model that is applicable to Kuwait, taking into consideration the metrological data for Kuwait area, has been developed. The hourly, daily and monthly SR on the horizontal surfaces over Kuwait area has been estimated, giving a clear indication of the visibility and potential of solar energy in Kuwait.

The SR data for Kuwait area may be used as an input to a selected PV module with a specific electrical data. The wiring and modeling of the PV cells or modules have been presented to show the *I-V* characteristic curves of the proposed PV module at different SR intensities. At last, we clarified how to determine the module or array peak power rating by plotting the *P-V* curves at different SR intensities.

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