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What Guarantee can be given for the Electrical Power Output from a Fixed Rooftop Solar Installation?

Prof J. Rohan Lucas
General Sir John Kotalawala Defence University, Ratmalana, Sri Lanka
Email: lucas@kdu.ac.lk

Abstract

Commercial and residential rooftops commonly use solar photovoltaic systems to reduce their electricity bills and to supply excess electricity to the grid. However, the fluctuations in irradiation, sometimes drastic, limits them to be regarded not as supplying capacity, but only energy to the electricity grid. A knowledge of these daily and monthly achievable targets will help supply authorities to consider solar energy as adding a partial capacity to the grid. This paper quantises the daily and monthly solar electricity production from fixed solar installations.

Analysis is based on actual data from a 4.16 kWp rooftop solar system in Mount Lavinia, Sri Lanka [1]. Results of the present study show that the average energy produced during a given month can be estimated somewhat accurately, but there may be large daily variations even within a given week. Since accurate statistics from a real site are not freely available, no payment is made for capacity provided even for the large solar producers, as supply authorities have to plan generation schedules without a knowledge of the likelihood of such variations.

Results of the study show that while 90% of the maximum solar energy production can be guaranteed for any month on only 17% of the days, 70% of the possible energy can be supplied on 60% of the days. The days on which less than 10% of the possible energy can be supplied is less than 2%. These results can be made use of to offer a partial capacity payment to rooftop solar producers. Further, knowledge of month-based statistics would be able to provide better guarantees on availability of solar energy.

Keywords: Solar Photovoltaic, Solar PV, Rooftop Solar, Solar Power, Fluctuations, Intermittency, daily variations, monthly variations, databank, statistics

Introduction

With Government of Sri Lanka aiming for a significant increase in renewable energy [2] many solar installations are coming up to harness solar electricity, including on rooftops. Incentives have made rooftop solar PV installations [3] to come up in both industrial and domestic sites. Mt Lavinia, located at a latitude of 6.83°N in the Colombo District (06.93°N) has been selected as the location for study. Thus, in solar electricity producing installations near Colombo, the rooftop system should preferably be facing South with a tilt angle of around 7°.

The daily electricity produced from solar would vary from most predicted values due to cloud cover, while monthly variations of a fixed panel installation would also depend significantly on the position of the earth relative to the sun [4,5] and the orientation of the solar panels. Seasonal weather variations [6,7] add on to the complexity in the estimations.

This paper provides an analysed summary of fluctuation statistics in terms of the number of days on which various percentages of nominal energy could actually be harvested.

Maximum Available Solar Energy

It is well understood that the total extra-terrestrial solar irradiance is around 1361 W/m^2 [8]. However, due to the degree of transparency of the atmosphere [9] the maximum direct beam irradiance reaching the earth's surface is 1050 W/m^2[10], and the maximum irradiance, on the horizontal Earth's surface. including diffused radiation, is around 1120 W/m^2.

The latitude of the specific location of the solar site determines the direction of the sun's rays on the Earth.

At the equator, as the day progresses, the direct rays of the Sun reach the Earth's surface from 6 am to 6 pm, with maximum radiation at mid-day. The Earth being nearly spherical, the horizontal projected area is one fourth of its spherical surface area. Thus, the maximum solar energy that could be captured would be $1.361\times24/4$ or 8.166 kWh/m^2/day.

However, as the solar panels heat up due to the hot sun, the solar cell temperature would also be highest at mid-day, reaching about 30 °C to 40 °C above ambient. In addition to the monocrystalline solar panel used in the system are of size 1 m × 1.65 m, have an efficiency of 18.6% and a temperature coefficient of -0.4 %/°C [11]. Thus, the peak realisable solar electricity production is 8.166×0.186

or 1.52 kWh/m²/day. Thus, for a rise in cell temperature of 30°C, there would be a 12% drop in solar power output, reducing the effective efficiency to 16.4%. As most production from the solar panel is at mid-day, the maximum electrical energy production from the panel would reduce to around 1.34 kWh/m²/day. Thus, the solar panel will probably yield 1.34×1.65 or 2.21 kWh per panel on a relatively clear day.

Monthly Variation of Solar Insolation

Even at the Equator, the rays of the Sun does not always fall vertically on the Earth's surface. The angle between the rays of the Sun and the plane of the Earth's equator is defined as the declination of the Sun. The continuous daily variation of the declination angle is between ±23.45° and contributes to the reduction is solar power output in a fixed panel installation. Representative values of declination angle for each month, is given in Table 1.

Table 1: Monthly Declination Angle

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-20.1°	-11.2	0°	11.6°	20.1°	23.4°	20.4°	11.8°	0°	-11.8°	-20.4°	-23.3°

Further, the clearness of the sky or cloud cover [9] greatly affects the energy that can be harvested and is a major parameter to be considered in estimation of solar power production. Thus use of local storage during daylight hours could mitigate the effects of fluctuations [11, 12].

Site in Mount Lavinia

The solar data extraction is at a site in Mt Lavinia, Sri Lanka. 12 monocrystalline panels have been installed with the capacity stated for it in the online monitoring platform being 4.16kWp.

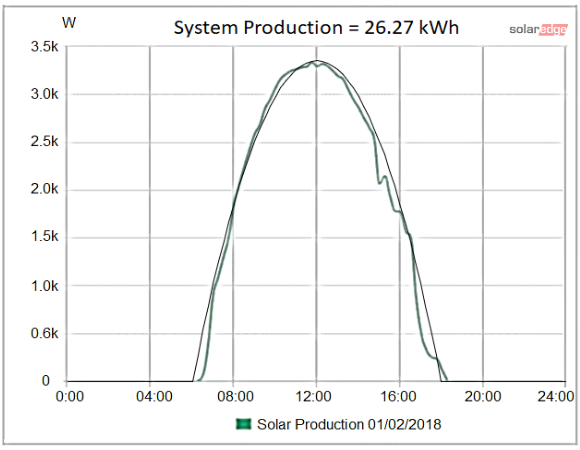
As the solar panel does not operate at test conditions, but much hotter, a rule of thumb is to use an 80% efficiency on rated capacity to give a maximum peak of 0.8×4.16 or 3.328 kW at around mid- day, with a maximum expected yield of around 12×2.21 or 26.5 kWh/day. It is obvious that this value would only be obtained on a clear sky at optimum declination conditions for the orientation of the solar panels. On other times the values would be lower,

Solar Power Output Measurements

Solar output measurements are available online for the Mt Lavinia site on a monitoring portal provided by the solar panel manufacturer. An analysis has been carried out on the data for the 4 year period from August 2017 to July 2021.

The solar irradiance curve at the surface of the Earth is usually considered ideal, similar to a part of a parabola as in Figure 1. Mathematically it could be shown that a parabola of the form, ~~shown~~ has a mean value equal to two-thirds of it's peak. Thus, when the period from 6 am to 6 pm is considered, the energy in kWh works out to exactly 8 times the peak value in kW. This ideal parabolic shape is rarely seen in practice, but a near ideal actual situation was observed on 1st February 2018 at the site and is shown along with the parabola in Figure 1.

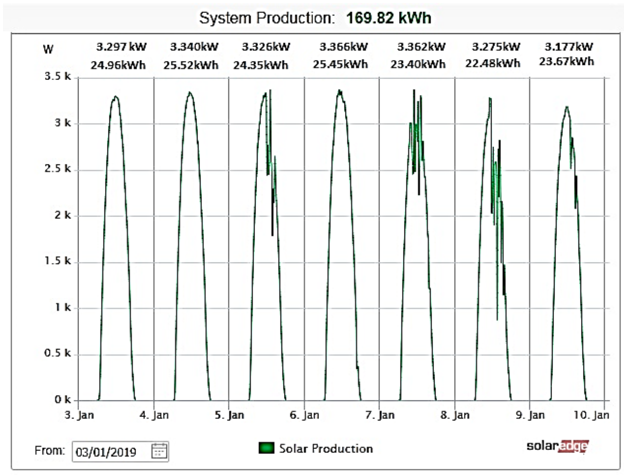
Figure 1: Peak Solar Energy Day 1st February 2018



The recordings on this day on the monitoring portal show a peak power production of 3.332 kW and an energy of 26.27 kWh for the day. These values correspond very well with the earlier predicted maximum values of 3.328 kW and 26.5 kWh/day.

Although blue skies are commonly observed in January and February, ideal days do not occur every day of the week. A plot of the production of the best week during the 4 year period from 3rd to 9th January 2019 is shown in Figure 2.

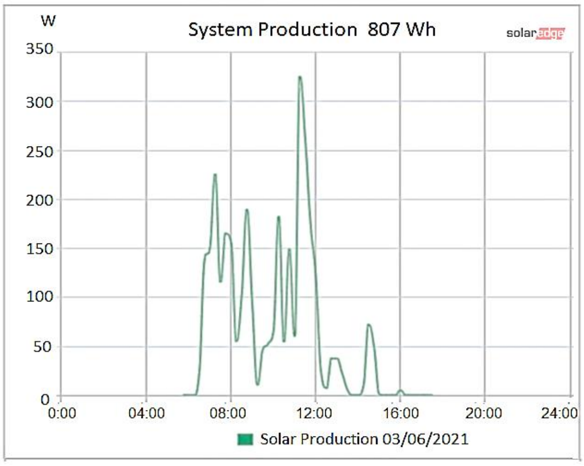
Figure 2 - Solar Output in a Good Week in January



It is observed that during this week, the peak power is constant at around 3.3kW, but the production of energy varied a little between 22.5 kWh and 25.5 kWh, with a total weekly production of 169.8 kWh.

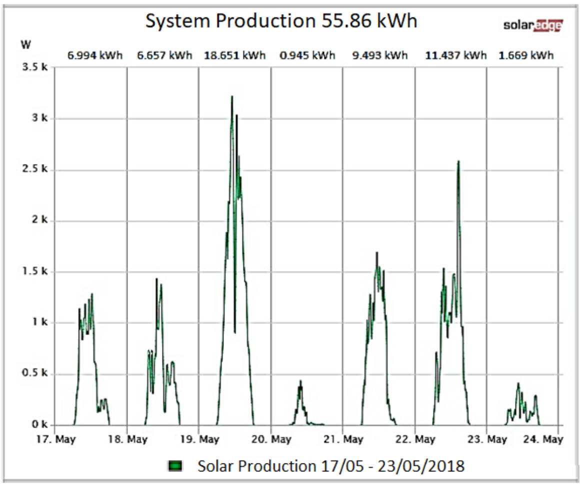
3rd June 2021 recorded the worst production during the 4 year period at the site, with a peak power of just 0.324 kW, and total electricity production being just 0.807 kWh as shown in Figure 3.

Figure 3: Minimum Energy Day in June 2021



The week of 17th May to 23rd May 2018, shown in Figure 4, is one of the worst energy producing weeks on record with the peak power varying between 0.43 kW and 3.22 kW on adjacent days.

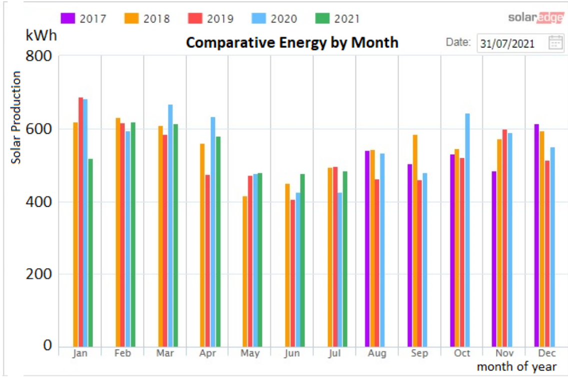
Figure 4: Solar Output on a Week of High Fluctuations



The corresponding output of electrical energy varied substantially from day to day, between 0.94 kWh and 18.65 kWh. As planning for such weeks is quite complex, it is important to know how often such days or weeks occur. This issue is addressed in this paper.

The monthly solar energy output as recorded for the period August 2017 to July 2021 is ~~as~~ shown in Figure 5.

Figure 5: Monthly Energy Output Aug 2017-Jul 2021



The pattern of monthly energy production is seen to be somewhat consistent for the same month over the 4 years, but with reductions caused by the declination angle and the orientation of the solar panels. It is worthy to note that the reduction occurred in certain months as the solar panels were fixed and not rotated to capture maximum of the Sun's direct rays.

The peak of the base parabolic curve shown in Figure 1, and the near ideal curve for 1st February 2018 correspond to the maximum energy of 26.5 kWh. However, depending on the orientation of the solar panels, a correction for the maximum solar yield on a particular season would need to be done. Observation suggests that the solar system has been oriented to give maximum output around January. This will be assumed for the rest of the study.

Thus, the declination angles given in Table 1 are corrected to give 0° on 1st January, and the corresponding correction factors *cos* ε are given in Table 2. As the maximum energy obtained in any single month over the four-year period was 687 kWh, this figure has been selected for determining the maximum solar energy output practically obtainable in any month, and tabulated in the same table using the declination angle correction factor suggested.

Table 2: Correction Factor for Declination

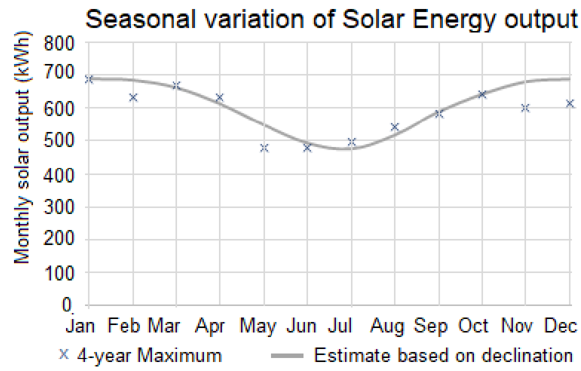
Month	δ	ε	Cos ε	Max kWh	Observed Max
Jan	-20.1⁰	0⁰	1	687	686.5
Feb	-11.2⁰	6⁰	0.994	683	631.5
Mar	0⁰	16⁰	0.961	660	667.3
Apr	11.6⁰	27⁰	0.891	612	555.9
May	20.1⁰	37⁰	0.799	549	455.3
Jun	23.4⁰	44⁰	0.719	494	427.6
Jul	20.4⁰	46⁰	0.695	477	472.5

Aug	11.8^0	41^0	0.755	519	519.7
Sep	0^0	31^0	0.857	589	506.4
Oct	-11.8^0	21^0	0.934	641	560.2
Nov	-20.4^0	9^0	0.988	678	561.5
Dec	-23.3^0	2^0	0.999	687	568

δ - Declination angle
ε - Correction angle

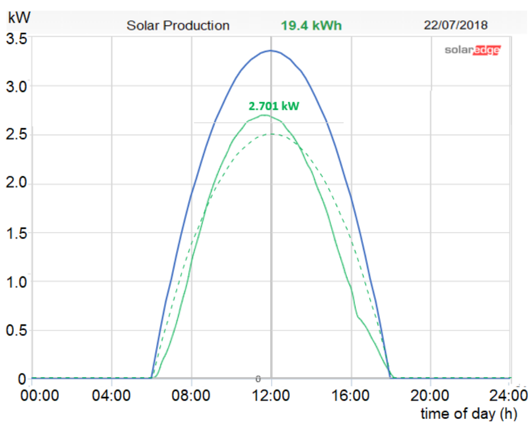
Table 1 further compares the maximum estimated monthly energy predicted and compares it with the maximum monthly energy observed over the four-year period.

Figure 6: Comparison with Seasonal Variations



This is presented in Figure 6 for easy assimilation. A very close relationship is observed. To understand the significance of this reduction, and to evaluate its validity, an ideal curve for 22nd July 2018 is presented in Figure 7 together with the ideal maximum parabola with a peak of 3.33 kW, and the corrected ideal parabola, with a peak of 2.70 kW for July based on change of declination angle. The actual curve for July is close to that predicted, but with a slightly different shape. As the correction factors are based on energy, rather than peak power, the peak energy theoretically expected of 20 kWh compares well with 19.4 kWh actually produced.

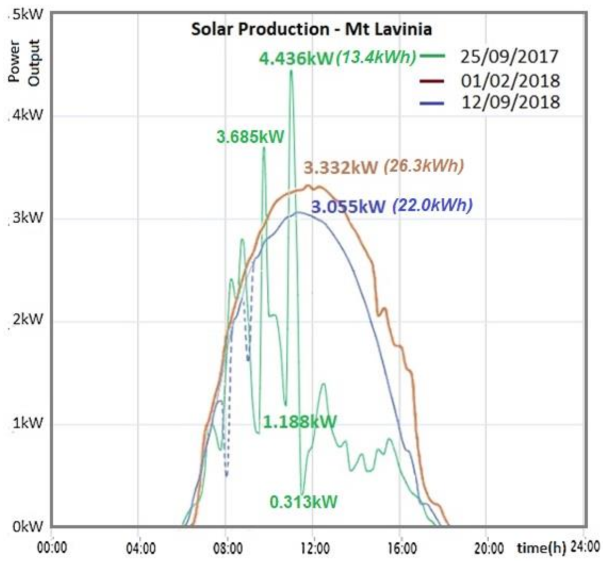
Figure 7: A Near Ideal Day in July



Analysis of Fluctuations of Solar Power Output

The day 25th September 2017 can be considered a highly fluctuating day for solar power production with energy produced of 4.436 kW, as seen in Figure 8. Although this day produced just 51% of maximum energy, the peak power fluctuated between extreme limits of 0.313 kW and 4.436kW. It seems surprising to reach a peak of 4.436 kW, even surpassing the rated peak power 4.16 kWp, on a day with just half the energy. However, close examination of the output curve shows that the power was just 1.188 kW an instant earlier, and the solar cells would have been completely cool (perhaps even cooler than normal due to the rainy weather) so that when the sun came out briefly from under the clouds, a much higher efficiency would have occurred due to the negative temperature coefficient. To understand the significance of this behaviour further, the output of 25th September has been compared with that of the overall maximum energy day and a near ideal day in September to account for the reduction due to declination.

Figure 8: Analysis of Solar Output during Fluctuations



A Sample of Solar Output Patterns

Ideal days like in Figure 1 are very rare and seldom occur even in clear sky months. In months such as May, June, and July the electrical power output is low caused by lack of clear skies and declination angle preventing even the solar radiation falling on the panel not to be fully captured. For a fixed installation, rotation of panels to capture maximum irradiation is not economically feasible. The other option, to mitigate the effects of fluctuations economically, is to have a hybrid system with optimum choice of battery or other storage device. To understand the implications of lack of clearness in the sky, samples of daily solar output on a somewhat clear day, partially cloudy day, cloudy day and overcast day are shown to give an insight. The curves are plotted together with the ideal maximum parabolic curve.

The date 9th February 2018 was a relatively clear day with partial clouds in the morning but with output power dropping by 20%, as shown in Figure 9.

Figure 9: Solar Output on a day with Morning Clouds

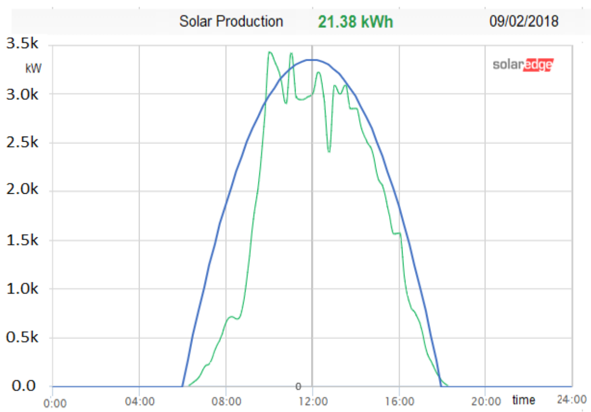


Figure 10 shows a partially cloudy morning, and improper declination which have given rise to a 30% reduction in power output.

Figure 10: Solar Output on a Partially Cloudy Morning

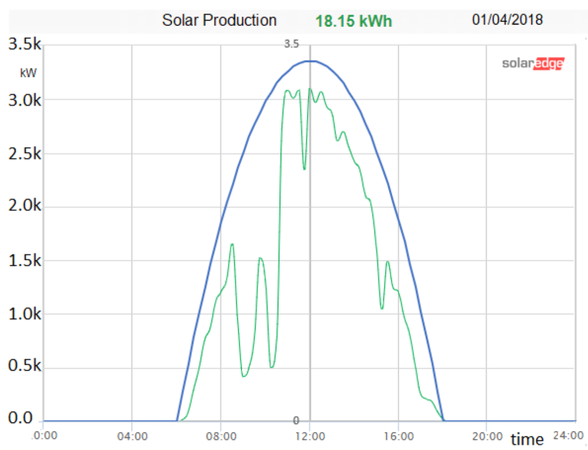


Figure 11 shows the solar output on 25th September 2017 with a heavy movement of clouds in the morning and overcast conditions in the evening giving a 50% reduction in energy.

Figure 11: Solar Output on Cloudy Morning and Overcast Evening

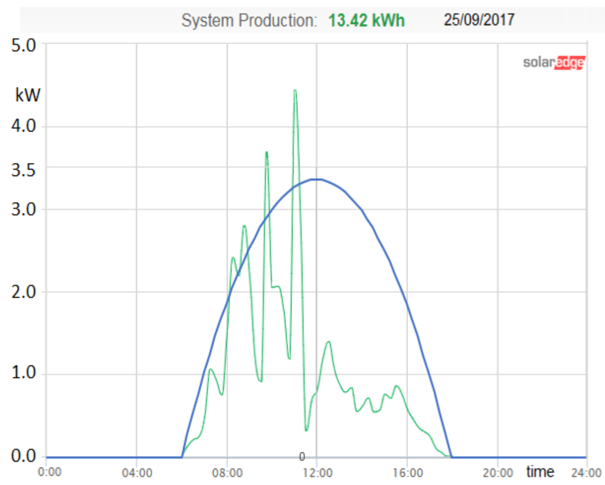


Figure 12 on 9th October 2017 is an unusual day with heavy clouds conditions at mid-day, giving a reduction of the energy of just over 55%.

Figure 12: Solar Output on a Very Cloudy mid-day

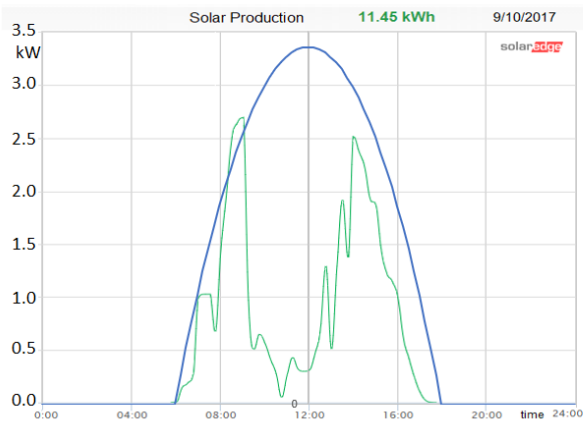
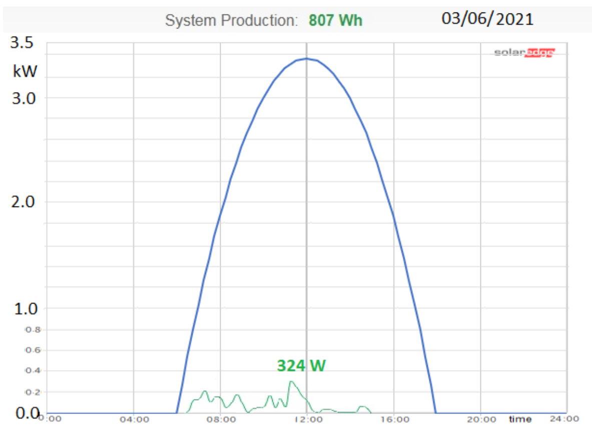


Figure 13 corresponds to the solar output on a fully overcast day, 3rd June 2021.

Figure 13: Lowest Solar Electricity Producing Day



This day had a peak output electric power of only 324 W (one-tenth of the normal peak) and the lowest energy of 807 kWh, a significant reduction of 97%, with only 3.07% of maximum energy being delivered on this day.

Categorisation Statistics of Solar Power

Considering the solar power output ranges on different days during the four-year period, categorisation was done. Since the peak energy output on any day is estimated to be 26.5 kWh, 2.5 kWh steps were considered in the categorisation and given in Table 3.

Table 3: Categorization of Solar Output Days

Category (kWh)	No. of days in range	%	Days in Jan '19	Days in May '19
< 2.5	10	0.7%		1
2.5 – 4.99	17	1.2%		1
5.0 – 7.49	37	2.5%		1
7.5 – 9.99	59	4.0%		1
10.0 – 12.49	71	4.9%		1
12.5 – 14.99	144	9.9%		3
15.00 – 17.49	233	15.9%	3	10
17.50 – 19.99	324	22.2%	2	13
20.0 – 22.49	320	21.9%	11	
22.5 – 24.99	222	15.2%	12	
>25	24	1.6%	3	
Total	**1,461**	**100%**		

Table 3 shows that for any month, while 90% of the maximum solar energy production could be guaranteed on 17% of the days, 70% of the possible energy can be supplied on 60% of the days. The days on which less than 10% of the possible energy can be supplied is less than 2%. These results can be made use of to offer a partial capacity charge to rooftop solar producers for perhaps half the capacity which can be guaranteed on 86.7% of the days or 317 days of the year. However, if we go month by month, a better guarantee can be made. Columns 4 and 5 of Table 3 give the number of days in each category for two selected months of January 2019 and May 2019. For example, in January 2019, 15 kWh (60% of the maximum power) could be guaranteed 95% of the time with an average availability of 21.43 kWh. Similarly, no day in May 2019 did the power exceed 19 kWh, and on 80% of the days the power exceeded 55% of this capacity (10 kWh).

Conclusions

The paper has presented an analysis of solar output for solar photovoltaic systems, considering a 4.16 kWp monocrystalline rooftop solar system in Mount Lavinia, Sri Lanka. Fluctuation of actual power and energy have been observed over a four-year period from August 2017 to August 2021. It is seen from the analysis that not only is the generated power intermittent, with the solar power output peaking at instants to even exceeding 4.5 kW, but also going down to as low as 0.324kW on a heavily overcast day. Similarly, variation of daily solar electric energy output varied from 0.807 kWh to 26.27 kWh. It was also seen that on 2% of the days over the four-year period, the daily energy produced was less than 20%, while an amount of 50% of peak power could be guaranteed on 86.7% of the days, considering all months as similar. However, the study has given a glimpse to better guarantees than could be made if analysis is carried out on a month wise basis. For example, for January, no day in January 2019 produced less than 15 kWh per day with an average production of 21.43 kWh, while no day in May 2019 has registered even 19 kWh with 80% of the days exceeding 55% of that month's maximum. Thus, further analysis could be made to establish the amount of solar power output that could be reasonably be guaranteed for each month.

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