Evaluation of Solar Resource and Technical Performance of 180kWp Commercial Scale Solar Photovoltaic System at Timau, Kenya

Nickson Bukachi Ongeri[1], Kinyua, Robert[2], Keren Kaberere[3]

[1]Jomo Kenyatta university of Agriculture and Technology, Institute of Energy and Environmental Technology, Nairobi, Kenya

[2]Jomo Kenyatta university of Agriculture and Technology, Department of Physics, Nairobi, Kenya

[3]Jomo Kenyatta university of Agriculture and Technology, College of Engineering and Technology, Nairobi, Kenya

Abstract: ***Both developed and developing countries are grappling with the need to meet their increasing energy demand in a sustainable and affordable manner. This has made it necessary to exploit the potential of renewable energy technologies. One of the options that has been considered is the use of distributed commercial scale solar PV systems installed on medium or large energy consuming facilities. The systems are designed to supply part of the energy needs of the facility with the deficit drawn from the utility's grid. In some cases, the solar PV systems may bank any excess energy generated onto the grid depending on the existing regulatory framework. Success in implementation of these systems requires knowledge on the available solar resource and expected performance of the solar PV systems. In this study, the solar resource potential at Timau area (0.089238 ^{o} N, 37.274860 ^{o}E), Meru County-Kenya and the performances of a 180kWp ground-mounted Commercial Scale Solar Photovoltaic System installed to supply a flower farm at the location were analysed. In the paper,the design configuration of the solar PV plant is elaborated. The monthly average daily reference yield for the site, annual average daily yield, performance ratio and monthly average capacity utilization factor for the 180kWp plant are also computed. The monthly average daily reference yield based on the monitored solar insolation was found to range between 4.60 - 7.33 kWh/kWp-day. This is1.1% higherthan the long-term insolation data obtained from the PVGiS database during the hot season and 3.3% lower during cold seasons. Similarly, the annual average daily yieldis 5.21 kWh/kWp-day based on the monitored irradiance values and 4.25 kWh/kWp-day based on the metered energy supplied by the solar PV plant to the flower farm. Lastly, the highest daily average performance ratio for the months of February and March 2017 was 80.8% and the monthly average capacity utilization factor ranged between 13.28% - 21.19% over the one year monitoring period.***

Keywords: Solar Energy, Commercial Scale SolarPhotovoltaic Systems, PVGiS, Performance Ratio

1. Introduction

Modern day scientists are faced with the challenge of matching world energy supply systems with the ever-increasing energy demand. The growth in demand is associated with faster growth in world population compared to the establishment of additional energy supply. For instance, the International Energy Agency (2016) estimates that at least 1.4 billion people around the globe have no access to modern energy services, majority of whom are in the rural and pre-urban areas of Sub-Saharan Africa and Asia.Similarly, high costs attached to purchasing conventional energy systems that are rapidly diminishing and their resultant negative environmental impacts have forced the world to shift focus to alternative energy sources. Multiple studies have been conducted on the use of solar photovoltaic (PV) systems to enhance reliability and security in electricity supply [1]. This is in addition to cutting down on emissions associated with use of fossil fuel.

Solar PV installations range from small solar home systems to large utility scale systems. Design of the solar PV systems requires knowledge on the expected energy yield performance. The performance is specific to particular locations due to varying climatic conditions from one place to another. In addition, the designs require reliable solar insolation databases that can be applied in simulating solar PV systems performance.

A number of past researches have focused on evaluating the solar resource for specific locations and the technical performance of different categories of solar PV systems based on measured and/or simulated data. This includes evaluating the performance of commercial scale solar PV systems. Reference [2] assessed the generation potential of photovoltaic systems within the Caribbean regions of Colombia using data extracted from the NASA database. The workestablished the potential of electricity that can be generated in Columbia from photovoltaic systems at 1554.47 kWh/kW, performance ratio of 79.63% and 17.75% capacity utilization factor. The results indicated that the theoretical potential of in the region 258,300 TWh/yr was much higher than the technical potential of 12,300.87 TWh/yr. Reference [3] measured the performance of a 1.72 kW rooftop grid connected solar photovoltaic system in Ireland. It is recorded that the capacity factor ranged between 5.0% in December and 15.5% in June. The author reported that the capacity factor for the various months is determined by the seasonal variation in solar insolation. The months of high insolation were found to have a higher capacity factor in normal operating conditions. Reference [4] - [6] conducted an evaluation of solar radiation of different locations in Kenya, that is Nairobi and Thika, Naivasha and Nakuru respectively. The studies focused on providing information on the potential of solar energy in the four locations using pyranometer measurements and Kenya Meteorological data. From the analysis of solar radiation, data monitored using a pyranometer, Nairobi and Thika had a minimum average annual daily insolation of 4 kWh/m^2/day and a maximum of 6 kWh/m^2/day .The average monthly daily insolation for the two locations ranged between 3 and 7 kWh/m^2/day. Reference [5] recorded a monthly daily solar insolation of 1.21kWh/m^2 minimum and a maximum of 6.5kWh/m^2. Similarly, reference [6] analysed meteorological radiation data for Nakuru (35^{o}28' and 35^{o}36' East and 0^{o}12' and 1^{0}10'S) and recorded that Nakuru has an average daily solar insolation ranging from a minimum of 4.8 kWh/m^2/day to a maximum of 6.9 kWh/m^2/day. Therefore, studies [4] – [6] show solar resources are site specific and depend on prevailing weather conditions.

This paper builds on and contributes to the knowledge on the solar resource by monitoring the solar radiation at Timau area (0.089238 ^{o} N, 37.274860 ^{o}E), Meru County-Kenya using an SMA SensorBox and SensorWeb.The solar radiation of the site was monitored for a period of one year between April 2016 and March 2017. Further to this, the study provides an additional insight by comparing the monitored solar insolation with the insolation data obtained from the Photovoltaic Geographical Information System (PVGiS) including an analysis of the technical performance of a commercial scale solar PV systems based on the monitored irradiance and actual energy metered from a 180kWp solar PV plant.The technical performance analysis of the commercial scale solar PV system is based on the BS EN, 61724 Standard performance parameters for solar PV systems.

2. Description of the Commercial Scale Solar PV System

The ground mounted commercial scale solar PV system situated in Timau area, Meru County-Kenya (0.089238 ^{o} N, 37.274860 ^{o}E) is of 180kWp. The system is meant to supply electrical energy to Timaflor Limited flower farm that uses electricity for pumping, lighting and refrigeration. This is to complement the utility electricity and existing standby diesel generator. It consists of 720, polycrystalline silicon modules that are connected in 12 strings of 50 modules each connected in series. The modules are oriented at a fixed tilt of 15^0 with half facing southand the other half facing north. Module specificationsare provided in Table 1.

Table 1: PV Module Specifications

PV Module	Specifications
Type of Material	Polycrystalline
Maximum Power (P_{max})	250 Wp
Open Circuit Voltage (V_{OC})	37.4 V
Maximum Power Point Voltage (V_{max})	30.1 V
Short Circuit Current (I_{sc})	8.83 A
Maximum Power Point Current (I_{max})	8.31 A
Maximum Series Fuse Rating	20 A
Module Area	1.62688 m^2
Power Specification at STC	1000 W/m^2 @25 ^{o}C, AM 1.5

12, 15KVA, Sunny Tripower 15000TL inverters are used to convert DC to AC with the output of the inverters fed to the flower farm depending on the available energy demand. The Sunny Tripower inverters are transformerless PV inverters consisting of two MPP Trackers that convert direct current produced by the solar PV array to three-phase current that is grid compliant. The specifications of the inverter are provided in Table 2.

Table 2: Inverter Specifications

Inverter	Specifications
Model	15000TL
Number of Inverters	12
MPP voltage range	360 V to 800 V
Maximum input voltage	1000 V
Rated input voltage	600V
Power	15000 VA

The solar PV plant is configured such that the solar PV system does not feed to the utility's grid. In case theenergy generated is more than the available demand, the output is curtailed using an MPPT tracking ability of the inverter.The block diagram for the commercial scale solar PV system is presented in Figure 1.

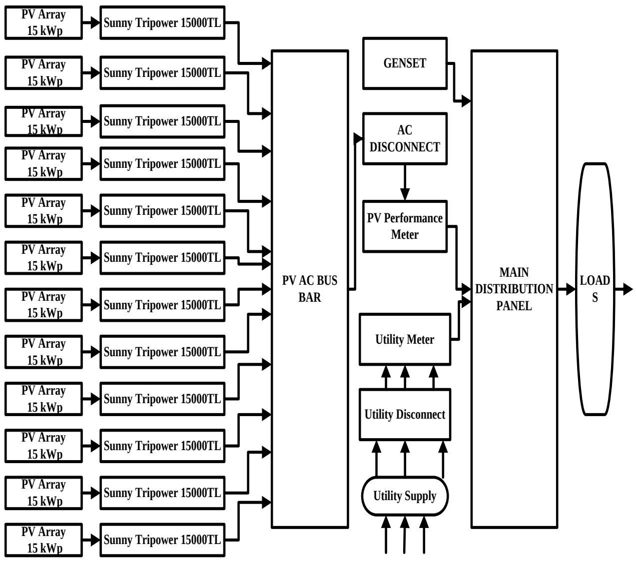

Figure 1: Block diagram of 180kWp solar PV plant at Timaflor Limited Flower farm

Figure 2: 180kWp solar PV plant at Timaflor Limited Flower farm

3. System Performance Parameters

The performance of the 180kWp commercial scale solar PV system is assessedbased on the BS EN, 61724 Standard performance parameters for solar PV systems [7]. The performance parameters considered include:energy output, reference yield (Y_R), final yield ($Y_{F,m}$), performance ratio (PR) and the plant capacity factor (CF).

The total energy generated daily ($E_{AC,d}$) is determined by aggregating the hourly values in kWh of the energy generated by the solar PV plant. To obtain the total monthly energy generated ($E_{AC,m}$) daily energy values are aggregated for the given month. The daily energy generated is expressed as:

$$E_{AC,d} = \sum_{t=1}^{t=24} E_{AC,t} \quad (1)$$

Equation (2) represents the monthly energy generated by a solar PV plant

$$E_{AC,m} = \sum_{d=1}^{N} E_{AC,d} \quad (2)$$

Where N represents the number of days in the month

The final yield ($Y_{F,m}$)represents the hours that a solar PV plant would need to operate at the rated power to provide the same amount of energy as the total AC output of the solar PV plant. It can be evaluated for a period of one day, month or year. The monthly final yield is given by [6, 8]:

$$Y_{F,m} = \frac{E_{AC,m}}{P_{PV,rated}} \quad (3)$$

where$E_{AC,m}$ is total monthly AC energy output in kWh while $P_{PV,rated}$ is the nominal power of the PV array installed at standard test conditions (STC). The parameter is used to compare the performance of similar PV systems located in a given geographic region.

The reference yield (Y_R)or peak sunshine hoursis a ratio of the in-plane solar insolation Ht measured in kWh/m^2 to the array reference irradiance (1 kWh/m^2). The ratio gives an indication of the continuous number of hours a particular site would receive 1000 W/m^2 of solar irradiance within a given period. It is given by [9];

$$Y_R = \frac{H_{t\,in\,kWh/m^2}}{1\ in\,kW/m^2} \quad (4)$$

The monthly reference yield is used to provide a reference point when sizing solar PV systems in cases where the solar insolation is not monitored before sizing. The worst case scenario is normally preferred in designs hence the month with the least peak sunshine hours.

The performance ratio (PR) gives a ratio between the actual yield of a solar PV system to the target yield assuming the system were to be operated at the standard test conditions. It gives the fraction of energy that is available after factoring the energy losses. The PR is expressed as [8,9]:

$$PR = \frac{Actual\ \ yield\ \ (in\ kWh)}{Calculated\ \ nominal\ \ yield\ \ (NY)} \quad (5)$$

The nominal yield value is calculated from the products of GHI (kWh/m^2), the global horizontal irradiance, the area covered by the modules, and the rated module efficiency [2]. This ratio gives an evaluation of the PV plant's efficiency. This parameter has no dependence to the plant's location, the modules' orientation, and the plant's rated nominal capacity.
The capacity utilization factor (CF) is the ratio of the actual generated energy by a solar PV plant to the anticipated energy generation if the plant were running at its full rating over a specified period. It aims to establish the performance of the plant in relation to its maximum performance. The capacity factor would thus be unity if the system delivered constantly, its overall rated power over a given period. The annual capacity factor of a solar PV plant is expressed as [3]:

$$CF = \frac{Y_{F,a}}{P_{PV,rated}\ \ x24\ x\ 365} = \frac{E_{AC,a}}{P_{PV,rated}\ \text{x}\ 8760} = \frac{H_t \text{x PR}}{P_{PV,rated}\ \text{x}\ 8760} \quad (5)$$

4. Results and Discussion

4.1. Solar Resource

Data on the solar insolation of a site is crucial when sizing the different configurations of the solar system. Figure 3 shows a comparison between the solar insolation values based on the monitored radiation for the period of April 2016 to March 2017 and the long term average values downloaded from the PVGiS database.

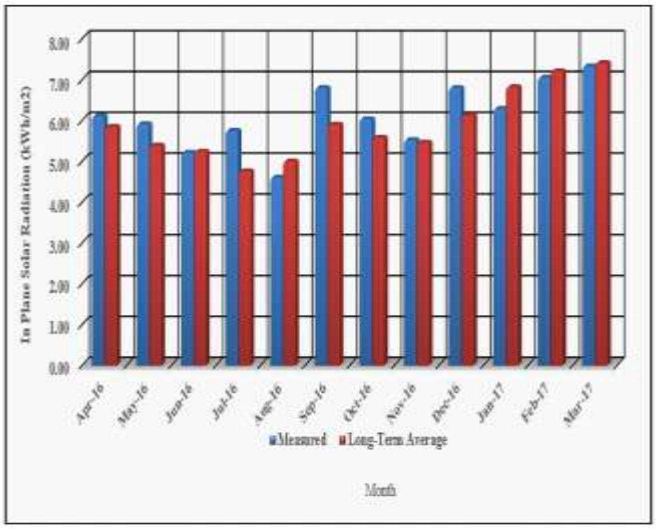

Figure 3: Comparison between Monthly average daily reference yield based on measured and long-term solar radiation

Here, the monthly average daily reference yield based on the monitored irradiance ranges between 4.60 - 7.33 kWh/kWp-day. On the other hand, the monthly average daily reference yield based on the long-term data ranges between 4.76 - 7.41kWh/kWp-day corresponding with March-2017 and July-2016 respectively.The monthly average daily total insolation obtained from the monitored irradiance values is 3.3% lower than the long-term values obtained from the PVGiS database in the cold season and 1.1% higher in the dry season. Similarly, the annual average daily total insolation obtained from the monitored irradiance values is higher than annual average daily total insolation based on the long-term average values by 3.8%.

Figure 4 shows the comparison between the computed monthly annual yield based on long-term and Sensorboxmonitored irradiance, and the measured monthly annual energy yield. The obtained annual energy yield based on monitored solar radiation is 341,346kWh, 328,823 kWh based on the long-term insolation values and 278,461 kWh based on the actual energy supplied by the solar PV plant to the flower farm. In addition, it is noted that the estimated annual energy generated based on the long-term solar insolation database is less than the metered energy supplied to the facility from the solar PV plant by 38,309 kWh and the calculated energy generated using the monitored irradiation data by 12,523 kWh. Therefore, from the annual energy yield computed using the monitored insolation data, 62,884kWh (22.6%) of the 180kWp solar PV plant is not utilized.

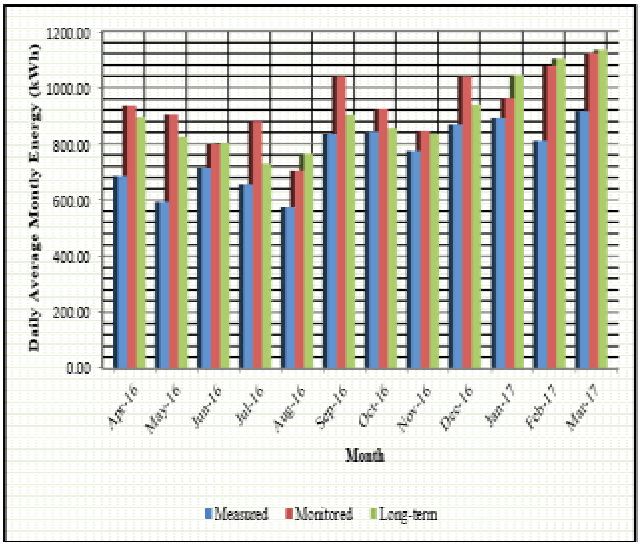

Figure 4: Comparison of Daily Average Monthly Energy based on long-term irradiance, measured irradiance and meter energy supplied to the facility

4.2. Performance Parameters

Figure 5illustrates the monthly final yields obtained from the data collected. Final Yield1 represents results obtained based on the actual energy supplied to the facility from the solar PV plant during the monitoring period while Final Yield2 represents results obtained based on the expected energy determined from the monitored solar radiation.

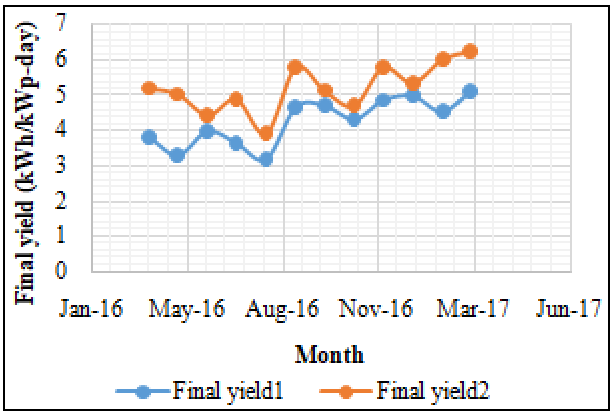

Figure 1: Comparison of Monthly Average Daily Final Yields based on Monitored Irradiance and actual Energy Supplied by the 180kWp Solar PV Plant

The monthly average daily final yields using the energy determined based on the monitored solar insolation and actual energy supplied to the facility by the solar PV plant have similar trends. However, the final yield values determined by actual energy supplied to the facility by the solar PV plant are lower than the values determined from the monitored solar insolation. This is as a result of curtailment of the solar PV plant output by the MPPT to match the demand in cases where the supply exceeds the demand. The annual average daily yield is 5.21 kWh/kWp-day based on the monitored irradiance values and 4.25 kWh/kWp-day based on the metered energy supplied by the solar PV plant to the facility.

Figure 6 show the obtained hourly average PR for the months of February and March 2017.

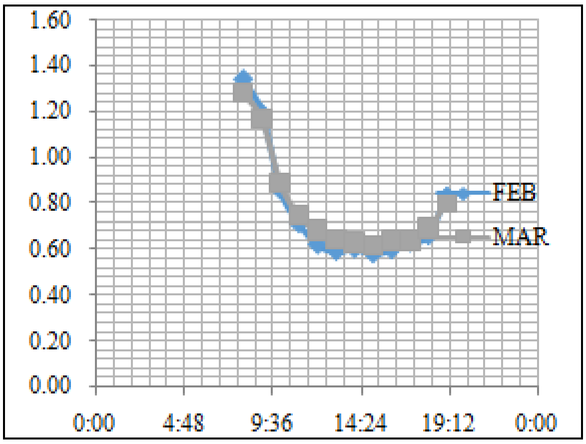

Figure 6: Average hourly PR for February and March 2017

The hourly average PR ratio ranges between 0.5827-1.3411 and 0.6169-1.2829 respectively. The solar PV plant is utilized better between 8:00 A.M-11:00 AM where the PR ratio is more than 0.7. On the other hand, the PR ratio is less than 0.7 where the solar PV plant output is highest. This indicates a potential for grid energy banking to improve the PR to more than 0.7. The PR values for March were found to be generally higher than the corresponding values obtained for Feb indicating better utilization of the energy generated by the solar PV plant in March 2017 compared to February 2017. The monthly performance is a quotient of the total actual energy supplied to the facility by the solar PV plant to the total nominal energy in a given month. The computed PR for the months of February and March was 65.24291% and 69.3610763% respectively.

Figure 7 (a) and (b) shows the daily average PR for the months of February and March 2017 based on metered daily energy supplied to the facility.

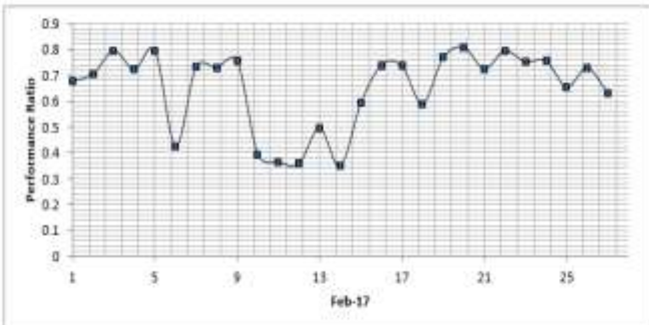

Figure 7(a): Daily average performance ratio for February 2017

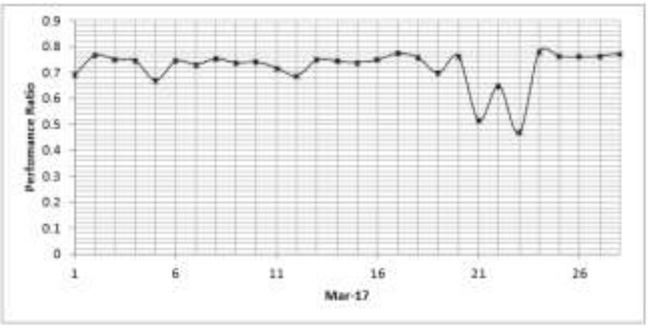

Figure 7 (b): Daily average performance ratio for March 2017

The maximum performance ratio realized by the Solar PV plant for the individual days was 80.8% on 22nd February, 2017 while the least is 31.0% on 15th February, 2017. Similarly, the maximum PR achieved in March was 77.9% on 24th March, 2017 with a minimum of 36.2% on 30th March, 2017. Therefore, the utilization of the solar PV plant varies on a daily basis depending on the activities within the facility. The higher the energy demanded by the facility the better the solar PV plant is utilized. The computed PR for the months of February and March was 65.24291% and 69.3610763% respectively. The highest performance ratio obtained during the monitoring period is 80.82442% on 22nd February, 2017 which is much higher than average performance ratio for the two months.

Figure 8 shows a comparison of the solar PV plant capacity factor using three different scenarios. This is based on the actual energy supplied to the facility by the solar PV plant (CP1), the calculated energy generated by the solar PV plant from the monitored solar insolation (CP2) and the calculated energy generated by the plant based on the long-term insolation values obtained from the long-term insolation (CP3).

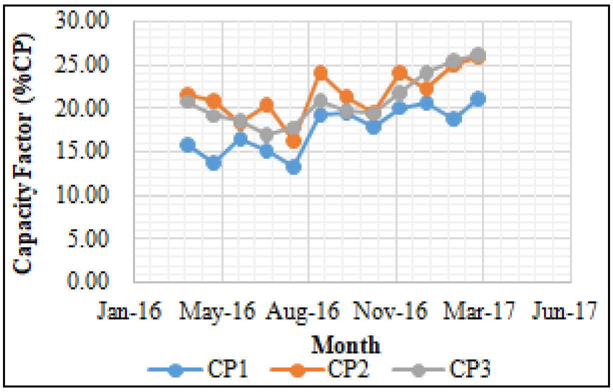

Figure 8: Comparison between Monthly Average Capacity Factor based on solar PV energy supplied to the facility (CP1), monitored solar insolation (CP2) and long-term average solar insolation

The monthly average capacity factor ranged between 13.28% - 21.19% based on the actual energy supplied to the facility and 16.30% - 25.96% using the energy computed from the long-term solar insolation data. The maximum and minimum values of the monthly average capacity factor for the actual energy supplied to the facility and the long-term solar insolation data correspond to the months of August-2016 and March-2017 respectively. On the other hand, the monthly average capacity factor based on the energy generated by the solar PV plant calculated from the monitored solar insolation received by the solar PV plant ranges between 16.86% - 26.24% with the lowest value corresponding to July-2016 and the highest value March-2017. The annual average capacity factor of the solar PV plant is 17.67% considering the actual energy supplied to the facility over the year under study, 20.88% based on energy determined from the long-term average solar insolation and 21.67% based on the energy determined from monitored solar insolation.

The 17.67% annual average capacity factor based on the actual energy supplied to the facility indicates a generation curtailment of the solar PV plant by 4% when compared to the energy determined by the monitored insolation. This agrees with the determined performance ratio of the plant that was found to vary depending on the utilization of the solar PV plants in different days. In addition, the annual average capacity factor based on the monitored solar insolation is higher than the annual average capacity factor based on the long-term average solar insolation by 0.79%. Therefore, the long-term average solar insolation values obtained from the PVGiS give a good indication of the solar insolation of the site and thus can be usedin designing systems and studies for other sites.

5. Conclusion

The solar resource potential at Timau area (0.089238 ^{o} N, 37.274860 ^{o}E), Meru County-Kenya was assessed. This includes conducting a performances analysis of a 180kWp ground-mounted Commercial Scale Solar Photovoltaic System installed to supply a flower farm located in the area. The following main observations and conclusions were drawn from the analysis:

a) The monthly average daily reference yield for the site ranges between 4.60 - 7.33 kWh/kWp-day with the minimum in July and maximum in March. Therefore, compared to the results of other studies [1-3], the site has a high solar potential and hence suitable for solar power generation.
b) The monthly average daily reference yield is 3.3% lower than the long-term values obtained from the PVGiS database in the month with the least insolation and 1.1% higher in the month with the highest insolation. Therefore, the PVGiS data provides a good approximation of the solar potential of the site.
c) The annual average daily yield is 5.21 kWh/kWp-day based on the monitored irradiance values and 4.25 kWh/kWp-day based on the metered energy supplied by the solar PV plant to the facility. Thus, the solar PV plant output is curtailed by 22.6% due to lack of demand. Load shifting or incorporating energy storage or use of grid energy banking canimprove the solar PV plant utilization.
d) The highest performance ratio obtained for the months of February-2017 and March 2018 during the monitoring period is 80.82442%. The months of March and February had an average performance ratio of 65.24291% and 69.3610763% respectively due to solar PV plant output curtailment.
e) The monthly average capacity utilization factor ranged between 13.28% - 21.19% based on the actual energy supplied to the facility and 16.30% - 25.96% using the energy computed from the long-term solar insolation data

The study shows that the utilization ofcommercial scale solar PV system can enhanced with grid energy banking. However, further studies need to be conducted on the impact of such systems on the grid stability and national energy planning.

6. Acknowledgements

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