Original Research Article

Performance Evaluation of 780 Wp rooftop Solar PV Power Backup System in Western Kenya

ABSTRACT

Aim: This study aimed to carry out performance analysis of a 780 Wp PV power backup system installed at a learning institution in Western.

Study design: To achieve this goal, site solar radiation received, ambient temperatures, dc current and dc voltages were measured in order to carry out performance evaluation of the PV backup system.

Place and Duration of Study: Department of electronics and electrical, Kaiboi Technical Training Institute in Nandi County, western Kenya was studied, between January 2020 and December 2020.

Methodology: Performance of any PV system depends on the operating conditions (solar radiation, ambient/module temperature, etc.) available at the site (geolocation dependent), installation (tilt and orientation) of the arrays, and finally proper system sizing (PV array, battery, BOS). In this paper, standard performance parameters reported in literature were utilized to evaluate the performance of the studied PV backup system. The array comprises of four panels interconnected in series/parallel to produce an output power rating of 780 W. A Pyranometer was mounted on the plane of array (POA) to measure solar radiation intercepted by the PV array where daily data were acquired at an interval of five minutes. I-v data were also recorded. Different literature was reviewed to identify the way to do this work.

Results: Based on the performance of the studied PV system, results obtained show that annual effective energy output is 3412.94 kWh, array efficiency range between 11.6 % to 14.1% depending on amount of solar radiation, fill-factor (FF) of 0.6, array yield of 4.88 kWh/kW, reference yield of 5.5 kWh/kW, annual average performance ratio of 76.3 % and average array capture losses of 0.52 kWh/kW.

Conclusion: It found that the PV backup system need ~5-6 hours to operate at the array's rated output power, and the low FF (<<1) indicate that it is not optimized attributed to non-optimized installation with respect to orientation and inclination and poor maintenance.

Keywords: PV module, I-V characteristics, Irradiance, performance parameters.

1. INTRODUCTION

Power shortages in Kenya are frequent and their occurrences disrupt the smooth operations of many businesses and institutions leading to financial and productivity losses or even loss of life in case of health facilities. Consequently, majority of the entrepreneurs and institutions have resorted to diesel generators as back-up systems to supply electricity whenever such outages occur. Photovoltaic (PV) is the direct conversion of sunshine into electricity through photoelectric effect, and can be an ideal substitute for the diesel backup generators because of its cleanliness and no running cost. Kenya is located in the equatorial Sunbelt of the earth, thereby receives some of the highest levels of annual radiation globally. For this reason, Kenya has the potential to generate orders of magnitude more electricity from solar PV than is consumed each year from its national grid [1]. Kenya is cited widely in literature as an African nation which has successfully achieved accelerated growth in the application of PV technologies. PV can be used in every corner of Kenya, both in urban dwellings and rural remote villages as either grid-connected or non-grid systems. PV electricity in Kenya is market driven unlike the national grid which is government controlled, and for this reason, grid-connected systems have experienced slower growth rate as compared to non-grid systems. The non-grid systems consist of 8 to 50 Wp polycrystalline or amorphous PV modules with a 12 V storage battery and are used for home lighting and radio/TV powering mainly by the rural and pre-urban populace. These systems are normally called the solar home system (SHS) and constitute the largest installed capacity in Kenya [2]. A business model, trademarked as “M-KOPA”, was launched in 2012 in Kenya, and is a successful credit financing scheme that has enabled many low-income households to acquire SHS through installment payment using mobile phones. The M-KOPA kit comes with an 8 Wp solar panel, four LED lights, a portable solar radio (and TV for upgraded system), phone charger and one portable LED torch [3].

The grid-connected systems in Kenya, on the other hand, have experienced slower growth compared to SHS despite the favorable incentives in terms of policy and institutional frame works. Kenya relies predominantly on renewable electricity generation, mainly hydro and geothermal power, and available statistics indicated that PV electricity contributes 2% of the national energy mix. At present, Kenya has installed capacity of 56.25 MW, and out of which 54.5 MW is at the Garissa mini-grid Solar Farm, which is owned by the government through its Rural Electrification and Renewable Energy Corporation (REREC) [4]. In the recent past, the government of Kenya has been expanding geothermal power mainly, with some attempt on un-utilized wind and solar energy sources. Kenya introduced feed-in-tariff (FIT) policy to promote installation of solar PV systems in 2008 and revised it in 2010 and 2012. Despite existence of this incentive, the uptake of grid-connect PV electricity in the country has been very slow, a situation that has been described as a lukewarm attitude of the country to solar. In response, Kenya in 2017, through its utility company, signed the power purchase agreements (PPAs) for four 40 MW each solar PV plants [5]. Two of them has already been tendered and awarded and are under development in Eldoret, Western Kenya, while the remaining two are still being evaluated in terms of PPA conditions and financing with the developers. The four projects will receive a tariff of $0.12/kWh (FIT, 2012) for 20 years, but this figure has been contested as overly generous.

For effective utilization and penetrability of solar PV systems, knowledge on the performance of a selected technology under outdoor conditions at the site is beneficial. This is necessary because PV systems are usually specified under controlled indoor conditions or STC, which are always different from outdoor conditions. Thus, to elucidate the actual performance of any PV technology, outdoor performance evaluations of installed PV systems have been undertaken in different parts of the world and reported in the literature. From such studies, disparities in the performance of PV systems are attributed to various factors such as balance-of-system (BOS) [6], meteorological factors [7, 8], solar irradiance [9], cell temperature [10, 11] and effects of dust [12, 13]. Bhuvaneswari, *et. al*., [14] carried out studies on performance analysis of a 15-kW standalone solar PV system installed in Vellore District, Tamil, and reported E_{Dc} ranging from 6,500–7,000 kWh, P_r of 78%, and utilization factor of 6.97%. Ezenugu, *et. al*., [15] carried out performance analysis of stand-alone PV system in a health clinic in Nigeria, and reported annual E_{Dc} of 5269 kWh/year, P_r of 58.4%, operating efficiency of 8.83%, loss of load probability of 7.1%.

This paper reports the findings on the outdoor experimental performance evaluation of an operating 780 Wp PV system installed at the roof of the social/dining hall at Kaiboi Technical Training Institute, in Western Kenya region within the tropical climate. Performance parameters evaluated included reference yield, conversion efficiency, module energy output, performance ratio and array losses. Experimental data were collected throughout the year 2020.

2. PV SYSTEM DESCRIPTION AND METHODS

2.1 Study location

An existing PV system at Kaiboi Technical Training Institute located in Nandi County, western Kenya was studied. The geographical coordinates of the site are 0.42 N (hence is almost at the equator), and 35.03 E and the elevation above sea level is 1993 m. In addition, the average daily ambient temperature varies between 18 ^{o}C to 22 ^{o}C, and the average rainfall range from 1200 mm to 2000 mm per annum.

2.2 Experimental setup

Fig. 1 shows the picture of the solar PV system studied. The system is installed at the roof of the institution's social/dining hall and an air gap of ~18 cm left between rear of the arrays and top of corrugated iron sheet roof to provided natural air convective cooling. The array comprises of four panels interconnected in series/parallel to produce an output power rating of 780 W. Two modules are connected in series and the resulting two series pairs are in turn are connected in parallel, giving array output bus voltage of 24 V. The arrays orientation is in the NE-SW direction. Specifications of the PV modules from the manufacturer are summarized in Table 1.

Figure 1: Photograph of the installed PV Array on the institution's social/ dining hall roof.

Table 1: Technical specification of PV modules

Parameter	Value	Parameter	Value
A	12790 cm^2	I_{sc}	5.90 A
V_{oc}	21.9 V	$NOCT$	45±2 ^{o}C
P_o	195 W	η_{ref}	15.6%
I_{mp}	5.56 A	β	0.0041 K^{-1}

The BOS components are four 12-V lead oxide batteries with power rating of 200 Ah and one inverter. Two batteries are connected in series and the resulting two series pairs are in turn connected in parallel to produce a bus voltage of 24 V to match that produced by the PV array. The inverter is connected as an interface between the PV generator and ac loads. The inverter specifications are 96% efficiency, 13 A maximum output current, 230±5% V ac voltage and 50 Hz line frequency (i.e., the frequency of ac grid in Kenya). In addition, the inverter has an automatic grid-solar switch over control and also an inbuilt battery charge controller.

A Pyranometer was mounted on the plane of array (POA) to measure solar radiation intercepted by the PV array where daily data were acquired at an interval of five minutes. The output dc voltage and current of the PV array were measured and recorded by an internal data acquisition and storage card integrated in the inverter system.

2.3 Performance parameters

Efficiencies of PV modules and other components of PV systems have increased continuously over the past decades, and hence system performance has improved considerably. The PV array performance in this study is reported using conversion efficiency, field factor (FF), yield ratios and performance ratio as discussed below.

2.3.1 <u>Array Efficiency</u>

PV array efficiency was evaluated using the usual equation [16]:

$$\eta_{array} = \frac{P_{max}}{A \times G_t} \times 100\% \qquad (1)$$

The array area, *A* and plane of array (POA) irradiance, G_t in equation (1) were measured. The P_{max} was calculated from the measured values of V_{max} and I_{max} at the MPP as:

$$P_{max} = V_{max} \times I_{max} \qquad (2)$$

2.3.2 <u>Fill Factor</u>

Fill factor (FF) gives an idea of the quality of the array, and the closer it to unity (1), the more power the array can provide. Typical values are between 0.7 and 0.8. The FF is defined as [16]:

$$FF = \frac{V_{max} \times I_{max}}{V_{oc} \times I_{sc}} \qquad (3)$$

2.3.3 <u>Yield Ratios</u>

Two DC yield ratios were selected to evaluate the PV power system performance. The yields indicate the amount of time during which the array would be required to operate at the array's rated output power, P_o to provide a particular quantity. These ratios are array energy yield Y_A and the reference yield Y_r and are defined by IEC 61724 standard by the following equations [6, 16, 17]:

$$Y_A = \frac{E_{dc}}{P_o} \qquad (4)$$

$$Y_r = \frac{G_t}{G_o} \qquad (5)$$

These ratios are usually determined for a period of one year. In addition, the difference between these ratios gives, i.e.

$$L_A = Y_r - Y_A \quad (6)$$

The E_{dc} is determined as [9]:

$$E_{dc} = \sum_{i=1}^{n} \frac{1}{6000} G_t A \eta_{array} \quad (7)$$

where *n* is the number of days in one month.

2.3.4 Performance Ratio

Performance ratio (also known as quality factor) is usually used as a proxy for PV system performance, and gives a measure for the degree of utilization of an entire PV system [14]. It indicates the overall effect of losses on the overall performance of the PV system, and includes effects of PV array temperature, incomplete utilization of irradiation, system component limited efficiencies, and failures. It is defined in the standard IEC 61724 as the ratio of final PV system yield (Y_F) to reference yield (Y_r) and denoted P_r:

$$Pr = \frac{Y_F}{Y_r} \quad (8)$$

Performance ratio (P_r) (also called quality factor) is a loss factor incurred in converting PV DC output power to AC power [18]. The P_r of a PV system is the ratio of actual yield to the reference yield [6].

3. RESULTS AND DISCUSSION

Figure 2 shows the monthly averages of ambient temperature and solar irradiance on the plane of array. Highest monthly average solar insolation occurs in the months of February, March and September with respective values of 650.08 W/m^2, 609.04 W/m^2 and 597.61 W/m^2. The lowest average monthly insolation was observed in the month of June with 480.52 W/m^2. Furthermore, the measured maximum and minimum average monthly ambient temperatures are 19.0 ^{0}C and 16.3 ^{0}C recorded in the months of March and August respectively. Over 12 months, the yearly average values of the ambient temperature and the solar irradiance are 17.9 ^{0}C and 551.63 W/m^2 respectively.

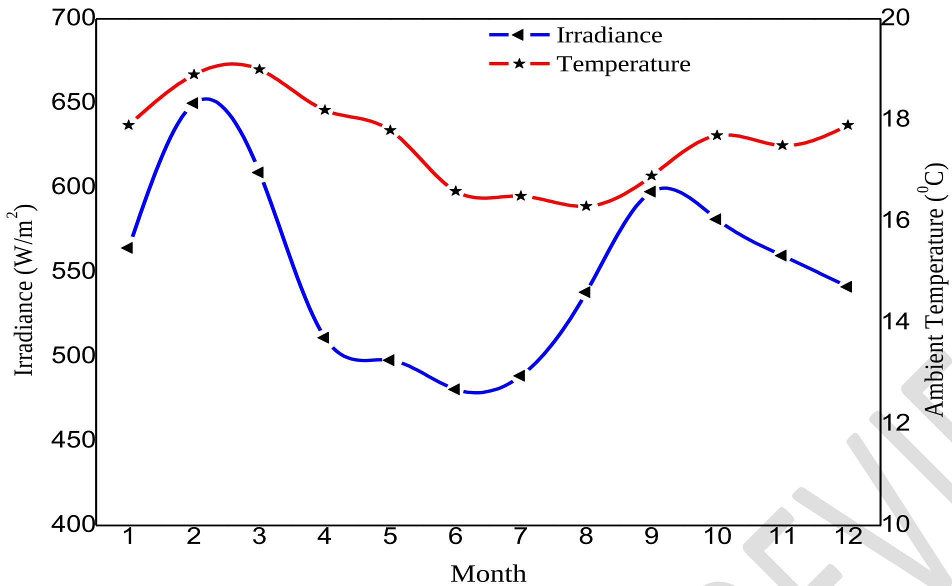

Figure 2. Monthly average solar irradiance and ambient temperature at the site.

Figure 3 shows representative raw (5-minute intervals) results for two days of the measured solar insolation at the site on a typical clear sky condition (good day) on 22nd February, 2020 and overcast day weather condition (bad day) on 14th June, 2020. It can be observed that the peak solar radiation is attained at around midday and can be as high as 1200 W/m^2 on a good day and 793 W/m^2 on a bad day.

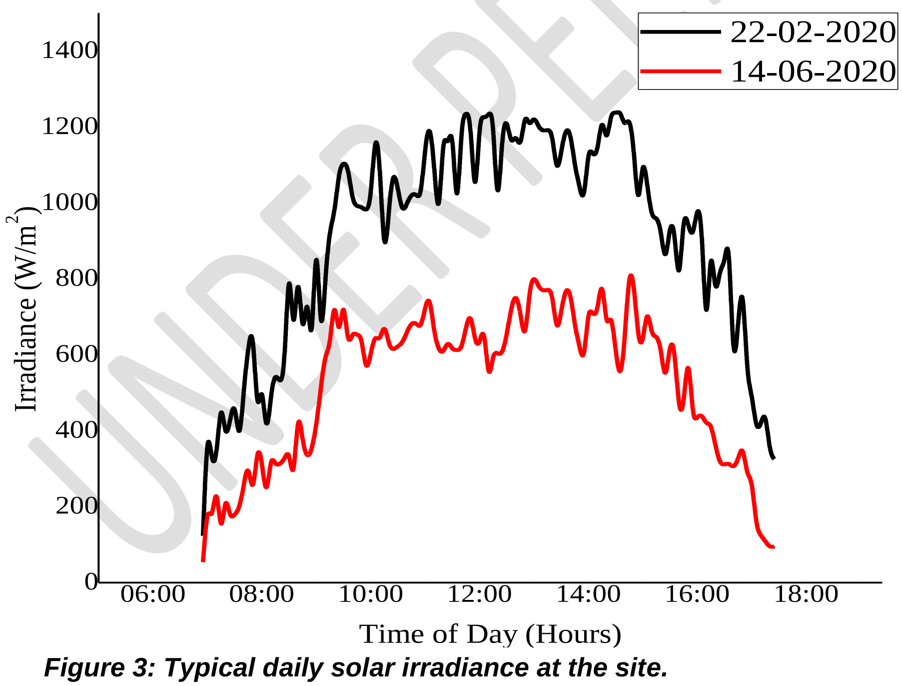

Figure 3: Typical daily solar irradiance at the site.

Figure 4 shows typical representative *I-V* characteristic curve for two selected representative days - 19th March, 2020 (good day) and 26th May, 2020 (bad day).

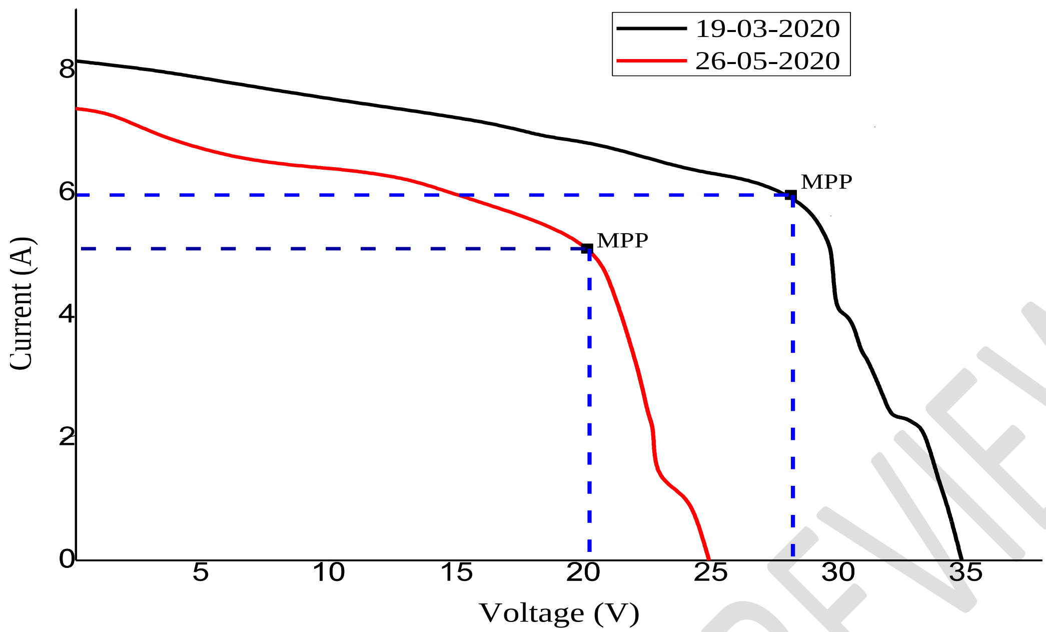

Figure 4: Typical I-V characteristic of the PV backup system.

From the I-V curves in Figure 4, I_{max} and V_{max} are 5.82 A and 28.05 V for good day and 5.07 A and 20.16 V for the bad day. Module efficiency for the two days were evaluated by combining equations (1) and (2) as follows:

$$\eta_{array} = \frac{V_{max}\times I_{max}}{A\times G_t}\times 100\% = \frac{5.82\ A\times 28.05\ V}{1.28\times 1095}\times 100\% = 11.6\% \qquad \text{(Good day)} \qquad (9)$$

And

$$\eta_{array} = \frac{V_{max}\times I_{max}}{A\times G_t}\times 100\% = \frac{5.07\ A\times 20.16\ V}{1.28\times 606}\times 100\% = 13.1\% \qquad \text{(Bad day)} \qquad (10)$$

The efficiency of the PV power backup system obtained at 606 W/m^2 (bad day) is high compared to that obtained at 1095 W/m^2 (good day). These observations are attributed to the high and low temperatures of the modules during the good day and bad day respectively. This behavior of efficiency with irradiance was observed in the work done by [19].

The field factors for the two days were calculated using equation (3) as:

$$FF = \frac{V_{max}\times I_{max}}{V_{oc}\times I_{sc}} = \frac{5.82\times 28.5}{8\times 35} = 0.58 \qquad \text{(good day)} \qquad (11)$$

And

$$FF = \frac{V_{max}\times I_{max}}{V_{oc}\times I_{sc}} = \frac{20.162\times 5.07}{25\times 7.2} = 0.57 \qquad \text{(bad day)} \qquad (12)$$

Thus, the FF of the studied system is 0.6 (<< 1), and since it is below the typical values specified in literature, then the installed PV power backup systems is not operating optimally. Possible reason is non-optimized installation of the PV array with respect to tilt angle and orientation, hence POA irradiance is lower than what is possible at the site.

The monthly E_{DC}, $Y_{r,}$ Y_A, L_A and P_r over the monitored period are shown in Table 2. The effective energy output varied from 244.63 kWh to 320.42 kWh and are recorded in the months of June and February respectively. The yearly average energy output is 284.41 kWh. The array yield varied from a minimum value of 4.43 kWh/kW in April to a maximum value of 5.46 kWh/kW in February. Monthly array losses were relatively higher in months of January to April and October to December compared to other months. The yearly average array losses were 0.52 kWh/kW. These results further show that monthly daily average reference yield highest and lowest values of 6.5 kWh/kW and 4.8 kWh/kW were realized in the months of February and June, respectively. The energy available at the site given by yearly average monthly reference yield is 5.5 kWh/kW which agrees well with previous studies that gave the average value across the country [20, 21]. It can further be seen that performance ratio ranges from 72 % to 80.5 % with average annual P_r of 76.3 % which means that 23.7 % of insolation were not converted into useful energy in other words the system is not operating optimally.

Table 2: ***Monthly average reference yield, Performance ratio Effective energy output, Array yield and capture losses***

Month	E_{DC} (kWh)	Y_r (kWh/kW)	Y_A (kWh/kW)	L_A (kWh/kW)	P_r (%)
Jan	244.64	5.64	4.8	0.81	0.769
Feb	308.91	6.5	5.46	1.04	0.805
Mar	320.41	6.09	5.10	0.99	0.796
Apr	260.25	5.11	4.43	0.68	0.728
May	261.87	4.97	4.76	0.21	0.730
Jun	296.86	4.80	4.78	0.12	0.745
Jul	257.04	4.88	4.72	0.16	0.730
Aug	283.12	5.38	5.20	0.18	0.720
Sep	304.25	5.97	5.40	0.57	0.798
Oct	305.81	5.81	4.09	0.62	0776
Nov	284.98	5.59	5.00	0.59	0.784
Dec	284.76	5.41	4.92	0.47	0.779

4. CONCLUSION

Site performance characterization of a 780 W_P off-grid PV power backup system within tropical climate was presented based on measured data for one year (2020). Results show that the highest monthly average solar irradiation was 650.08 W/m^2 in February and lowest of 480.52 W/m^2 in June. However, on typical sunny days, solar irradiance at the site can be as high as 1200 Wm^{-1}, with about 5-6 SPH (solar peak hours), and average of ambient temperature 17.9 ^oC. The PV backup system typical two-day representative I-V characteristic gave array efficiencies of 13.1 % and 11.63 % on a bad day and good day respectively. Calculated FF is 0.6 and since it is << 1, then installed PV power backup systems is not operating optimally. The yearly average effective energy output of the PV system was 3412.94 kWh with the month of February giving the highest value of 320.42 kWh and the month of June producing the lowest value of 244.63 kWh. The yearly average array yield was 4.88 kWh/kW with values ranging from 4.43 kWh/kW to 5.46 kWh/kW whereas the array losses varied from 0.12 kWh/kW to 1.04 kWh/kW. The average yearly reference yield was 5.5 kWh/kW and P_r varied between 72.0 % and 80.5%. These results show that the PV backup system performance is adequate with regard to yield and performance ratios. However, the low value of FF can be attributed to non-optimized installation with respect to orientation and inclination.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Definition for the term

I_{mp}	Nominal current (A)	P_r	Performance ratio (%)
V_{oc}	Open circuit voltage (V)	V_{max}	Maximum voltage (V)
I_{SC}	Short-Circuit Current (A)	E_{Dc}	DC output energy (kWh)
η_{ref}	Reference Module efficiency (%)	Y_A	Array yield (kWh/kW)
A	Module area (m^2)	Y_r	Reference yield (kWh/kW)
G_t	Measured solar irradiance (W/m^2)	Y_f	Final yield (kWh/kW)
P_o	Module rated power (W)	η_{mod}	Module efficiency (%)
β	Cell temperature parameter (K^{-1})	L_A	Array capture loss (kWh/kW)
P_{max}	Maximum power (W)	I_{max}	Maximum current (A)
FF	Fill Factor		