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Design and performance evaluation of a solar PV system at Karume Institute of Science and Technology for grid power outage mitigation

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Abstract

Karume Institute of Technology (KIST) in Zanzibar has been faced with electricity blackouts for a prolonged period. This has been due to its sole reliance on main grid power. This problem can be solved by utilizing renewable energies available in Zanzibar Island, such as solar photovoltaic (PV). Therefore, a solar PV plant rated at 25.21 kWp is installed at KIST in 2021 to act as the main source of power. With this technology, the grid is used as a backup when there is little sunlight or during the nights. The solar PV system performance is measured by several tools to collect the data of solar array yield, final yield, reference yield, performance ratio, inverter efficiency and average capacity. The results show that maximum array yield is about 10.2 kWh/kWp, final yield is 8.195 kWh/kWp, reference yield is 5.2 kWh/kWp, and performance ratio is 64.7%. The maximum efficiencies for the PV, inverter and system are shown to be 37.6%, 89.8% and 63.1% respectively. The average capacity was observed to be around 22.45%, the load demand for the building is about 18 kW/day and the annual average energy generated by the PV system is 395.5 kWh of the installed capacity energy.

1.0 Introduction

Tanzania suffers from severe power shortages due to low production, poor infrastructure (for example in Zanzibar Islands [1], [2]), dependence on hydroelectricity [3], and many others. The country has about 61.74 million people, out of which, 1.89 million live in the Zanzibar Islands [4]. These people, the public and private organizations are affected by the mentioned power outages. As a result, several areas of life are affected, such as the Karume Institute of Science and Technology (KIST). KIST is located in Zanzibar, and had suffered severe voltage fluctuations and power outage, when only the grid was connected. However, there are possible solutions to reduce the power outage problems, not depending on the national grid. This is the possibility to harness available renewable energies. Renewable energy sources are regarded as alternative energy sources [5] because they cause little environmental pollution [6], contribute little to global warming effects, and have minimal impact on ozone layer depletion associated with the greenhouse effect. Further, these sources have the potential to increase electrification rates in both rural [7]–[13] and urban [14]–[16] locales. One source of renewable energies is the solar photovoltaic (PV) plants. The solar PV systems can be connected to grid or off-grid connected. The grid connected solar plant has a potential to generate electricity, and sell the surplus electricity to the grid. This way, the solar plant if installed on a building can lead to a 'carbon neutral' building. The use of solar PV on buildings can clean the air, stave off global warming, and help eliminate dependence on fossil fuels for electricity generation. Further, these on-site solar PV plants eliminate the problems of voltage fluctuations caused by long transmission lines [17].

Modern solar panels are smaller, more durable, and more efficient than in the past. Their performance is especially improving under low-light conditions. Additionally, product quality is on the rise, driven by consumer demand for higher standards and longer warranties. With all these advancements combined, it's no surprise that solar energy is progressing so rapidly [10, 14]. For many applications, the improvement of the efficiency of the system from impacts of incident solar radiation levels, is achieved by observing the angle of the sun sunlight reaching a panel throughout the day. Some changes in the sun's position, cloud cover, and other atmospheric conditions and tilt and azimuth (orientation) helps in raising this efficiency [19], so that people see solar is used to effectively generate electricity and power up civilizations [18]–[22]. The voltage and current of a solar PV panel are caused by the light falling on the solar panel (this light energy is called insolation). However, excessive insolation can lead to saturation, ultimately reducing power output due to increased electron mobility and a rise in the temperature at the solar cell junctions [23]–[25]. The solar PV are plagued by low efficiencies due to nonlinear variations of output voltage and current with insolation levels, temperature, and output current [26]. Further, to effectively harness the insolation the solar panels need to track the sun such that they receive maximum irradiance [19, 23]. This implies that effectively connecting to and harnessing solar energy requires a thorough understanding of solar resource availability at a specific location [27]–[29]. A typical solar PV system consists of the following components:

(a) Solar PV panels, arranged in series and/or parallel configurations to directly generate DC power from the sun's captured solar irradiance.

(b) DC to AC inverter, used for power conditioning.

(c) System safety components such as DC to AC breakers and fuses, installed in compliance with the standards and regulatory requirements.

As mentioned earlier, the KIST suffers from power outages. As a result, a solar PV plant is designed and operated to supply the needed power. For backup, the national grid is there to supply power during the days of low solar insolation. The following discussions explains the KIST solar PV plant in details. Figs. 1 – 2 have shown that the installed solar PV system at KIST is delivering power as was specified. In Fig. 3, the I-V characteristics of the solar PV at KIST is displayed. Since, its installation, there have been some minor maintenance like cleaning the solar panels and no reported failure. So far, the system is used as the main source of power and the grid is used in days of little sunlight and night times. All the connected loads are supplied, thus creating a value to the users.

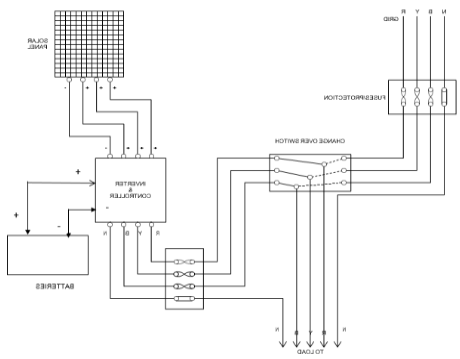


Fig. 1. KIST solar PV system connection diagram.

Fig. 2. Picture showing KIST solar PV system.

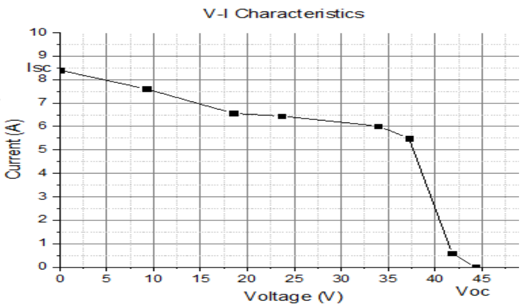


Fig. 3. The I-V characteristics of the solar PV at KIST.

2.0 Materials and Methods

In this study, the work was conducted on the KIST solar PV plant. All the experimental data collection and analysis is done there.

Site Location and System Specific Information

KIST, located on Zanzibar Island in Tanzania, sits at latitude -6.16 (6°09'36" S), longitude 39.2 (39°12'00" E), and an elevation of 0 meters above the Indian Ocean, approximately 72 km from the coastline. Site- specific meteorology data was collected hourly using data logger at Administration Building and the descriptions of the processes are shown in Table 1. This area has global irradiation of 4.51 kWh/m^2 per day which makes it suitable for solar PV plant installation. These data were simulated on PVsyst software version 7.4 and results simulated were used to compute performance ratio, energy and power produced by solar PV, array temperature, daily input/output energy used, daily array output energy and array power distribution of the installed system.

Table 1. KIST meteorology recorded data.

Description	Daily values
Wind resistance	2,400 Pa
Total solar global radiation	4.51 kWh/m²
Specific panel energy	3.41 kWh/kWp
Nominal output	25.21 kWp
Capacity factor	18.476%
Production per year	40,803 kWh/year
Mean output per day	111.79 kWh/day
Mean output power	4.658

1.2. Technical Data of the Solar PV System

Solar panels are rated based on their performance under Standard Test Conditions (STCs). Table 2 presents the technical specifications of the existing KIST solar PV panels examined in this study.

1.3. KIST Solar PV Connections and Operations

The KIST solar PV system is made up of solar panels with characteristics captured in Table 3.

Table 2. Technical details of the KIST solar PV system.

Item	Characteristics
Power	25.21 kWp
Coverage	176.94 m^2
Tracking system	None
Tilt of the panels	30°
Orientation/azimuth	0°
Type of installation	Rooftop installation, small separation distance less than 10 cm
System start-up {date of starting to operate as standalone}	15/08/2021
Series modules	15
Parallel modules	2
Number of phases	3
Number of modules	90
Type of module	Hanwa SF260 Poly (280 W)
Type of inverter	SMA SMC 8000TL
Number of inverters and rating	3 each 8 kW
Batteries	24 series connected, each 2 V, 1600 Ah, autonomy 13 hours,

Table 3. KIST solar PV modules and their characteristics

Quantity [Unit]	Values	
	STC	NOCT
Maximum rated power (P_{max}) [Wp]	280	204
Voltage at open circuit (V_{OC}) [V]	44.3	40.8
Short circuit current (I_{SC}) [A]	8.45	6.84
Maximum power rated voltage (V_{MP}) [V]	36.2	32.9
Maximum power rated current (I_{MP}) [A]	7.87	6.21
Module efficiency (η) [%]	14.3	
Module weight [kg]	11.6	

Module dimensions [length × width × thickness]	1,483 mm × 668 mm × 35 mm
Maximum system voltage (V_{max}) [V]	1,000
Nominal operating cell temperature (NOCT)	46±2 ºC

1.4. Data Collection and Tools

The data from the KIST solar PV system were collected using power conditioning devices (Model: SMA SMC 8000TL) at 60-minute intervals, from 1:00 AM to midnight. The connection diagrams of the systems are shown in Fig. 1. The Fig. 2 shows the pictures of the actual connected systems in operation.

1.5. Performance Parameters Definitions and Meanings

In a PV system, performance is typically assessed using factors such as energy or power output, reference yield, array yield, final yield, system energy losses, system and inverter efficiencies, performance ratio, and capacity factor [30], [31]. These are calculated using Eqs. (1) – (13). Energy output (E_{AC}) is defined as the amount of alternating current (AC) power generated by the system over a given period of time. The total hourly (E_{AC-h}), daily (E_{AC-d}) and monthly (E_{AC-h}) energy produced can be determined respectively as Eqs. (1) – (3). The energy generated at time t [minutes] is denoted by E_{AC-t}, at hour h is denoted by h, at day d by E_{AC-d}, at month m by E_{AC-m}. For these computations, the total days in a particular month is denoted by N .

$$E_{AC-h} = \sum_{t=1}^{60} E_{AC-t} \tag{1}$$

$$E_{AC-d} = \sum_{h=1}^{24} E_{AC-h} \tag{2}$$

$$E_{AC-m} = \sum_{d=1}^{N} E_{AC-d} \tag{3}$$

The array yield (Y_a) is defined as the ratio of the power output from the solar PV system (P_{DC}) to its rated power ($P_{PV\text{-}rated}$), as expressed in Eq. (4). Final yield (Y_{Fd}) is calculated by dividing the net energy output by the nameplate DC power of the installed solar PV array. It indicates the number of hours the PV array would need to run at its rated power to generate an equivalent amount of energy measured in hours or kWh/kW. It is defined as the ratio of the net daily, monthly, or annual AC power output (P_{AC}) delivered by the system to the rated power of the installed solar PV array, as calculated in Eq. (5).

$$Y_a = \frac{P_{DC}}{P_{PV-rated}} \times 100\% \tag{4}$$

$$Y_{Fd} = \frac{P_{AC}}{P_{PV-rated}} \times 100\% \tag{5}$$

Reference yield (Y_r) is calculated by dividing the total in-plane irradiance (H_t) by the PV reference irradiance (G_0). It represents the number of hours during which the energy could be generated under ideal solar irradiance conditions. If G_0 is equal to 1 kW/m², then Y_r represents the number of peak sun hours. It is influenced by the location, the orientation of the PV array, and weather variability across months and years. [32], [33]. The PV module efficiency (η_{PV}) is captured by Eq. (7), where V_{mpp} and I_{mpp} are the voltage and current at maximum power point, respectively. The solar panel area is represented by S . The I-V characteristics of the KIST solar PV panels are captured by Fig. 3. This figure displays the Vmpp V_{mpp} and I_{mpp} respectively as 36.2 V and 7.87 A.

$$Y_r = \frac{H_t}{G_0} \tag{6}$$

$$\eta_{PV} = \frac{V_{mpp} I_{mpp}}{S G_{avg}} \tag{7}$$

The operating temperature (T) affects the solar cell's efficiency. This effect is demonstrated by Eq. (8), where reference efficiency is η_{ref}, temperature coefficient is β_{ref}, and the reference temperature is T_{ref} .

$$\eta_{PV} = \eta_{ref}\left(1 - \beta_{ref}\left(T - T_{ref}\right)\right) \tag{8}$$

The nominal operating cell temperature (*NOCT*) of the module, as specified by the manufacturer, is attained under standard conditions with an irradiance of 800 W/m² and an ambient temperature of 25°C (T_{amb}). Then, the operating temperature is computed by Eq. (9).

$$T = T_{amb} + \left(\frac{NOCT - 25}{800}\right) G_0 \qquad (9)$$

Inverter efficiency (η_{inv}) can range from slightly above 50% at very low power levels to over 90% when operating near its rated output [34]. There are several methods to compute this efficiency and are better explained by Mertens [35]. This efficiency indicates the proportion of DC power from the solar PV that is converted and delivered to the AC side (see Eq. 10).

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \times 100\% \qquad (10)$$

Solar cell efficiency refers to the fraction of sunlight energy that a photovoltaic cell can convert into electrical energy. Therefore, the solar PV system efficiency combines effect of factors such as the type of solar cells, latitude of the site, climatic conditions, and the size of the solar panels. Then this paper [36] proposed that solar PV system efficiency can be computed by Eq. (11).

$$\eta_{sys} = \frac{P_{AC}}{SG_0} \times 100\% \qquad (11)$$

The performance ratio (*PR*), is defined in IEC 61724 [37], [38], is a widely used metric for evaluating the performance of solar PV plants during acceptance testing and operation. This parameter (see Eq. 12) quantifies the plant's efficiency in converting sunlight into AC energy, accounting for losses from system components, cell mismatch, wiring, high temperatures, surface soiling, downtime, shading [39]; and failures of component [40]. Total operating hours is represented by h_{OP}.

$$PR = \frac{E_{AC}}{h_{OP} P_{DC}} \qquad (12)$$

The capacity factor (*CF*) of a renewable energy generator indicates how effectively the solar PV plant operates relative to its nameplate power rating. This is succinctly captured by Eq. 13 [41]. The total time in one year is represented by h_{OP-Y} which is equal to 8760 hours. This is followed by how much losses (L_{Tot}) have occurred within the system shown by Eq. (14), which denotes the difference between the reference yield and the final yield of the solar PV system.

$$CF = \frac{E_{AC}}{h_{OP-Y} P_{PV-rated}} \times 100\% = \frac{E_{AC}}{8760 P_{PV-rated}} \times 100\% \qquad (13)$$

$$L_{Tot} = Y_r - Y_{Fd} \qquad (14)$$

3.0 Results and Discussions

The array yield, final yield, reference yield, and performance ratio were analyzed, showing ranges of 3.00 to 3.94; 2.83 to 4.41; 4.76 to 6.00; and 0.49 to 0.775 respectively. The average values were found to be 3.53 kWh/kWp for array yield, 3.57 kWh/kWp for final yield, 5.52 kWh/kWp for reference yield and 0.647 (64.7%) for performance ratio. The detailed results are shown in Figs. 4 - 5. The system is performing as per specifications for the installed site at KIST.

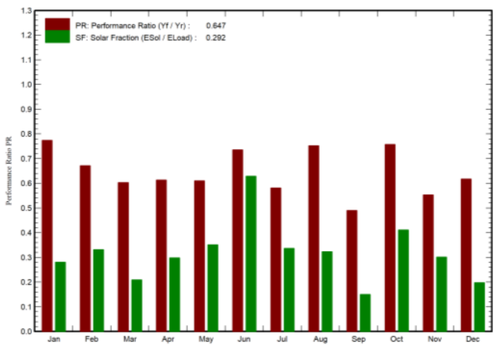
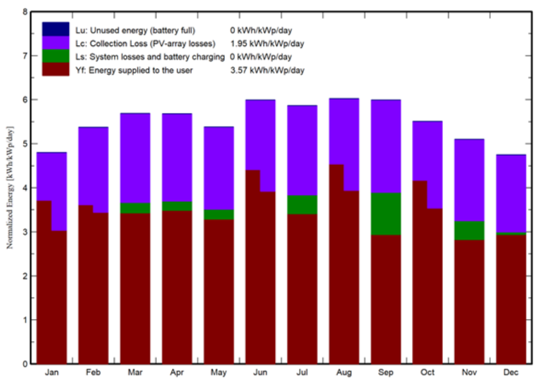
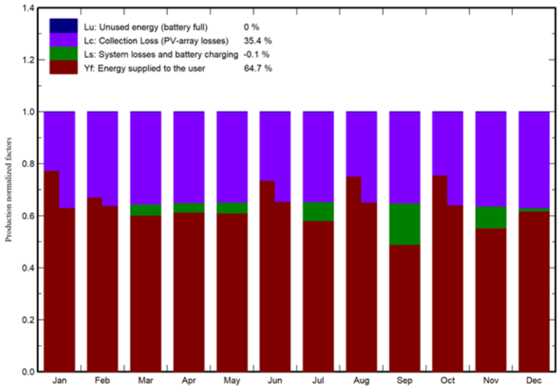


Fig. 4. Performance ratio and solar fraction vs months.



(a)



(b)

Fig. 5. (a) Normalized energy production (per installed kWp) vs months (b) Normalized production and loss factor vs months.

The solar PV array loss, energy supplied to the user, collection loss (system losses) and battery charging were investigated and found to be 1.95 kWh/kW/day (35.4%), 3.57 kWh/kW/day (64.7%) -0.1% respectively. The energy produced per day and ambient temperature of the system were found to be from 10 kWh/day to 160 kWh/day and from 25.3 °C to 28.58 °C for solar PV system. The detailed results are represented in Figs. 6 - 7. They detail a system capable of utilizing the available and plentiful insolation for immediate use and storage for later use.

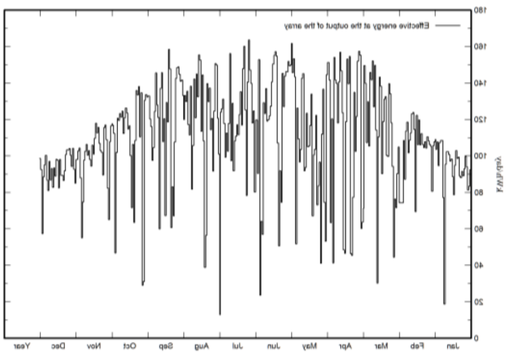


Fig. 6. Daily array output energy vs months

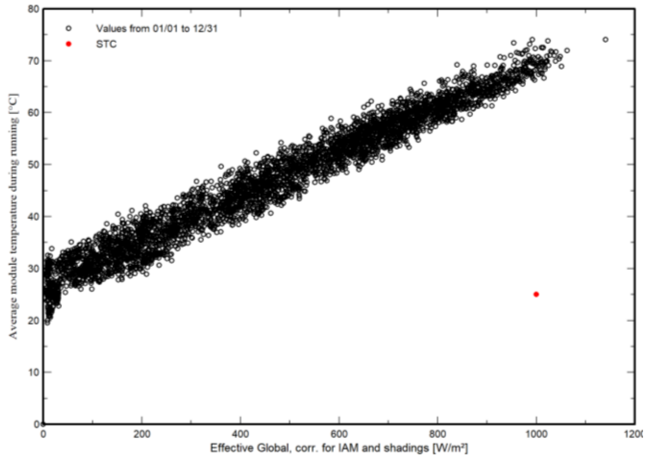


Fig. 7. Array temperature vs Effective irradiation

The reference incident energy or the amount of solar energy striking a surface indicates that panels are typically tilted to optimize sunlight capture throughout various times of the day and across different seasons. The average values were found to be 5.516 kW/m^2/day for energy produced from inverter output as shown in Fig. 8. These shows the capacity of the designed system to serve the load at KIST during outages, and also to supply few selected loads to reduce the bills from the grid.

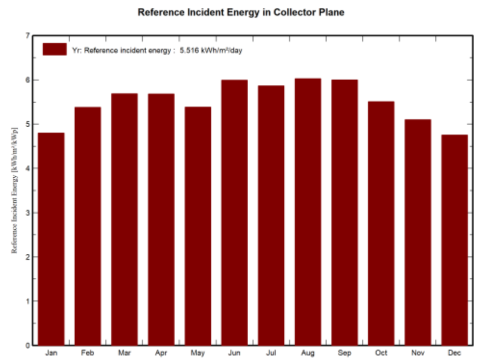


Fig. 8. Reference incident energy vs month

5.0 Conclusions

This paper presents the installed solar PV plant at KIST that was used to solve the problem of power outages from the grid, voltage fluctuations, and increase power availability. The system has shown that average array yield is about 8.72 kWh/kWp, final yield is 5.823 kWh/kWp, reference yield is 4.63 kWh/kWp and performance ratio is 16.7. The maximum efficiencies for the PV, inverter and system are shown to be 34.9%, 66.8% and 39.2% respectively. The average capacity was observed to be around 15.95%. The annual average energy generated by the system is 395.5 kWh of the installed capacity, however it decreases due to insufficient sunlight in some months. The financial implication of this KIST solar PV is not included in this study, and could potentially form an excellent future study.

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Declaration of conflict of interest

The authors have jointly contributed to the conceptualization, design, and execution of this study. They collaborated on drafting the manuscript and critically revising it to ensure the inclusion of substantial intellectual content. This manuscript has not been submitted to, nor reviewed by, any other journal or publishing platform. Furthermore, the authors declare no affiliations with any organizations that hold direct or indirect financial interests in the subject matter addressed in this work.

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