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# Performance and reliability analysis of an off-grid PV mini-grid system in rural tropical Africa: A case study in southern Ethiopia

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## ABSTRACT

Although some progress has been made in recent years, ensuring universal access to electricity remains a major challenge in many countries in sub-Saharan Africa, particularly in rural areas. In light of this challenge, solar photovoltaic (PV) mini-grid systems have emerged as a promising solution for off-grid electrification. However, little is known about their actual performance and reliability when used in real-world applications. Using real-time monitored data and IEC's evaluation standard, this paper examines the performance and reliability of a 375 kWp off-grid PV mini-grid system installed in a remote small town in Ethiopia. The findings showed that the mini-grid produced 1182 kWh/day of electricity compared to the estimated generation of 2214 kWh/day, a difference of 1032 kWh/day (46.6% less). In contrast, 87% of the average daily electricity generated was delivered to the load. The discrepancies can be attributed to average PV capture losses of 2.75 kWh/kWp/day and system losses of 0.40 kWh/kWp/day. The performance evaluation results revealed that the mini-grid system is performing poorly, with average on-site module efficiency ( $\eta_{pc}$ ), temperature corrected performance ratio ( $PR_{corr}$ ), capacity factor (CF) and overall system efficiency ( $\eta_{sys}$ ) of 9.85%, 42%, 13%, and 8.76%, respectively. It was found that the daily PV energy output could not meet the daily demand. As a result, the load is shed off from the power supply for 13 h a day; between 17:00 and 19:00 and again between 21:00 and 08:00. The study demonstrated that accurate demand assessment and robust system sizing, taking into account the impact of local weather conditions and prospective electricity demand growth is critical to ensure high performance and reliability of off-grid PV mini-grid systems.

## 1. Introduction

“Ensuring access to affordable, reliable, sustainable and modern energy for all” is at the heart of the United Nations Sustainable Development Goals (SDG 7) (IEA, 2020). However, providing access to electricity remains a major challenge in many sub-Saharan African (SSA) countries, particularly in rural areas. While some progress has been made in recent years, more than 500 million people in SSA still live without basic access to electricity, most of them in rural areas (IEA, 2020). The difficulty arises, in part, from the fact that extending national grids to remote and isolated villages requires huge investment owing to their geographic location and the high cost of transmission lines and sub-stations (Wassie and Adaramola, 2021). Against this backdrop, decentralized renewable energy systems such as solar photovoltaic (PV) mini-grids and micro hydropower plants have emerged as viable alternative solutions to provide electricity in off-grid areas (Vezzoli et al., 2018). With the rapid fall in the price of solar panels in recent years, a

growing body of evidence suggests that stand-alone PV mini-grid systems with batteries are cost-effective options to deliver affordable and reliable electricity to remote off-grid communities in many developing countries (Moner-Girona et al., 2018), (Come-Zebra et al., 2021). These systems work independent of the main grid, and deliver electricity near the point of use. In this regard, successful experiences of rural electrification using off-grid PV mini-grid systems have been documented, for example, in India, Kenya, Tanzania, Nepal, and Namibia (Come-Zebra et al., 2021), (Pedersen et al., 2021). Other studies, however, have found that many PV mini-grid systems installed in developing countries are either underperforming; have reliability issues; have failed or have been abandoned prematurely (Azimoh et al., 2016), (Hartvigsson et al., 2018), (Katre et al., 2019), (Numminen and Lund, 2019).

In light of this, substantial research has been conducted to evaluate the performance of PV power systems. For example, the German Development Agency (GIZ) assessed the performance of two off-grid PV mini-grid systems in rural Indonesia. The study found that the performance ratio (the ratio of the annual measured energy output to the

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**Abbreviations**

<i>A</i>	PV array effective area (m <sup>2</sup> )
<i>AC</i>	Alternating current
<i>CF</i>	Capacity factor (%)
<i>DC</i>	Direct current
<i>DOD</i>	Depth of discharge
<i>E<sub>DC</sub></i>	DC energy output (kWh)
<i>E<sub>AC</sub></i>	AC energy output (kWh)
<i>E<sub>AC Load</sub></i>	Energy consumed by the load (kWh)
<i>EEU</i>	Ethiopian Electric Utility (electricity provider)
<i>ESMAP</i>	Energy Sector Management Assistance Program of the World Bank
<i>G<sub>STC</sub></i>	Irradiance at standard test conditions (1,000 W/m <sup>2</sup> )
<i>G<sub>total</sub></i>	Total solar irradiance incident on the tilted PV array (kWh/m <sup>2</sup> )
<i>IEC</i>	International Electrotechnical Commission
<i>L<sub>C</sub></i>	Capture losses
<i>L<sub>S</sub></i>	System losses
<i>MG</i>	Mini-grid

<i>MMEMS</i>	Mini-grid Monitoring and Energy Management System
<i>MPPT</i>	Maximum power point tracker
<i>P<sub>nom</sub></i>	Rated power/nominal capacity of the PV array (kWp)
<i>PR</i>	Performance Ratio (%)
<i>PR<sub>corr</sub></i>	Temperature-corrected Performance Ratio (%)
<i>PV</i>	Photovoltaic
<i>SAIDI</i>	System's Average Power Interruption Duration Index
<i>SOC</i>	State of charge
<i>SSA</i>	Sub-Saharan Africa
<i>STC</i>	Standard Test Conditions (25 °C, 1 kW/m <sup>2</sup> ; A.M. = 1.5)
<i>UEAP</i>	Universal Electricity Access Program
<i>U<sub>i</sub></i>	Total power interruption time per day (hours)
<i>Y<sub>A</sub></i>	Array yield (kWh/kW <sub>p</sub> )
<i>Y<sub>F</sub></i>	Final yield (kWh/kW <sub>p</sub> )
<i>Y<sub>R</sub></i>	Reference yield (kWh/kW <sub>p</sub> )
<i>η<sub>pc</sub></i>	Power conversion efficiency of PV modules under real working conditions (%)
<i>η<sub>STC</sub></i>	Module efficiency under STC (%)
<i>η<sub>sys</sub></i>	Overall system efficiency (%)

estimated output based on the system name-plate rating) was below 30% due to the high energy losses in the energy capture and conversion process (GIZ, 2017). Sharma and Chandel (2013) investigated the performance of a 190 kWp grid-tied PV plant in northern India; and found that the plant produced 98.8% of the estimated annual energy yield. The authors reported the annual mean performance ratio and overall system efficiency of the plant to be 74% and 8.3%, respectively. Costa and Villalva (2020) studied the performance of a PV-diesel hybrid mini-grid system for the Tapajós-Arapiuns extractive reserve in Brazil, and showed that with a 'load-following' dispatch strategy, 85.6% of the energy demand can be met by the PV system and 14.4% by the diesel generator (DG). Using an estimated annual electricity demand of 63,875 kWh, Akinyele and Rayudu (2016) assessed the performance of different-sized PV micro-grids for a small village in Nigeria. They found that PV micro-grids with a capacity of 55–82.5 kWp can deliver sufficient power to the communities. Similarly, Banguero et al. (2019) evaluated the performance of a 20 kWp off-grid PV micro-grid in Chocó, Colombia, and discovered that the micro-grid's overall efficiency ranged from 10.3% to 11.09%.

These studies, along with many others, provide insight into the performance of PV mini-grid systems. The majority of these studies, however, were simulations based on synthetic (artificial) load profiles generated from assumed energy demand and usage. But, artificial load profiles are prone to error and may not accurately reflect actual energy demand. As a result, performance assessment of PV mini-grid systems based on artificial load data may fall short of accurately measuring the performance and reliability of the systems when operated in real-world situations (Louie and Dauenhauer, 2016), (Mandelli et al., 2016). In this regard, Hartvigsson and Ahlgren (2018) found that the night load per household estimated from appliance data collected through interviews in a rural village in Tanzania was 37 W, compared to the measured night load of 280 W per household. The authors showed that the interview-based load profile underestimated the load factor and the capacity factor of the plant by 34–117%. This shows that assessing mini-grid performance based on estimated load data could lead to poor conclusions about the system's technical and economic viability. Furthermore, previous mini-grid performance analyses have been focused on technical issues, largely overlooking the impact of local economic activities and productive use customers on the magnitude and timing of the peak load; and the performance responses of the PV plants once operational (Hartvigsson et al., 2021).

There have indeed been a few studies that used real data to evaluate

PV mini-grid systems, but nearly all of these studies focused on grid-connected systems. As a result, not much is known about the performance, reliability and efficiency of off-grid PV mini-grids when used in real-world conditions, particularly in hot tropical climates in developing countries. This gap in knowledge and on-site practical experience can hinder future development and improvement of off-grid PV mini-grid systems as a viable alternative solution for rural electrification.

The main aim of this study is to investigate the actual performance, efficiency and power supply reliability of a 375 kWp off-grid PV mini-grid system with energy storage batteries installed in a remote small town in Ethiopia using real-time measured weather data, and power generation and load data. The paper essentially seeks to answer the following research questions.

- What is the efficiency of PV modules in converting available solar energy to useful electrical energy under real conditions compared to under standard test conditions?
- How does the measured energy yield and performance of the mini-grid system compare with its nominal capacity, nominal efficiency and estimated/calculated energy yield?
- How has the power supply reliability of the PV mini-grid system changed over time?
- What factors are affecting the energy performance and reliability of the PV mini-grid system?

## 2. Methodology

### 2.1. Research approach

Research on rural electrification through PV mini-grids involves analyzing the interactions and relationships between a wide range of variables, from the technical and operational elements of the mini-grid to the economic and institutional characteristics of customers (Hartvigsson et al., 2021). Therefore, the present study was conducted using an interdisciplinary case study approach that integrates both quantitative and qualitative research methods. The application of the interdisciplinary research methodology allows for a more comprehensive understanding of the influences and interactions of various factors on the performance of the mini-grid system, as well as the mapping of these influences to underlying problems or causes. The case study method, on the other hand, allows the researchers to conduct an in-depth investigation and contextual analysis of the phenomenon/problem within a

defined real-world setting, using real-time data drawn from multiple sources, and methods. As shown in Fig. 1, the current case study was conducted following six linear but iterative processes based on Yin (2014). These processes include 1) planning the case study research and identifying the research questions, 2) developing the case study research design, defining the unit of analyses and criteria (standards) for interpreting the results, 3) preparing the case study protocols and data collection instruments, 4) collecting data, 5) analyzing and interpreting the data, and 6) sharing the findings and knowledge gained.

## 2.2. Description of the case study

### 2.2.1. Location of the case study site

The case study was conducted on a stand-alone PV mini-grid system (hereafter MG) installed in a small remote town named Omorate in southern Ethiopia. The MG was selected for the study owing to its location in a hot tropical climate, the availability of operational data and the fact that the MG is among the first PV power plants installed in Ethiopia. The town lies between 4° 80' 16"N Latitude and 36° 3' 29" E Longitude with an average elevation of 368 m. a.s.l. The mean annual temperature in Omorate is 28.2 °C. In 2021, the town had a population of 3,852, which included 770 households. The MG system began generating electricity in late April 2021. In May 2021, the number of customers served by the MG was 97. However, by the time this case study was completed (January 2022), the total number of customers had climbed to 443; of which 301 (68%) were ordinary households, 112 (25.3%) were small enterprises, mostly household-based businesses, and 30 (6.7%) were public institutions. As the number of customers grew sharply, the power generated by the MG was no longer sufficient to meet the daily electricity demand. As a result, daily load shedding has been in effect since mid-July 2021.

### 2.2.2. Technical specification of the MG system

The MG in Omorate has a total installed capacity/rated power ( $P_{nom}$ ) of 375 kWp. The PV array consists of 1210 series-connected monocrystalline PV modules from Jinko (Model: JKM310M-60). Each PV module has a rated power of 310 Wp and a rated efficiency of 18.94%. The modules are assembled into 9 strings in two parallel rows (Fig. 2). Each string is connected to one inverter from Growatt (Model: MAX 50KTL3 LV) that has a maximum output power of 50 kWp. Each inverter has 6 maximum power point trackers (MPPT). All the modules in each string are fixed on ground-mounted racks and positioned in a direction facing towards south at a tilt angle of 15°. The MG system is alternating current (AC)-coupled and is equipped with five Lithium Iron Phosphate ( $\text{LiFePO}_4$ ) battery packs with a total rated storage capacity of 600 kWh. A schematic diagram of the MG system in Omorate is presented in Fig. 3.

The main system components of the MG include: PV modules, converters (solar direct current (DC) to alternating current (AC) inverters, and battery DC/AC inverters), battery energy storage system (BESS), MG monitoring and energy management system (MMEMS), a diesel generator (DG), a distribution panel (with three AC power feeders) and loads. However, the DG has not been used thus far due to the high cost of diesel fuel (US\$1/liter) in the area. A detailed technical description of the MG system is presented in Appendix 1.

## 2.3. Data sources and collection methods

### 2.3.1. Measured meteorological data

Measured data on solar irradiation on the tilted panels and ambient air temperature were obtained through direct access to the Ethiopian Electric Utility's (EEU) Universal Electricity Access Program (UEAP) database; and from the contractor that built the MG system. Although the MG began producing power in late April 2021, on-site measurement and recording of incident solar irradiance and ambient air temperature had been underway since January 2020. The measurement and recording of the solar irradiance ( $\text{W/m}^2$ ) and ambient temperature (°C) were performed in accordance with the IEC standard 61 724-1: 2017 for measuring equipment and methods (IEC, 2017). Two standard pyranometers had been used; one mounted at an angle on the array plane for measuring the in-plane irradiance, and the other one hidden to measure the ambient temperature. The irradiance was measured between 06:00 and 19:00 and the ambient air temperature recorded for 24 hours. Both measurements were taken on a daily basis at 15 min intervals, with uncertainty of <2%. Using these recorded values from two years, the average total solar insolation ( $\text{kWh/m}^2/\text{day}$ ) and the average ambient air temperature are calculated for each day from January to December. These values are used to estimate the reference yield of the array and calculate some of the performance metrics.

### 2.3.2. Real-time PV electricity generation and load data

This study is based on measured on-site power generation and consumption data. The data on hourly DC output power from the PV array, hourly AC electricity generated by the PV inverters, and the hourly energy consumed by the load were all retrieved directly from the mini-grid's Monitoring and Energy Management System (MMEMS) portal as shown in Table 1.

As the MG began operating on April 20, 2021, complete data on hourly power generation and consumption were available only for the first 245 days or 8 months (1 May – December 31, 2021) of the MG's operation by the time this case study was completed. The MMEMS system captures data from all inverters in the PV array, the battery system (BESS), the DG, and the power feeders to the loads. The data is

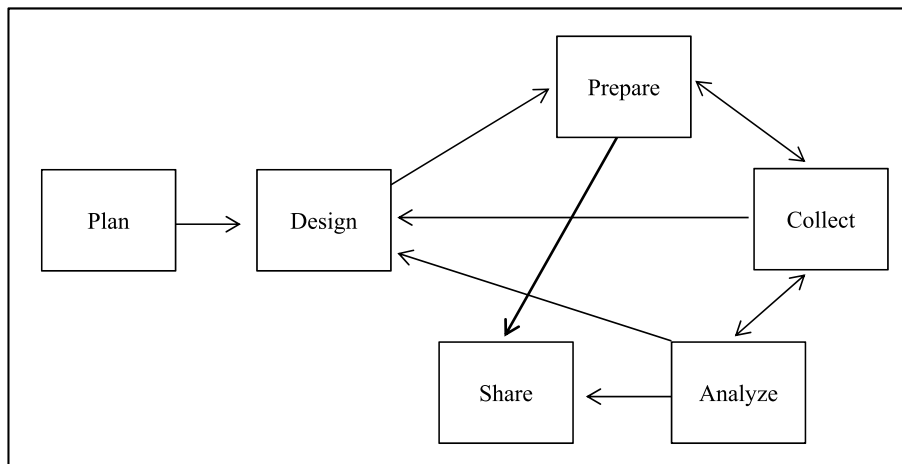


Fig. 1. Processes in conducting a case study research (Yin, 2014).



Fig. 2. A view of the PV MG infrastructure in Omorate, Dasanech district, southern Ethiopia.

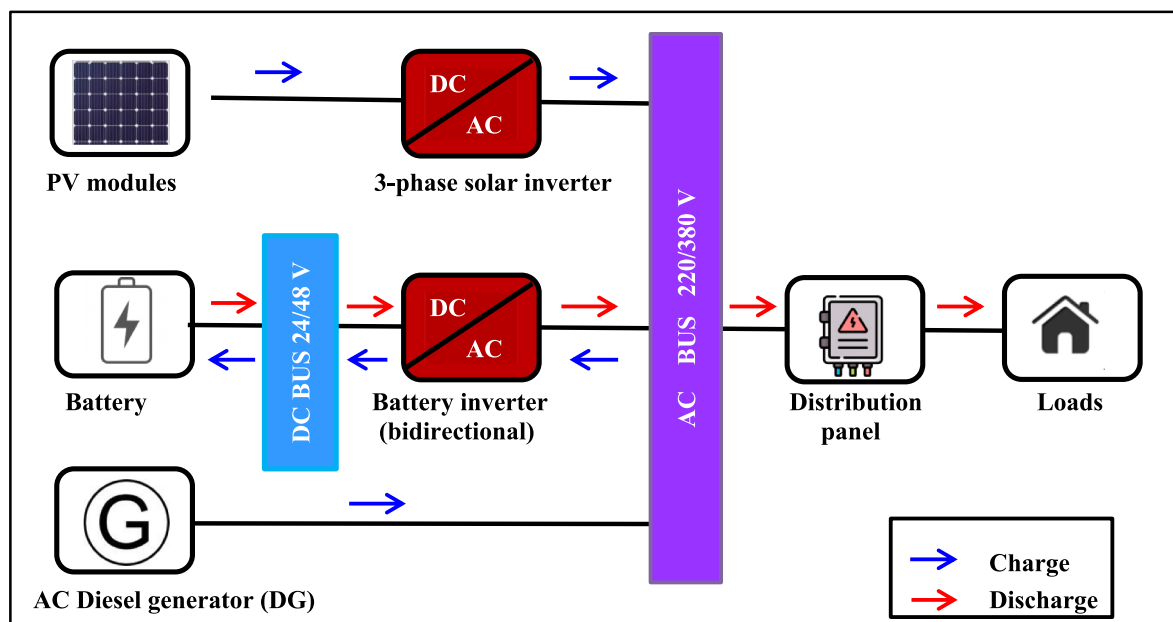


Fig. 3. Schematic diagram of the AC-coupled PV mini-grid system in Omorate, southern Ethiopia.

Table 1

Partial display of the daily AC power report retrieved from the MG's monitoring system.

Site	OMORATE						Date 2021-12-31					
Time	PVG						BESS					
	Ia(A)	Ib(A)	Ic(A)	P (kW)	Q (kVar)	COS	Ia(A)	Ib(A)	Ic(A)	P (kW)	Q (kVar)	COS
00:00	0	0	0	0	0	0.00	14	1	4	4	0	0.98
01:00	0	0	0	0	0	0.00	1	1	4	1	0	0.93
02:00	0	0	0	0	0	0.00	1	1	4	1	0	0.93
03:00	0	0	0	0	0	0.00	6	1	4	2	0	0.99
04:00	0	0	0	0	0	0.00	6	1	4	2	0	0.99
05:00	0	0	0	0	0	0.00	1	1	4	1	0	0.93
06:00	0	0	0	0	0	0.00	1	1	4	1	0	0.94
07:00	15	15	14	9	-1	0.90	14	15	13	-10	0	-0.99
08:00	89	89	89	62	2	1.00	83	89	86	-60	-2	-1.00
09:00	211	211	211	140	41	0.96	72	74	63	-47	12	-0.96
10:00	303	303	303	208	38	0.99	164	156	150	-97	17	-0.97
11:00	363	363	363	248	53	0.98	206	209	208	-145	3	1.00
12:00	223	223	224	152	29	0.99	70	79	88	-48	24	0.84



made available from the MMEMS portal on a daily basis in three power report formats: 1) hourly DC output power from the PV array, 2) AC power output from the PV Generator (PVG), the BESS and DG, and 3) power supplied to loads through the feeders. All the power reports are in kW. As shown in Table 1, the daily AC power report, for example, provides detailed information on the hourly PV generation, peak generation amount and the hour, battery charging (-ve values) and discharging (+ve values), and depth of charging, among other things. Likewise, the daily load report provides detailed information on hourly electrical loads, the peak load, load-shedding hours, etc. Using these daily power and energy reports, a time-series dataset was created for the 8 months. This dataset is utilized for many of the analyses in this paper.

### 2.3.3. Field visits, customer surveys, and in-depth interviews

In addition to the real-time energy data extracted from the MMEMS of the power plant, data on the monthly electric consumption of each customer was obtained from the local EEU billing office. Furthermore, surveys were conducted with customers from different sectors (households, productive/commercial users, and public/state institutions). The surveys were conducted by using semi-structured questionnaires that were designed, pre-tested and revised following a pilot study and guidelines suggested by Yin (2014). The surveys were administered through face-to-face interviews from 20 November to December 15, 2021 by the researchers. Throughout the field study period, repeated visits to the MG, as well as in-depth interviews and discussions with the operators, EEU staff, local authorities, community leaders, and business owners were conducted.

### 2.4. Data analysis and evaluation parameters

The system performance analyses were carried out according to the IEC Standard guidelines and methods IEC-TS 61724-3: 2016 (IEC, 2016). The IEC standard specifies methods and parameters for measuring and evaluating the power generation and energy yield of a power system under real-world conditions relative to estimated energy output from the same plant under Standard Test conditions (STC). The IEC performance evaluation methods also allow for comparative analysis of the PV module and system efficiencies of a PV MG in real-time situations against nominal efficiencies at STC. The normalized parameters and equations used to evaluate the performance, efficiency and reliability of this MG system are presented as follows.

#### a) The Reference Yield ( $Y_R$ ):

The Reference Yield ( $Y_R$ ) represents the theoretically possible energy output of the PV array if it operated at its nominal efficiency normalized by the rated power of the plant under STC without any losses. Following Ma et al. (2013) the daily  $Y_R$  of a PV plant is given by equation (1):

$$Y_R = \frac{\int G_i dt}{G_{STC}} = \frac{A * \eta_{STC} * G_{total}}{1 * P_{nom}} [kWh / kWp / day] \quad (1)$$

where  $A$  is PV array total effective surface area ( $m^2$ ),  $\eta_{STC}$  is the PV module efficiency at STC,  $G_{total}$  is the total daily in-plane solar irradiance ( $kWh/m^2$ ),  $P_{nom}$  the MG system's rated power ( $kW_p$ ), and  $G_{STC}$  is the global tilted irradiance at STC ( $1 kW/m^2$ ).

#### b) The Array Yield ( $Y_A$ )

The Array Yield ( $Y_A$ ) denotes the total daily DC energy output from the PV array (kWh) normalized by the PV's rated power. The daily  $Y_A$  is given by equation (2):

$$Y_A = \frac{E_{DC}}{P_{nom}} [kWh / kWp / day] \quad (2)$$

where:  $E_{DC}$  is the DC energy output (kWh/day), and  $P_{nom}$  is the rated

power of the PV array ( $kW_p$ ).

#### c) The Final Yield ( $Y_F$ ):

In stand-alone PV MGs, the Final Yield ( $Y_F$ ) represents the energy actually delivered to the load by the plant in a given time period normalized by the rated power of the plant (Ma et al., 2013). The daily  $Y_F$  is expressed by equation (3):

$$Y_F = \frac{E_{AC, Load}}{P_{nom}} [kWh / kWp / day] \quad (3)$$

where  $E_{AC, Load}$  is the daily total AC energy delivered to the load (kWh/day) and  $P_{nom}$  is the rated power/nominal installed capacity the MG system ( $kW_p$ ).

#### d) Capture Loss ( $L_C$ ):

The Capture Losses ( $L_C$ ) embodies energy losses from the PV array during the energy collection and conversion process. These losses can stem from the effect of weather conditions such as high temperature, module quality, ageing, wiring, shading and soiling, dirt and dust deposition or any other inefficiency in the PV array. It is calculated as shown in equation (4):

$$L_C = Y_R - Y_A [kWh / kWp / day] \quad (4)$$

#### e) System Loss ( $L_S$ ):

The System Loss ( $L_S$ ) denotes energy losses and inefficiencies in the various system components including the battery bank, wiring and distribution losses, energy used by the plant for operation and unused losses. It is expressed by equation (5):

$$L_S = Y_A - Y_F [kWh / kWp / day] \quad (5)$$

#### f) Solar power conversion efficiency/on-site module efficiency ( $\eta_{pc}$ ):

The solar power conversion efficiency (also known as electrical efficiency) of a PV MG system ( $\eta_{pc}$ ) can be defined as the ratio of the PV array's actual energy output ( $E_{AC}$ ) to the total solar radiation incident on the array surface ( $kWh/m^2/day$ ). It measures how much of the solar energy incident on the PV plane is converted to useable electrical energy when operating under real conditions. Following Joshi et al. (2009),  $\eta_{pc}$  is given by equation (6)

$$\eta_{pc} = \frac{E_{AC, generated}}{A * G_{total}} \quad (6)$$

#### g) Performance Ratio (PR):

The performance ratio (PR) of an isolated PV plant is the ratio of the energy delivered to the load ( $E_{AC, Load}$ ) to the energy (DC) that would be produced if the system was operating at its nominal efficiency and rated power at STC. PR reflects the influence of losses incurred during energy capture, conversion, storage and distribution on the rated output of the MG system (Ma et al., 2013). PR values are typically expressed in percentages and are given by equation (7):

$$PR = \frac{Y_F}{Y_R} [\%] \quad (7)$$

#### h) Temperature Corrected Performance Ratio ( $PR_{corr}$ ):

The performance of PV modules and therefore of the MG is strongly affected by temperature, especially in tropical climates (Kurnik et al.,

2011). Thus, it is imperative to calculate the Temperature Corrected Performance Ratio ( $PR_{corr}$ ) in order to measure the effect of the hot tropical climatic conditions at the site on the performance of the MG. The temperature corrected performance ratio ( $PR_{corr}$ ) can be calculated using equation (8) from the IEC (IEC, 2016)

$$PR_{corr} = \left[ \frac{PR}{1 + \alpha (T_m - T_n)} \right] \quad (8)$$

where  $\alpha$  is the temperature coefficient of power ( $\alpha = -0.39\%/^{\circ}\text{C}$ , according to the manufacturer's data),  $T_m$  is the module temperature, and  $T_n$  is the nominal module temperature ( $25^{\circ}\text{C}$ ).

Reliable measured data on the PV modules working temperatures were not available; the module temperature  $T_m$  was thus calculated by using equation (9) following Duffie and Beckman (1991).

$$T_m = T_a + G_T \left[ \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \right] \left[ 1 - \frac{\eta_c}{\tau\alpha} \right] \quad (9)$$

where  $T_m$  is the module temperature,  $T_a$  is the ambient temperature ( $^{\circ}\text{C}$ ),  $G_T$  is the solar radiation incident on the PV array ( $\text{kW}/\text{m}^2$ ),  $T_{c,NOCT}$  is the nominal operating module temperature ( $45 \pm 2^{\circ}\text{C}$ , manufacturer's data),  $T_{a,NOCT}$  is the ambient temperature at which the NOCT is defined ( $20^{\circ}\text{C}$ ),  $G_{T,NOCT}$  is the solar radiation at which the NOCT is defined ( $0.8 \text{ kW}/\text{m}^2$ ),  $\eta_c$  is the conversion efficiency of the PV array (18.94%) and  $\tau\alpha$  the product of the solar transmittance and solar absorbance. A  $\tau\alpha$  value = 0.9 is used as suggested by Duffie and Beckman (1991).

#### i) Capacity Factor (CF):

The capacity factor (CF), also referred to as the capacity utilization factor, is defined as the ratio of the AC energy output ( $E_{AC}$ ) of the MG system to the amount of energy that the system would generate if it operates at its rated power ( $P_{nom}$ ) continuously for 24 h a day throughout the year (8760 h). The annual CF of a PV plant is given by equation (10):

$$CF_{Annual} = \frac{E_{AC} \text{ generated } [kWh/year]}{P_{nom} [kW_p] \times 8760h} [\%] \quad (10)$$

#### j) Overall System Efficiency ( $\eta_{sys}$ ):

The overall system efficiency ( $\eta_{sys}$ ) of a MG system represents the ratio of the total amount of energy delivered to the load ( $E_{AC}$ ) in a given time to the total solar energy available at the PV array during that period. The monthly system efficiency ( $\eta_{sys,m}$ ) is given by equation (11):

$$\eta_{sys,m} = \frac{E_{AC,m}}{A * G_{total,m}} \quad (11)$$

where  $E_{AC,m}$  is the energy actually delivered to the load in the month,  $A$  is PV array's total surface area ( $\text{m}^2$ ),  $G_{total,m}$  is the total monthly in-plane solar irradiance on the PV array ( $\text{kWh}/\text{m}^2/\text{month}$ ).

#### k) Power supply reliability analysis:

Reliability is an important indicator when assessing the performance of stand-alone MG systems. The reliability of the MG in this study is evaluated from the angle of energy reliability. The energy reliability of a power system can be defined as the system's ability to supply customers with energy sufficient to satisfy demand with minimum power interruptions (Song et al., 2019). The energy reliability of a power plant is typically assessed by calculating the System's Average Interruption Duration Index (SAIDI) (Song et al., 2019). The SAIDI measures the monthly or annual power outage duration for a customer (or a group of customers) served by a power plant. The monthly SAIDI values of the

MG customers in this study were calculated based on the daily power interruption hours using equation (12). Data on the number of customers in each day ( $N_T$ ), the frequency of power interruptions per day, and the total duration of power interruptions per day ( $U_i$ ) were collected from the daily reports of the MG's energy monitoring system, daily operational reports of the operators, and from the customer surveys we conducted.

$$SAIDI_m = \frac{\sum_{i=1}^N U_i N_i}{N_T} \quad (12)$$

where  $N_i$  is the number of customers in the group,  $N_T$  the total number of customers served by the MG, which is the same as  $N_i$  in this case,  $U_i$  is the total duration of power outages (hours) in the month, and  $N$  is the total number of days in that particular month.

### 3. Results and discussion

#### 3.1. Solar irradiation and ambient temperature analysis

According to the measured solar irradiation data, the total annual solar energy resource incident on the tilted PV array is  $2247 \text{ kWh}/\text{m}^2/\text{year}$ . The average daily solar irradiation is  $6.1 \text{ kWh}/\text{m}^2$ , however, it varies between  $4.6$  and  $7.5 \text{ kWh}/\text{m}^2/\text{day}$ . The monthly average daily solar irradiation and ambient temperature are shown in Fig. 4. The figure displays that the lowest average daily solar irradiation ( $5.59 \text{ kWh}/\text{m}^2/\text{day}$ ) is recorded in July. The peak irradiation ( $7.05 \text{ kWh}/\text{m}^2/\text{day}$ ) is recorded in January. The average daily ambient air temperature at the MG site is  $30.1^{\circ}\text{C}$ , with a minimum of  $28.2^{\circ}\text{C}$  in July and a maximum of  $33.0^{\circ}\text{C}$  in February. In general, Fig. 4 shows that the distribution of solar irradiation at the MG site has little seasonal variation.

#### 3.2. Module efficiency under real conditions (power conversion efficiency)

The  $PV_{AC}$  power conversion efficiency ( $\eta_{pc}$ ), in lieu of the nominal module efficiency at STC, is often used to determine the energy conversion and power generation efficiency of PV modules under real working conditions (Joshi et al., 2009). According to our results obtained from equation (6), the average daily power conversion efficiency of the PV modules over the 8-month period is 9.85%. The result indicates that only 9.85% of the solar energy incident on the PV plane is converted to useable electrical energy. It also reveals that the module efficiency under real outdoor working conditions is almost half of its nominal efficiency under STC (18.94%). Fig. 5 presents the monthly average daily on-site module efficiencies over the 8-month period.

Fig. 5 shows that the monthly average PV module efficiency ranges from 9.39% in September to 10.44% in June 2021. However, it is found that the average daily PV module efficiency varies considerably from 5% to 11.35%. The lowest daily module efficiencies (5–7.95%) were found in May, July and October, all of which coincided with daily radiation values below  $5.3 \text{ kWh}/\text{m}^2$ . The highest module efficiencies (10.94–11.35%) were observed in June and August, and were paired with radiation levels close to the total average daily radiation ( $6.1 \text{ kWh}/\text{m}^2$ ). Despite the strong correlation between PV module efficiency and daily in-plane solar irradiance level, the variation in module efficiency between the eight months was not substantial, as shown in Fig. 5.

The large difference between the on-site module efficiency ( $\eta_{pc}$ ) and the nominal efficiency at STC ( $\eta_{STC}$ ) can be due in part to the effects of the high module operating temperatures. The outdoor performance of PV modules primarily depends on the in-plane solar irradiance and the PV module temperature (Kurnik et al., 2011; Ma et al., 2017). The climate in Omorate is warm and hot all year round. Our calculations from equation (9), shown in Fig. 5, indicated that the average daily operating temperature of the PV modules in this MG is  $55 \pm 2^{\circ}\text{C}$ . This

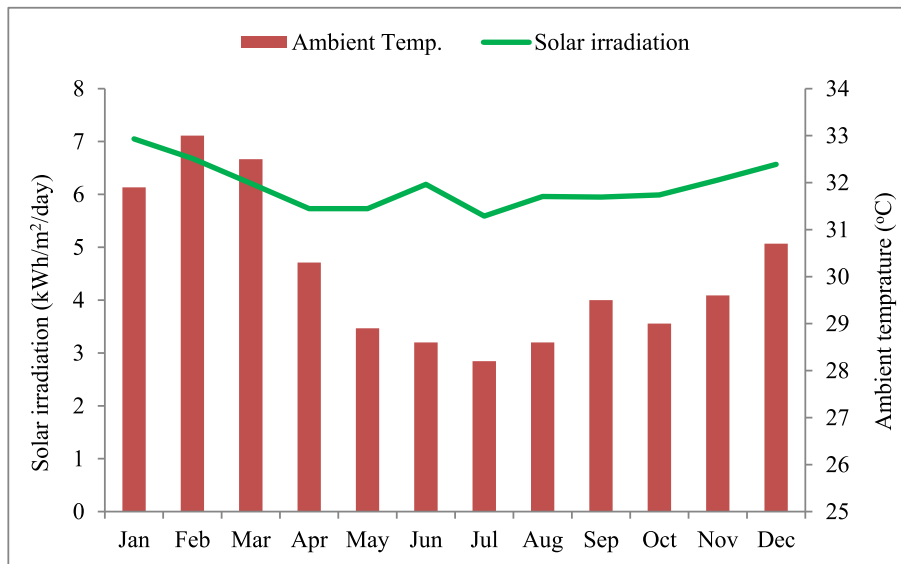


Fig. 4. The daily mean irradiation (kWh/m<sup>2</sup>/day) and average monthly ambient temperature (°C).

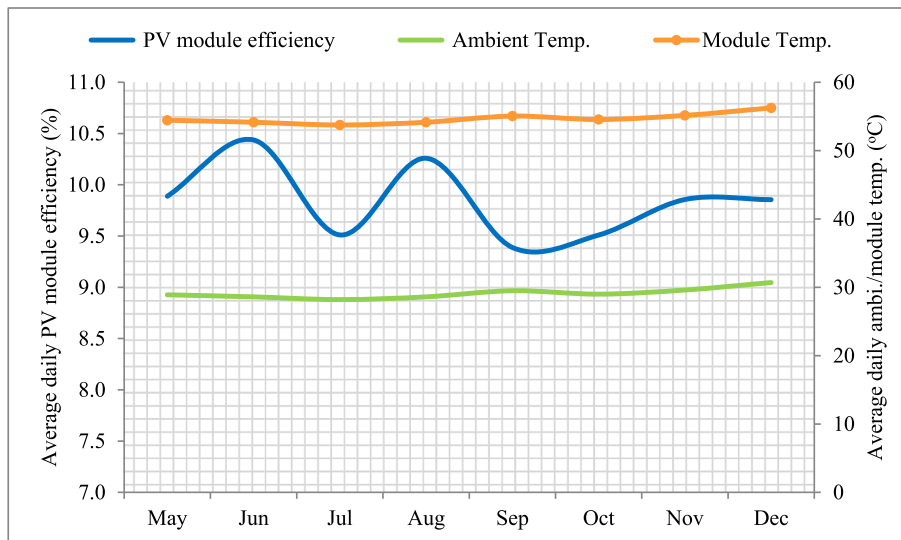


Fig. 5. Average daily on-site PV module efficiency and average daily ambient and module temperatures.

figure is 30 °C above the STC (25 °C), and 25 °C above the average ambient temperature (30 °C). According to Dash and Gupta (2015), the efficiency of monocrystalline PV modules decreases by 0.45% for every 1 °C increase in module temperature above the STC. Hence, the high operating temperatures may have negatively and significantly affected the efficiency of the PV modules by lowering the output voltage, and as a result, reducing the power output. As will be discussed later in this article, the low electrical efficiency of the PV modules is also related to the limited battery capacity.

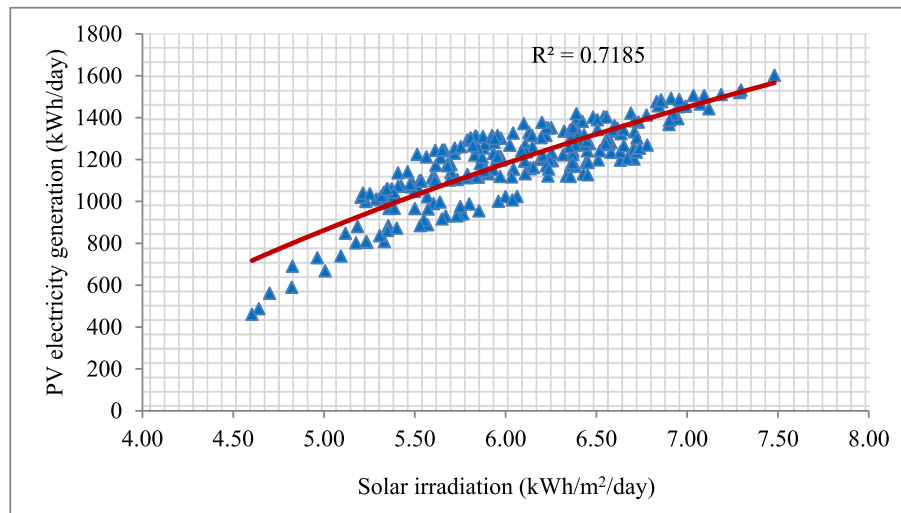
### 3.3. PV energy estimated, electricity generated, vs. electricity consumed/load analysis

Using the hourly real-time AC power generation data retrieved from the MG monitoring system (see Table 1), we calculated the daily, monthly and total electricity generated over the 245 days. The results showed that the total electricity generated by the MG plant during the 8-month period was 289 607 kWh. The average daily electricity production during the same period is calculated at 1182 kWh/day; but varies

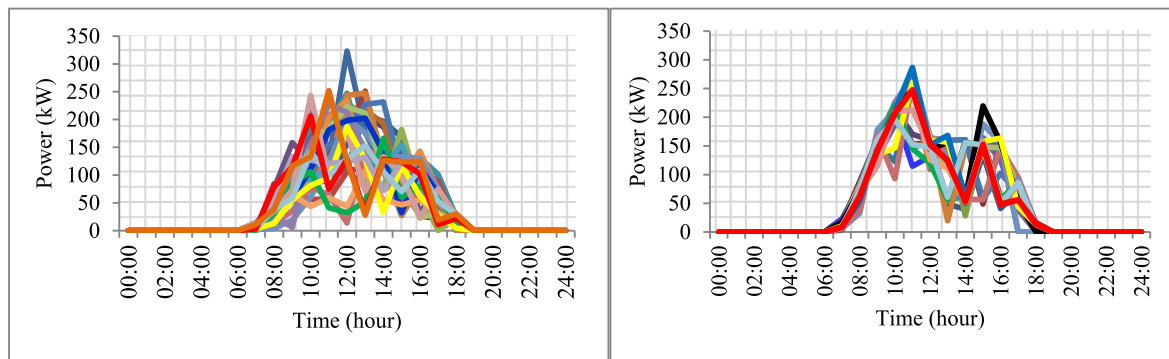
from 460.89 kWh/day to 1602.80 kWh/day. The fitted line in Fig. 6 illustrates that the daily electricity generation, given by the scatter points, is directly proportional to the solar irradiance level that hits the panel (adj.  $R^2 = 0.718$ ). In terms of monthly electricity generation, we found that the lowest monthly electricity generation 32,816 kWh was recorded in July, when the average daily solar irradiation was the lowest (5.59 kWh/m<sup>2</sup>/day). Conversely, the highest monthly electricity generation 40,294 kWh, was recorded in December, when the average daily solar irradiation was the highest (6.57 kWh/m<sup>2</sup>/day). Fig. 7 compares the daily power generation curves of the MG in July and December 2021.

As can be seen in Fig. 7, the daily electricity production curves for July and December have markedly different characteristics. While the power generation curves in July largely follow a typical PV plant, the curves in December behave oddly with the power generation consistently plunging between 12:00 and 15:00. One reason for this is active power curtailment or power clipping. Active power clipping occurs when the MPPT charge controllers deliberately limit the inverters' AC output power, as the battery reaches full charge, to match the inverters'





**Fig. 6.** Daily PV electricity generation (kWh/day) plotted versus daily solar irradiation (kWh/m<sup>2</sup>/day) (Based on data retrieved from the mini-grid's energy monitoring system, EEU, 2021).



**Fig. 7.** Daily PV power generation curves of the MG in July (left) and in December 2021 (right).

power to the load. As a result, with the high solar irradiation in December, the inverters' AC power out exceeds the load and battery storage capacity early in the day, around 11:00, before the mid-day peak load, and active power clipping occurs. This phenomenon was also confirmed during our field visits to the MG plant in December 2021. A similar problem of severe power curtailment was found by a GIZ study of two off-grid PV MGs in rural Indonesia (GIZ, 2017). The power clipping is also directly related to the limited battery capacity, as will be discussed in the next section.

Another reason could be the effect of high temperatures on module and inverters efficiency. The calculated average module temperature in December was around 56.3 °C compared to 53.7 °C in July. It is therefore possible that the high afternoon temperature and heat wave in December may have reduced the PV modules and inverters efficiency more than it did in July (rainy season).

Given the data on the daily electricity generated, and the daily electricity consumed by the load, the daily estimated DC energy output from the PV array was calculated using equation (1). The three energy

yields:<sup>1</sup>estimated electricity output,<sup>2</sup>electricity actually generated, and<sup>3</sup>electricity delivered to the load on a daily basis are shown in Fig. 8. The average daily estimated energy output of the MG (Eqn. (1)) was calculated to be 2214 kWh. When this value is compared to the average daily electricity generated by system (1182 kWh/day), a substantial difference of 1032 kWh/day is observed. This shows that only 53.4% of the rated power of the MG system is actually produced whereas the remaining 46.6% is not. In contrast, the average daily energy delivered to the load is 1030 kWh/day. This means that 87% of the daily electricity generated is consumed by the load whereas distribution and system losses account for the remaining 13% of the generated power. The significantly lower AC power output of the PV inverters compared to the estimated (rated) output can be explained by energy losses and inefficiencies in the energy capture and conversion process including losses due to inverter inefficiencies. Conversely, the high percentage of daily energy output delivered to the load shows that the load absorbs nearly all of the AC power generated by the plant each day.

During the field study and surveys, it was observed that the main

<sup>1</sup> Estimated electricity output denotes the maximum daily energy output of the plant calculated from the rated PV capacity, module efficiency at STC, array's effective surface area (m<sup>2</sup>), and daily in-plane solar irradiance (kWh/m<sup>2</sup>).

<sup>2</sup> Electricity generated represents the total daily AC energy output from all the PV inverters (kWh/day).

<sup>3</sup> Electricity delivered denotes the total daily AC energy output that is actually consumed by the load (kWh/day).

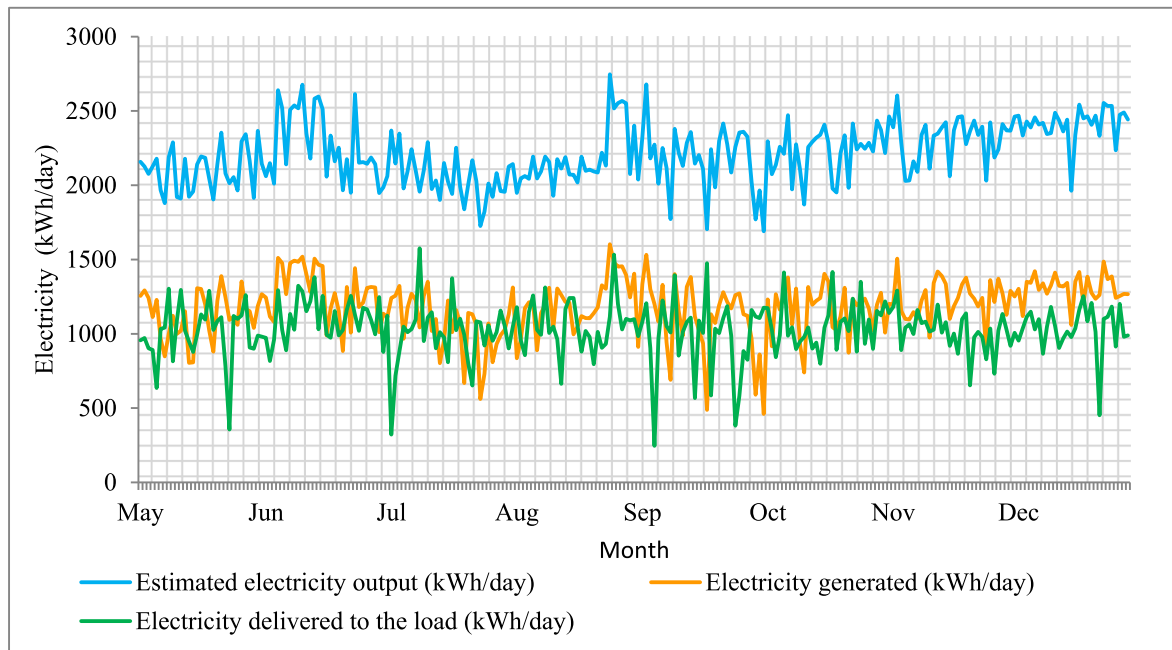


Fig. 8. Daily estimated, generated and consumed electricity (kWh/day) from the MG system.

power feeder to the loads is cut off between 17:00 and 19:00, and again between 21:00 and 08:00 almost every day in December. This is done by the operators as a load management strategy to save energy during low demand hours and supply it during the evening peak hours. It was also observed that the load profiles of productive use customers include a variety of high-power appliances such as welding machines, deep freezers, air conditioners, compressors, cooking stoves and hair dryers. A separate analysis of the load profiles of customers based on monthly electricity utility bill data and using equation (12) showed that productive use customers consumed 53% of the energy delivered by the PV installation in December despite representing only 25.3% of the total

customers. These findings are comparable to those of a study (Hartvigsson et al., 2021) in a rural village in Tanzania.

#### 3.4. Hourly energy flow and energy balance analysis

To further examine the energy performance of the MG, the hourly energy flows and hourly net energy balances were analyzed using the hourly AC power generation, energy consumption, and battery power data for December, as an example. The results, shown in Fig. 9, illustrate that the PV power output is in excess of the load during the morning hours, with the peak output power (230 kW) occurring at 11:00. While

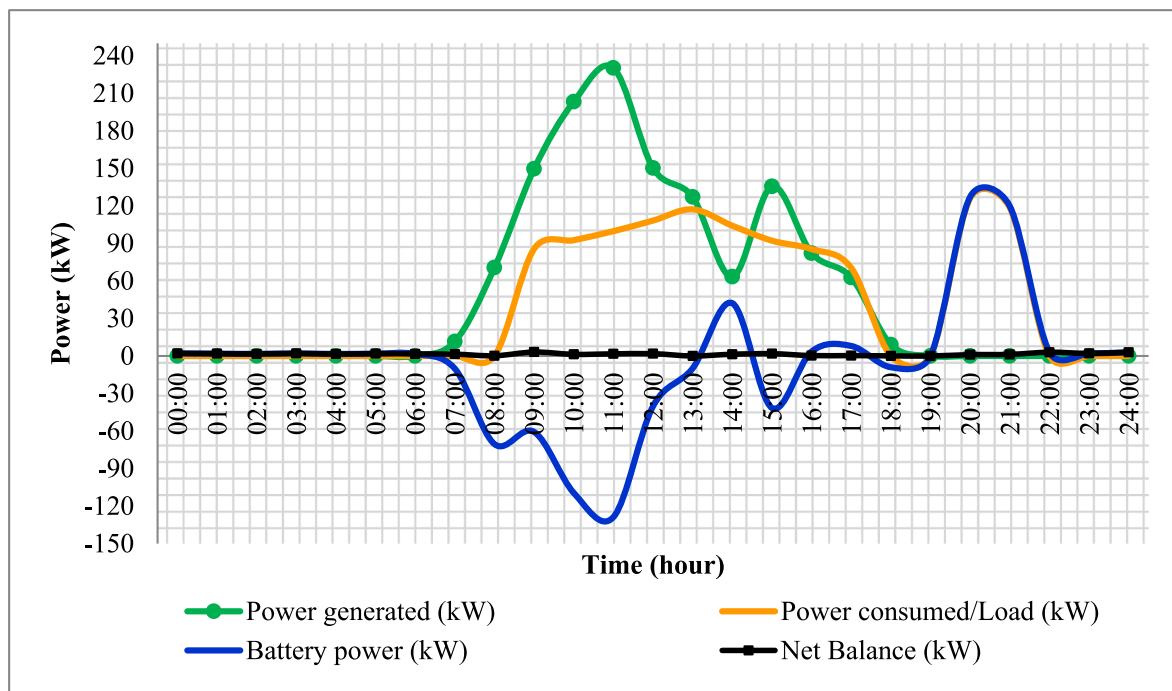


Fig. 9. Hourly energy flows and hourly net energy balances of the MG in December 2021.

the PV array is producing excess power during these hours, the battery is charging (negative values). The maximum charging power ( $-128.8$  kW) is reached at 11:00, coinciding with the peak generation. The load kicks in around 08:00 and shortly climbs to 92.55 kW at 10:00 and remains stable and above 90 kW until it is shed off at 17:00.

The power feeder is reconnected to the load at 19:00, and the load reaches its peak (126 kW) at 20:00 before being shed off again at 21:00. Throughout the 24 h, the net energy balance remains close to zero. In general, the figure demonstrates two significant phenomena. The first is that, given the high daily load, the rated battery capacity is insufficient. This is shown by the rapid depletion of the battery's state of charge (SOC) within 2–3 h of discharging between 19:00 and 22:00. The second is that, even when the solar radiation is good and the battery is fully charged, the PV electricity production is insufficient to fully satisfy the demand at certain hours of the day (13:00–15:00). In light of the observed low PV module efficiency, this could indicate a mismatch between the PV array's generation capacity and the demand, meaning that the installed capacity of the MG, including the battery, is undersized compared to the actual load.

### 3.5. Battery bank performance analysis

To evaluate the battery bank's performance, the hourly SOC were recorded and analyzed for the 31 days in December 2021. The battery SOC is defined as the ratio of the total amount of energy presently stored in the battery (available capacity  $Q_t$ ) to the maximum possible charge that can be stored in the battery (nominal capacity  $Q_n$ ) (Ma et al., 2017). The maximum depth of discharge (DOD) of the batteries in this MG is limited to 70% and the allowable maximum SOC is limited to 90%. As shown in Fig. 10, the battery SOC rises sharply from 30% at 07:00–72% at 13:00 following the surplus power generated by the PV array. Yet, from 13:00 to 15:00 the SOC is unsteady due to power discharging to offset the energy deficit created by the drop in PV power generation. The SOC peaks (89%) at around 17:00, about 6 h after the peak PV generation.

However, within 2–3 h of discharging, the SOC deteriorates to 40% at around 21:00. Fig. 10 shows that the battery undergoes unsteady and rapid charging/discharging rates. The battery is also discharging deep from 19:00 to 21:00. This confirms that the battery capacity is insufficient to store enough energy and discharge power to the loads smoothly over a longer period of time. Rapid charging/discharging and exposure

to prolonged deep-discharging can reduce the battery's efficiency and can shorten its life time. Considering the high likelihood of further increase in the electricity demand, expanding the battery's capacity may help improve the power supply. Other studies (Benavente et al., 2019), however, argue that increasing the MG system's capacity as opposed to the battery capacity alone is more cost-effective in overcoming power outages due to capacity shortages.

At the root of the PV generation and battery capacity shortages lie poor initial load assessment and subsequent undersizing of the MG infrastructure. From our interviews and discussions with UEAP officers at EEU headquarters in Addis, it was apparent that the EEU had not imposed any financial or other constraints when determining the capacities of the PV system and battery bank. However, the load assessment and demand forecast that laid the basis for the design and sizing of the MG including the battery bank was done remotely in Addis Ababa (850 km away from the MG site) by a Canadian consulting firm jointly with EEU staff. Apparently, the load assessment and demand forecast were performed based on data that was mostly inaccurate, outdated and/or insufficient such as the number of households in the town, and satellite imagery; as opposed to extensive and detailed on-site demand assessment. The underlying assumption of the consultant in the initial load assessment was that the demand for electricity in the town is low since most of the communities (Dasanech tribe) are pastoralists.

Contrary to the consultant's assessment, we found that the town is a melting point of people from all over the country with vibrant small-businesses. We also found that productive use customers are consuming a substantial amount of the daily power output, and were responsible for keeping the electrical load stable and high during the day as well as for the evening peak load. Our results imply that the dimensioning of the MG system, from the very beginning, has failed to account for the impact of the hot weather condition (hence the use of electricity for air conditioning and refrigeration), the large number of productive users, and the growing urbanization of the town on the electricity demand. These findings strengthen the assertions of Numminen and Lund (2019) that inaccurate initial load assessment and poor technical design are among the main factors behind the poor energy performance and reliability of PV MGs in developing countries.

### 3.6. Reliability of power supply from the MG system

The power supply reliability of this MG system was analyzed by

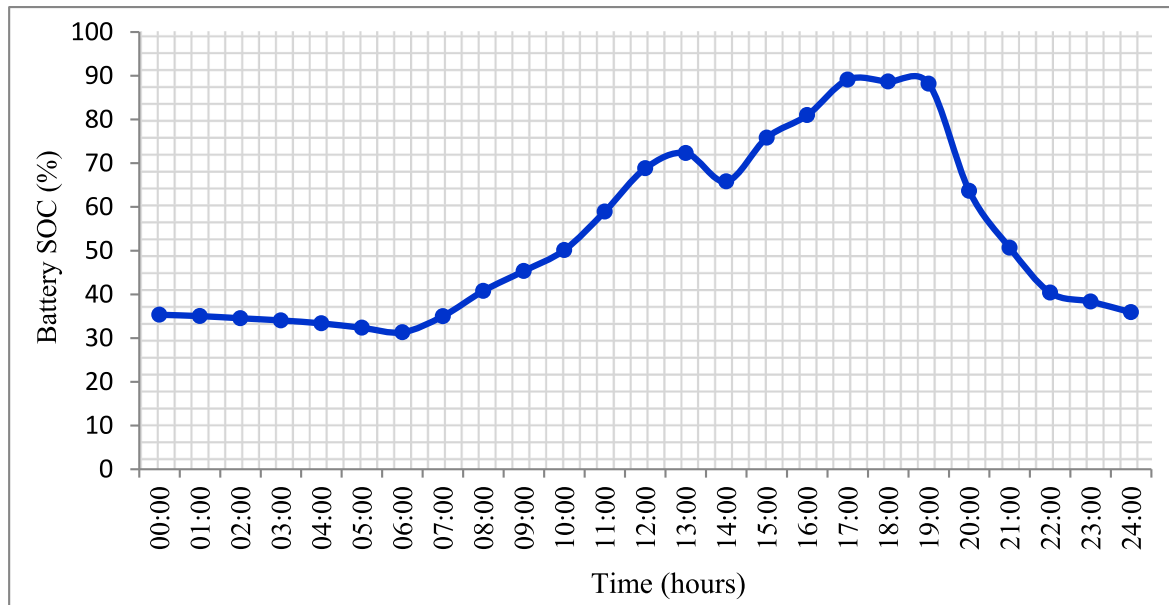
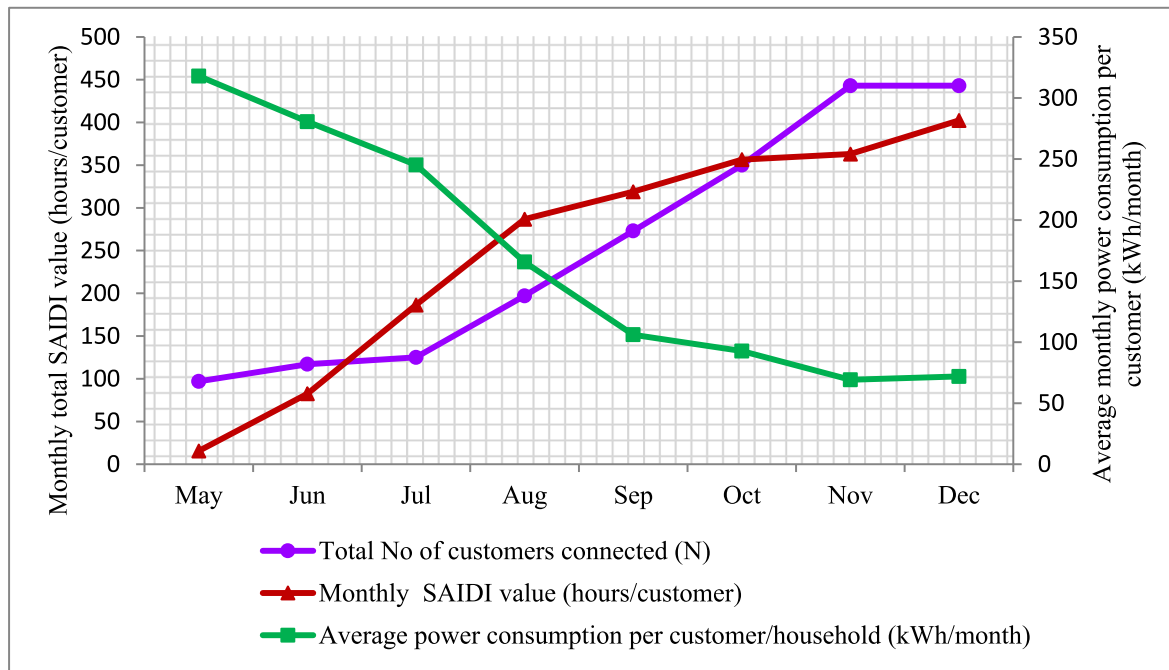


Fig. 10. Hourly mean variations in the battery state of charge (SOC) in December 2021.



**Fig. 11.** Monthly total SAIDI value (hours) and average monthly electricity consumption per customer (based on monthly electricity consumption data per customer from EEU, 2021 and using equation (12)).

calculating the System's Average Power Interruption Duration Index (SAIDI) values, and the average monthly electricity consumption per customer using equation (12). All calculations were made using the actual data on monthly electricity consumption of each customer obtained from the EEU billing records and our surveys. The results, presented in Fig. 11, show how the SAIDI increases and average power consumption decreases as the total number of customers increased from 97 in May to 197 in August and to 443 in December 2021.

Following the rapid growth in the number of customers, the monthly power interruption hours (SAIDI) per customer increased from 15.5 h (= 0.5 h/day) in May to 286.75 h in August (= 9.25 h/day) and 402.38 h (= 12.98 h/day) in December 2021. However, the monthly electricity supplied by the PV plant has not changed significantly over the 8-month period. As a result, the average monthly electricity consumption per customer fell from 318 kWh in May to 165.7 kWh in August and 71 kWh in December (a decline by 77%). The data showed that the power supplied by the MG in May was sufficient to meet the demand; with total power outage durations of only 15.5 h, mainly for operational reasons. In the months that followed, however, the number of customers grew fast while the supply remained essentially unchanged. In fact, the MG operator (EEU's district office) was aware that a sharp increase in the number of customers could compromise the reliability of the MG's energy supply but prioritized providing basic access to electricity to all initially registered and paying customers rather than limiting the number of customers. However, the operator no longer provides connections to new customers.

The surveys and in-depth interviews with key informants revealed that most early adopters of the MG service were small business owners; and they are the ones who are now losing much of their former access to reliable power supply. This, in turn, affects both the small businesses and the financial returns of the MG. The results illustrate that the MG is currently unreliable in terms of electricity supply, and that the average monthly electricity consumption per customer observed in December (71 kWh) is rather a 'suppressed demand' due to extended hours of load-shedding and power interruptions. A suppressed energy demand occurs when the energy supplied by a power system is insufficient to meet the basic needs of the customers due to limited installed capacity of the power plant, inadequacy of power supply, low user income, or other

barriers (Benavente et al., 2019). The findings clearly demonstrate the impact of the dynamics of the electricity demand and usage behaviors of rural communities on the reliability of MG systems and the need to account for such changes in initial system sizing of off-grid MGs.

According to the financial data collected from the MG operator, the average monthly operation and maintenance cost of the MG including staff salaries was US\$ 582 and the average monthly replacement cost was US\$ 1550. This puts the total average monthly expenditure necessary to run the MG at US\$ 2132. In contrast, the average monthly revenue collected from all customers was US\$ 1059 (i.e. US\$ 173 from ordinary households, US\$ 782 from productive use customers, and US\$ 104 from institutions). Comparing the average monthly expenditures and revenues of the MG operator shows that the MG is currently operating at a loss (of about 50% of its monthly expenditure). While the total economic benefits of the MG may outweigh its operation costs in the long run, as it stands now, the MG does not appear to be financially viable and sustainable. The data above also reveals that productive users (small businesses) account for nearly 75% of the revenues collected from customers while representing only 25% of the total customers.

### 3.7. Overall system performance analysis

Findings from the evaluation of the overall system performance and efficiency based on the IEC standard normalized parameters and equations 1–11 indicated that the MG system is performing poorly. The results of the energy yield and efficiency analyses are summarized in Table 2.

According to our results, the average daily reference yield ( $Y_R$ ), array yield ( $Y_A$ ) and final yield ( $Y_F$ ) of the MG over the 8-month period were 5.90 kWh/kWp/day, 3.15 kWh/kWp/day, and 2.75 kWh/kWp/day, respectively. These results confirm that only 53.4% of the potential solar energy available at the PV array's surface ( $Y_R$ ) is harvested by the inverter ( $Y_A$ ). As discussed earlier, the large disparity between the reference yield ( $Y_R$ ) and the array yield ( $Y_A$ ) relates to energy losses and inefficiencies incurred in the capture and conversion of the in-plane solar energy into useful electricity. Table 2 shows that the total average daily energy loss of this MG system is 3.15 kWh/kWp/day; which comes from average daily capture losses ( $L_C$ ) of 2.75 kWh/kWp/

**Table 2**

Summary of the results of the energy performance and efficiency analyses of the MG.

Parameters	$Y_R$	$Y_A$	$Y_F$	$L_C$	$L_S$	PR	PR corr	CF	$\eta_{sys}$
Month	(kWh/kWp/d)	(kWh/kWp/d)	(kWh/kWp/d)	(kWh/kWp/d)	(kWh/kWp/d)	(%)	(%)	(%)	%
May	5.60	2.99	2.67	2.62	0.31	47.8	45.6	12	8.93
Jun	6.08	3.43	2.94	2.64	0.49	48.7	45.1	14	9.09
Jul	5.46	2.82	2.65	2.63	0.17	49.1	46.4	12	9.17
Aug	5.81	3.21	2.81	2.60	0.40	48.5	46.5	13	9.08
Sept	5.88	3.05	2.59	2.83	0.47	44.5	39.8	13	8.42
Oct	5.81	2.97	2.81	2.84	0.17	48.7	40.6	12	9.01
Nov	6.14	3.27	2.74	2.87	0.53	44.8	36.5	14	8.36
Dec	6.43	3.47	2.77	2.96	0.70	43.1	34.4	14	8.01
Average	5.90	3.15	2.75	2.75	0.40	47.9	42.0	13	8.76

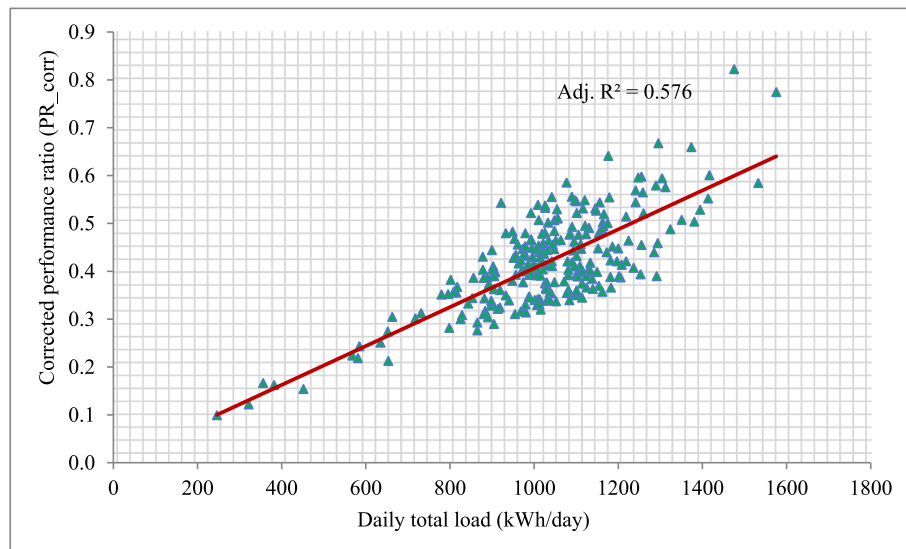
day and average daily system losses ( $L_S$ ) of 0.40 kWh/kWp/day. These figures reveal that energy losses during energy capture and conversion account for most (87%) of the total energy loss; while only 13% is a result of energy losses and inefficiencies in the distribution and system components.

The large capture losses can be linked to the low efficiency of PV modules, power clipping and the effects of high temperatures. Given that this is an off-grid PV MG with a storage battery and MPPT tracker, the PV array yield is also influenced by the quantity of energy needed to feed the instantaneous load and to charge the battery bank. In other words, how much of the available solar energy is harnessed by the inverter also depends on how much energy the battery bank can store, in addition to feeding the active load. The large difference between the reference yield and the array yield could thus be partly explained by the low storage capacity of the battery bank. Comparing the final yield ( $Y_F$ ) with the reference ( $Y_R$ ) observes that 46.56% (2.75 kWh/kWp) of the total available solar energy on the PV array surface ( $Y_R$ ) is delivered to the load each day.

The results of the efficiency analyses showed that this PV power plant performs poorly with an average performance ratio (PR) of 47.92% and an average temperature-corrected performance ratio ( $PR_{corr}$ ) of 42%. A PV power system is typically considered to have high performance when its PR value is above 70% (Kumar and Sudhakar, 2015). Compared to this, the performance of this MG system falls within the low range. Comparing the normal PR and the temperature-corrected  $PR_{corr}$  shows that the system experiences drops in performance of nearly 6% due to the effect of the high temperature in the area. The impact of temperature is most visible in December, where the MG experienced a PR drop of nearly 9% despite the high level of solar irradiation in the

month. However, it is also important to note that a low PR value for an off-grid PV plant does not necessarily mean that the system is experiencing technical difficulties. Instead, it can be caused by a poor match between the MG system's installed capacity and electricity demand. As noted by Hartvigsson et al. (2020) the viability and operational behavior of distributed MGs heavily depends on the interactions and feedback between endogenous factors (e.g., between electricity demand and supply) rather than exogenous factors. As such, the low PR value of this PV system might be due more to the limited battery capacity limiting the amount of solar energy the system can capture and deliver. As can be seen in Fig. 12, the  $PR_{corr}$  and the load in this MG are strongly and linearly correlated, suggesting that the  $PR_{corr}$  of the system could have been higher if the battery capacity had been larger and more energy was captured by the inverter and delivered to the load.

The average capacity factor (CF) of the system is 13%, indicating that the energy output of the plant is 13% of the theoretical energy output that the MG would provide if it had operated 24 h a day, including nights, at its rated capacity. The overall system efficiency ( $\eta_{sys}$ ) of this PV power plant is 8.76%. Previous research indicates that the overall system efficiency of PV power systems in tropical climates ranges between 5% and 15% (Joshi et al., 2009; Kumar and Sudhakar, 2015; Minai, 2022). A study on a 20 kWp PV micro-grid in a hot tropical climate in Colombia (Banguero et al., 2019), also found the overall system efficiency of the micro-grid to be 10.3–11%. Compared to these reports, the overall system efficiency of the current MG system is relatively low.

**Fig. 12.** Relationship between the  $PR_{corr}$  and energy delivered to the load by the MG system.



#### 4. Conclusions

The real-time performance and power supply reliability of a 375 kWp off-grid PV mini-grid system installed in a small remote town in Ethiopia is analyzed using measured meteorological data and real-time power generation and consumption data retrieved from the energy monitoring system of the mini-grid over an eight-month period (May 01 to December 31, 2021). Findings show that the average PV module efficiency ( $\eta_{pc}$ ) under real conditions is 9.85% compared to its nominal efficiency of 18.94% under STC. The disparity in module efficiency is related to the large PV array capture losses ( $L_C = 2.75$  kWh/kWp/day). The mean daily electricity produced by the MG 1182 kWh/day was found to be considerably lower than the mean estimated energy output of 2214 kWh/day; with a difference of 1032 kWh/day (46.6% less than the estimated). In contrast, 87% of the daily electricity generated was delivered to the load. System and distribution losses ( $L_S = 0.40$  kWh/kWp/day) accounted for the remaining 13%. It is found that the mini-grid system is performing poorly with an average daily array yield ( $Y_A$ ) of 3.15 kWh/kWp/day, final yield ( $Y_F$ ) of 2.75 kWh/kWp/day, performance ratio (PR) of 47.92%, temperature-corrected  $PR_{corr}$  of 42%, capacity factor (CF) of 13% and an overall system efficiency ( $\eta_{sys}$ ) of 8.76%.

Analysis of the daily energy flow and power supply reliability showed that the energy delivered by the PV plant does not meet the daily demand to the extent that the load is shed off the power supply for 13 h each day. The technical poor performance and managerial poor assessment and design of the MG can be attributed to three main factors: a) the low PV module conversion efficiency, mainly due to the effect of the high temperatures, large capture losses and active power curtailment; b) mismatch between the PV's installed capacity (375 kWp) and the demand, and c) insufficient rated battery capacity (600 kWh) compared to the load. The results suggest that the performance of PV power systems

in hot tropical climates can be significantly reduced by large drops in PV module efficiency and energy capture losses that come with operating at high temperatures. Hence, future deployment and system sizing of PV power plants in hot tropical areas of Ethiopia and the SSA at large should critically assess and take into account the effect of local weather conditions, economic activities and potential growth in electricity demand on the performance and reliability of MG systems. In this sense, the paper provides valuable lessons and practical experiences to inform policy makers, mini-grid developers, governments, researchers and organizations working on MG-based rural electrification in developing countries.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

#### Acknowledgements

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#### Appendix 1. Technical specification of the PV mini-grid system installed

Component	Parameters	Specification
Geographic location	Omorate, Dasanech district, Southern Ethiopia	
	Latitude	4° 80' 16"N
	Longitude	36° 3' 29" E
Installation	Elevation	368 m. a.s.l.
	Mean annual ambient temp	30.1 °C
	Fixed ground-mounted racks	
Configuration	AC-coupled with 9 strings in two parallel rows	
	PV module type Mono-PERC (mono-crystalline)	JKM310M-60-MX
	PV array	
	Number of PV cells per module	60
	Total number of PV modules	1210
	PV module dimension (Length x Width)	1.65 cm × 0.992 cm
	Surface area of each PV module	1.6368 m <sup>2</sup>
	Total effective area of the PV array	1980.5 m <sup>2</sup>
	Tilt angle	15° facing south
	Maximum power per unit of area at STC	189.4 W/m <sup>2</sup>
	Rated output power per module	310 Wp
	Global Horizontal Irradiation	5.904 kWh/m <sup>2</sup> /day
	Measured irradiation at the tilted plane	6.07 kWh/m <sup>2</sup> /day
	Module conversion efficiency at STC	18.94%
	Total installed/rated PV capacity	375 kWp
	PV lifetime	25 years
	Temperature coefficient	−0.39%/oC
Converter	Inverter model	MAX 50KTL3 LV
	Total Number of inverters	9
	Max input power (DC) of each inverter	75 kWp
	Max output power (AC) of each inverter	50 kWp
	Nominal voltage	585 V
	Max. AC apparent power (kVA)	55.5kVA
	Inverter output AC voltage	220/380 VAC three-phase
	Max output current	80.5 A
	Lifetime	10 years
	Maximum inverter efficiency	96%

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Component	Parameters	Specification
Energy storage (Battery)	Max energy storage capacity	600 kWh
	Number of battery blocks/racks	5 × 60 kW
	Battery cell chemistry	LiFePO <sub>4</sub>
	Minimum charge/discharge life cycles	3000 cycles
	Max lifetime per battery	10 years
	Round trip efficiency (%)	80
	Battery cell energy density	125 Wh/kg
	DC Power supply voltage	24 V
	Rated output power (kVA/kW)	125/100
	DG output AC voltage	220/380 VAC three-phase
Diesel generator (DG)	Load minimum ratio	30%
	Minimum fuel efficiency	32%
	Estimated life time in hours	10,000-15,000
	Power factor	0.8

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