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Performance Analysis of a 10kW Solar PV Embedded Generation (System Efficiency Analysis)

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Abstract

Rising energy demand in developing countries has sparked concern about energy security. This has made it critical in recent years to explore the untapped potential of renewable resources, among which Solar Energy stands out. Its expanding popularity and adoption have resulted in an increase in technological advancement of these systems, significantly reducing their costs and increasing their economic capability. PV growth for power generation is among the fastest in renewable energy, and this trend is projected to continue. PV power is increasingly being used for grid-connected applications as it gets more inexpensive. The system comprises of solar panels, a hybrid inverter, a battery, a bidirectional power meter, and a battery storage system. The performance or system efficiency of a 10kWp Solar PV grid-tied system installed at the Durban University of Technology (DUT), Durban, South Africa, is examined in this paper. This is accomplished through a three-year complete system examination of annual energy generated, system efficiency, and annual radiation. An analysis of the system's performance metrics, including energy output, system efficiency, and performance ratio, is carried out and compared to similar studies undertaken across the continent. This comparison shows that the performance is in a good range compared to the other installed Solar PV systems across the country and globally.

Keywords
Grid Tied PV system, PV performance, reference yield, Durban University of Technology, tilt angle.

1. Introduction
With the rising population and technological advancements, the global power sector is having difficulty meeting energy demands (Aslam et al., 2021). Furthermore, conventional primary energy sources, such as oil, coal, and natural gas, have a severe negative impact on the environment, including the depletion of these primary energy sources (Razi & Ali, 2021); as a result, the global community is looking for and investigating sustainable and clean energy sources that can meet energy demands. Renewable energy sources have grown in favour over the last 20 years due to their abundance and environmental benefits (Solar Resource Solutions, 2015). So far, solar energy has shown to be the most promising renewable energy source, and its popularity has expanded rapidly worldwide. Sunlight is turned into electricity in solar photovoltaic power-producing systems (Kumar, Subathra, & Moses, 2018). Solar radiation that strikes the PV panel is transformed into photon energy, which is then used to deliver electrical power to appliances (Matsumoto et al., 2017).

A PV system consists of solar panels, a hybrid inverter, a bidirectional power meter, AC and DC wires, a battery storage system, a supply grid, and a monitoring system as shown in Figure 1. Solar panels absorb solar radiation and convert it to direct current electrical power (Agrawal, Chhajed, & Chowdhury, 2022). A PV system consists of solar panels, a hybrid inverter, a bidirectional power meter, AC and DC wires, a battery storage system, a supply grid, and a monitoring system. Solar panels absorb solar radiation and convert it to direct current electrical power (Agrawal et al., 2022). The inverter converts direct current (DC) electricity into alternating current (AC) power and distributes it to the load. Excess solar energy is sent into the grid and used to supply power when there is a lack of solar energy or no backup power source. The monitoring system displays the PV system's current status (Høiaas et al., 2022).

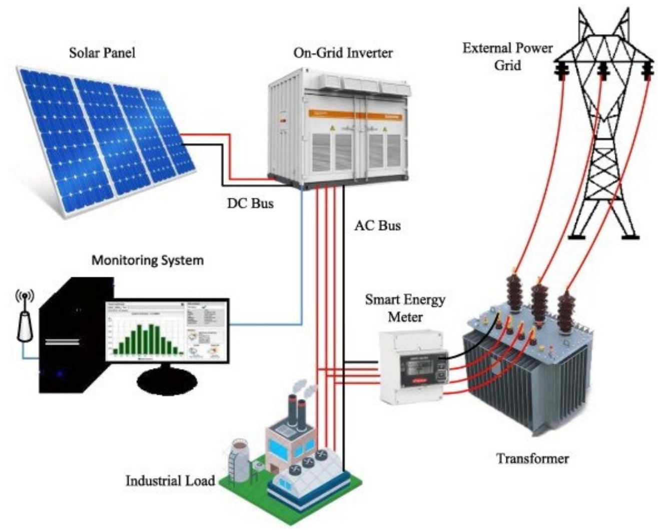

Figure 1. PV plant schematic diagram (Ahmed et al., 2021).

Due to external dynamic weather circumstances, the actual conversion efficiency of a PV power system is not the same as under conventional test settings (Agrawal et al., 2022). Furthermore, solar irradiance, tilt angle, ambient temperature, dust, and shading impacts, among other parameters, harm PV power system performance (Atsu, Seres, Aghaei, & Farkas, 2020). Researchers have worked hard to develop several ways to mitigate the detrimental consequences of these variables. Indeed, monitoring the operation of already existing PV power plants from a broader viewpoint is critical for accurate projections of PV power generation. Figure 2 depicts the installed global capacity of PV plants at the end of 2021.

Over time, researchers have undertaken diverse comparative analyses on photovoltaic (PV) solar systems to evaluate their effectiveness and appropriateness for specific installation contexts. Sharma, Palwalia, and Shrivastava (2019) conducted a performance analysis of grid-connected 10.6 kW solar PV systems, with a primary emphasis on commercial-scale installations and grid integration. Odeh (2018) delved into different performance indicators crucial for solar PV installations, employing six indicators including solar fraction, capacity factor, and performance ratio. Abbas, Bevrani, and Shafie (2022) proposed an integrated control approach for coordinating 10 kW solar PV systems within a microgrid setting. Mohammed et al. (2022) evaluated the technical performance of a 10 kWp solar PV plant tailored for residential buildings in Saudi Arabia. Alazazmeh, Ahmed, Siddiqui, and Asif (2022) conducted a comprehensive performance analysis of a 425 kW Building-Integrated Photovoltaic (BIPV) system, scrutinizing technical, economic, and environmental aspects. Babu, Dash, Bayındır, Behera, and Subramani (2016) investigated the performance of a 10 kW solar PV system within distribution networks, focusing on its impact on grid stability. Dheeban and Kamaraj (2016) analyzed the grid interaction of a 10 kW solar panel, examining the real power flow from the source to the utility grid. These studies furnish invaluable insights into the performance of 10 kW solar PV systems, encompassing aspects such as efficiency, energy yield, and the influence of factors like grid integration and meteorological conditions.

Therefore, this research focuses on the comparative efficiency and performance analysis of 10 kW PV systems in line with IEC standards and grid code rules required for integrated generating energy systems. The study made used of the already established 10 kW systems at the Durban University of Technology (DUT). This impact assessment considers the energy savings realized as well as the solar PV contribution to the University institution or building to which it is linked. Furthermore, several characteristics discovered to have a negative impact on the performance of PV power systems in earlier research are examined, and various techniques to improve the efficiency of these systems are investigated.

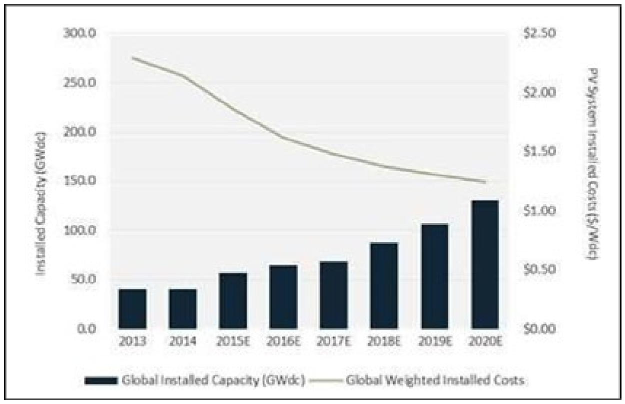

Figure 2. Global Solar photovoltaic system installations (Høiaas et al., 2022).

The system's performance is then compared to that of similar systems implemented in another South African academic institution. The findings are also compared to those of similar research conducted in Dublin (Republic of Ireland), Morocco, and India (Attari, Elyaakoubi, & Asselman, 2016; Martín-Martínez, Cañas-Carretón, Honrubia-Escribano, & Gómez-Lázaro, 2019). The remainder of this work is structured as follows: Section II contains a literature review, which is an overview of previous related work. Section III goes on the research methodology (data collection and system comparison formulation) and all of the formulas employed. The comparison analysis and performance findings are presented in Section IV. Section summarizes the work and makes future recommendations.

2. Solar PV Usage

Academic institutions are divided into two categories: residential and industrial. The residential component houses students and personnel, whereas the rest of the institution is industrial (heavy machinery laboratories, contemporary buildings, etc.). Figure 3 shows that the industrial and residential sectors account for 49% and 22% of total employment in South Africa. Several studies have been undertaken in and around the world to examine various solar installed photovoltaic systems. This study compares the performance of installed solar photovoltaic systems in academic institutions.

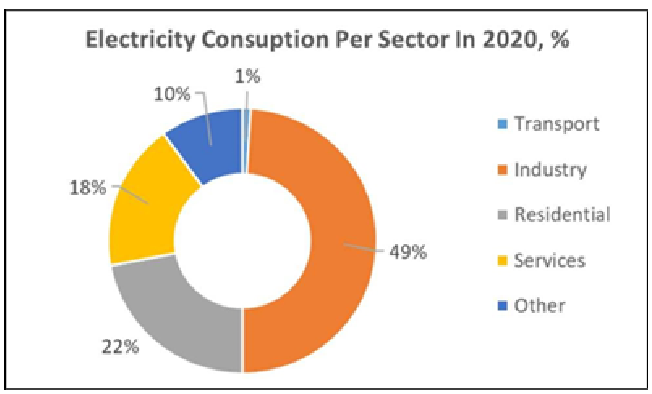

Figure 3. Electricity consumption in South Africa in 2020 (Høiaas et al., 2022).

Solar photovoltaic installations have grown in popularity during the last few decades. In South Africa, most rural electrification is accomplished using Solar Home Systems (SHS), modest photovoltaic systems catering to basic energy usage activities. Over 100 000 SHS systems have been installed through the Integrated National Electrification Program (INEP), with another 300 000 to be deployed in rural areas of the country (Christensen, Mackenzie, Nygaard, & Pedersen, 2015).

When considering solar photovoltaics on a global scale, over 125 GWp of installed capacity is estimated to be installed by the end of the year 2020. Figure 4. shows the estimated rise of solar photovoltaic system installations globally. The system installation cost is estimated to decrease from $2.16 per watt in 2014 to $1.24 per watt by 2024, which is an estimated 40% decrease in cost for installation. However, the cost will vary per region and market segment. Although the reduction in solar photovoltaic installation cost address one of the critical factors that the academic institutions have, the performance of the solar photovoltaic system is commonly one of the critical factors.

Many elements influence the performance of a solar photovoltaic system, including temperature parameters such as radiation, humidity, wind direction, and temperature conditions. Furthermore, system factors such as cell type (monocrystalline or polycrystalline), surface area, mounting type (roof mount or ground mounted), surface inclination of the system site, structural properties, and so on are evaluated. The amount of sunlight that falls on the surface of the solar array area is included in the radiation condition.

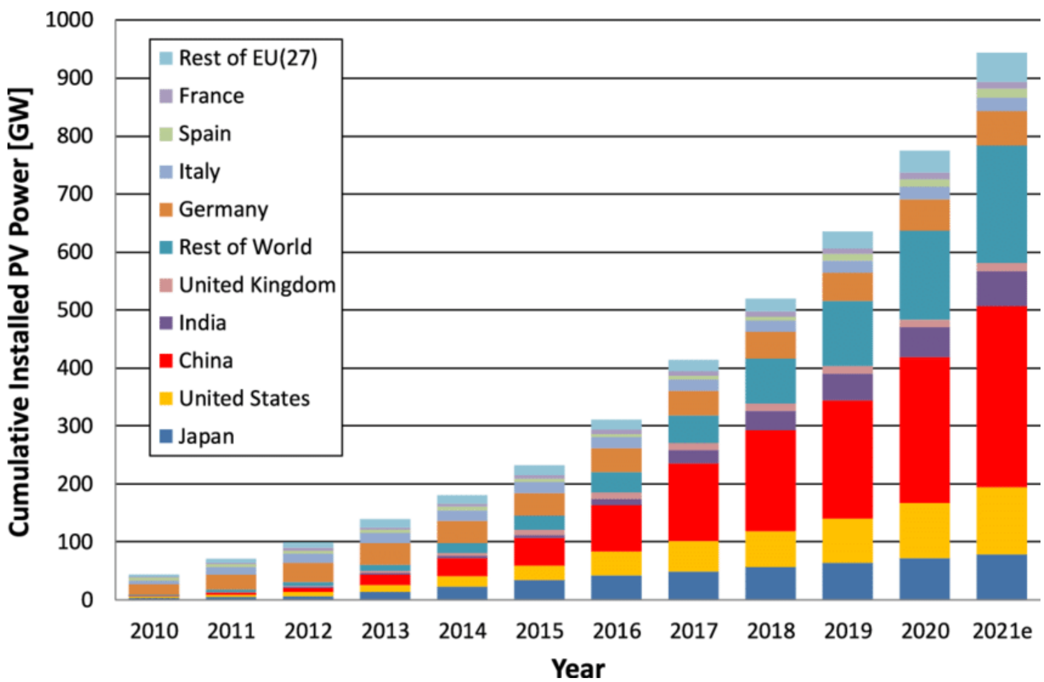

Figure 4. Global solar PV installation between year 2010 and 2021 (Jäger-Waldau, 2020).

Solar photovoltaic systems are regarded as one of the most important Climate Change Mitigation Options (CCMOs) for the transition to low-carbon energy systems (Michas, Stavrakas, Spyridaki, & Flamos, 2019). The analysis in (Ayompe, Duffy, McCormack, & Conlon, 2011) is of a roof top grid-connected solar system installed at Dublin Institute of Technology in Ireland. The system has a load capacity of 1.72kWp and 72 215Wp solar modules. The total annual energy generated by the system is 885.1kWh. With a pricing of € 0.29/kWh in Ireland for the 2019 fiscal year (Estelrich et al., 2021), the total savings for the year 2019 based on the solar photovoltaic impact are $256, 68. Using the carbon emissions factor of 1kg per kWh, the overall decrease in carbon emissions is 885,1kg. Expansion of the solar PV system will result in increased energy savings, lower costs, and lower carbon emissions.

Durban University in South Africa did a similar study on a solar PV system placed on campus. The system comprises of an 8kW solar PV grid-tied system installed at the Durban University of Technology's KwaZulu-Natal Industrial Energy Efficiency Training and Resource Center (IEETRC). The system is made up of thirty (30) polycrystalline solar panels, each rated at 220Wp and connected in series to produce 8kW of power. The monthly average radiation is between 110kWh/m2 and 190kWh/m2, with an ambient temperature between 160C and 260C. The system generates up to 220.6 kWh in June (South African winter season) and up to 415.7 kWh in January (South African summer season) (Adebiyi, Ojo, & Davidson, 2020; Ntsaluba & Dlamini, 2021). The results show that, as expected, the performance of the solar PV system falls with a drop in solar radiation on a yearly basis. In terms of generated energy, the total reduction in carbon emissions throughout the winter and summer seasons is 220.6 kg and 415.7 kg, respectively.

The authors of (Attari et al., 2016) did a similar study to examine an 11.2kWp solar photovoltaic system installed at Bhubaneswar University in India. On top of the roof, the system covers an area of 77.6m2. There are 72 solar PV panels in total, each rated at 280Wp. During August (India's autumn season), the system generates 4.01kWh/m2 /day and 5.46kWh/m2/day.

March (Indian summer season). In terms of maximum generated energy, the total energy created in summer is 423,70 kWh. During the summer, the solar system installed reduced carbon emissions by 423,70kg.

3. Design Methodology

This section depicts the methods used to carry out the data analysis and solar PV system comparison based on the research findings.

3.1 Data Collection of the installed system

The summary details and technical specifications of the Solar PV system installed at the DUT campus engineering building is reported by Agrawal et al. (2022). The system is monitored using the installed motoring software, which comprises (design, engineering, and solar array monitoring). The analysis considers solar PV losses, annual production, average ambient temperature, total system size, and other factors.

3.2 Mathematical formulation

Daily and Annual DC solar PV Energy Yield

The daily generated DC energy from the solar PV system, as measured across the combiner box output (sum of parallel strings), is reliant on the overall daily power usage, and the annual energy usage from the solar PV system is based on the system annual power usage. As illustrated below, the annual and daily yields can be calculated using equations 1 and 2.

$$E_{daily\_yield\_DC} = \sum_{t=1}^{t=T_{sun}} V_{dc} \times I_{dc} \times t_{sun} \quad (1)$$

$$E_{annual\_yield} = \sum_{n=1}^{n=365} E_{daily\_yield\_DC} \quad (2)$$

Where V_dc is the voltage (V) generated across the solar panels from sunrise to sunset. The load current (A) drawn from the solar PV system is denoted by I_dc. T_sun is the total daily sun hours, and t_sun is the hourly data recording period.

Daily and Annual DC solar PV Energy Yield

The output of the inverters is used to calculate the daily and annual PV system yield AC energy generated. The energy is calculated using Equations 3 and 4 below.

$$E_{daily\_yield\_AC} = \sum_{t=1}^{t=T_{sun}} V_{AC} \times I_{AC} \times t_{load} \quad (3)$$

$$E_{annual\_yield} = \sum_{n=1}^{n=365} E_{daily\_yield} \quad (4)$$

Where V_AC is the inverter's rated ac output voltage (V). The load current (A) drawn from the inverter is denoted by I_dc. I_dc is the load current (A) drawn from the inverter's alternating current output. The entire daily load use hours are represented by T_load.

Solar PV system losses and efficiency

The computer monitoring system package from installation is used to calculate the system's percentage losses. AC system losses, shading, inverted losses, wiring losses, mismatch, and reflection are among the system losses to be identified. Soiling. Temperature and irradiance. Equation 5 below is then used to calculate the system efficiency (%).

$$\eta_{system} = 100\% - \sum losses(\%) \tag{5}$$

Final Yield (Y_F)
The final yield represents the ratio of the daily, monthly or annual total summed AC energy ($E_{daily\ or\ monthly\ or\ annual\_yield}, kWh$) to the load and the total installed solar PV arrays rated power at $1\ kW/m^2$ irradiation at 25°C module temperature [9]. Equation 6 and 7 below is used to calculate the daily and annual final yield,

$$Y_{F\_daily} = \frac{E_{dc,d}}{P_{PV_{rated}}} \tag{6}$$

$$Y_{F\_annual} = \sum_{d=1}^{365} \frac{E_{dc,d}}{P_{PV_{rated}}} \tag{7}$$

Where, $E_{dc,d}$ is the rated dc output energy fed to the inverter. $P_{PV_{rated}}$ is the solar PV array rated peak power (kWp).

Performance Ratio
The performance ratio (PR) of a solar PV plant is referred to. The performance ratio (PR) is calculated using Equation 8 below.

$$PR = \frac{Y_F}{Y_R} \tag{8}$$

Where, Y_F is the final yield calculated from Equation 6 & 7, and Y_R present the reference yield calculated from equation 9 below.

$$Y_R = \frac{H_t(kWh/m^2)}{G_{i-ref}(\frac{kW}{m^2}/day)} \tag{9}$$

4. DUT 10 kW Solar PV System Description

Site Area Description
This study's research focuses on the performance of a rooftop solar photovoltaic system. The solar PV system is built in a new building owned by the Durban University of Technology (DUT) in Durban, South Africa, one of the main cities in the KwaZulu Natal province. At the Steve Biko Campus in Berea, Durban, the modern facility serves as an engineering administrative building, offices, and engineering laboratories. The installed system only feeds the S7 engineering building offices, which have 5 levels, and hence the performance evaluations isolate the load utilization to only certain offices in the building.

Building Daily Services
The building consists of engineering offices and engineering laboratories that are occupied during the day. On a workday basis, the building is open from 08h00 to 17h00.

Areal Temperature Conditions
The annual radiance (kWh/m2), daily irradiance (kWh/m2), and the irradiance variance (%) conditions in the DUT (Durban University of Technology) Steve Biko Campus are 2030.3 ,5.46, and 5, respectively.

DUT Engineering Building Energy Usage
The DUT S7 Engineering building energy usage from year 2021, 2022 and 2023 is shown in Figure 5 below. The installed solar PV system contributed significantly less to total building energy because it only feeds certain office plugs and low power consuming electrical sockets, and thus the system acts as a supplementary power source for emergencies during Loadshedding. Figure 5 also depicts the PV system's energy usage, the quantity of energy

generated, load consumption, and the amount of energy exported and imported to the grid over the course of three years from installation.

Figure 5 shows that the energy drawn from the utility during 2021 is less than that drawn during 2022 and 2023. The time of comparison was chosen between 2021 (when the system was installed) and 2022, to create a realistic comparison between 2021, 2022, and 2023 energy usage.

This study's corresponding rise in energy consumption is linked to the solar PV system. Future research will consider crucial elements such as occupation (student and staff availability), meteorological conditions (temperature, humidity, wind, etc.), and the Covid-19 pandemic, which was still very much a threat in 2021.

The selected building's energy usage during the month of July 2021 and 2022 was analyzed, presented, and compared. Table 1 shows the 2021 and 2022 annual energy usage comparison.

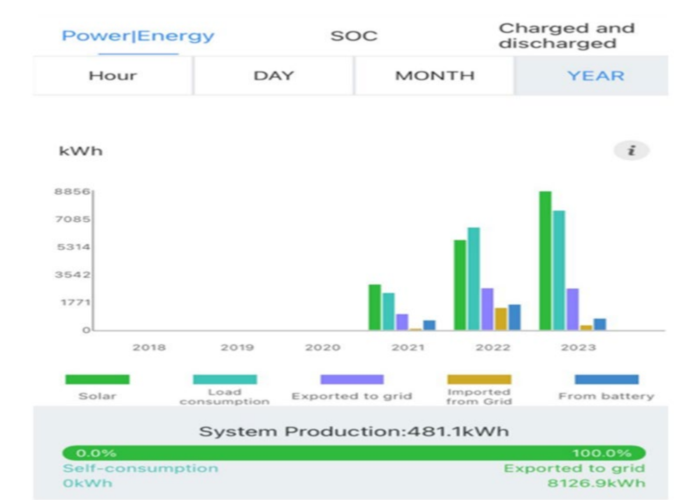

Figure 5. Years 2021, 2022 and 2023 Energy usage comparison.

Table 1. 2021- 2022 July Energy Usage Comparison

2021 vs 2022 July Energy usage summary			
Parameter	2021	2022	%Diff
Total energy usage (kWh)	75326.40	75724.16	25.75
Maximum kWh demand	481.12	357.76	22.68
Average kW demand	316.51	235.00	25.75
kW demand Load factor	68.40%	65.69%	2.71
Maximum kVA demand	463.46	357.76	22.81
Average kVA demand	316.69	235.01	25.79
kVA demand Load factor	68.33%	65.69%	2.64
Average power factor	0.999	1	0.1

In comparison to the overall Engineering Building at DUT Steve Biko campus during the month of July for the year 2021 and 2022, the building energy accounts for 32.35% and 26.22% for the year 2021 and 2022 respectively. Furthermore, to investigate and analyze the PV systems current energy usage and efficiency, the month of October 2023 was selected as the recent reference point for performance analysis looking at 3 different period duration:

- 2023 October hourly energy usage shown on Figure 6.
- 2023 October daily and monthly energy usage shown on Figure 7.

The hourly energy production of the Solar PV system is shown in Figure 6. From the figure, the maximum energy Production occurs during the hours between 11: 55 to 14: 00 daily.

5. System Performance Results & Comparison

Based on the results of the system analysis and comparison. The performance ratio is 83.6. When this value is compared to the system installed at the University of Johannesburg (same country as Durban), the performance ratio of the system installed at Johannesburg is 3.5% more while it is 2.1%, 4.6%, and 12% high than that of Dublin, Morocco, and India respectively as shown in Table 2.

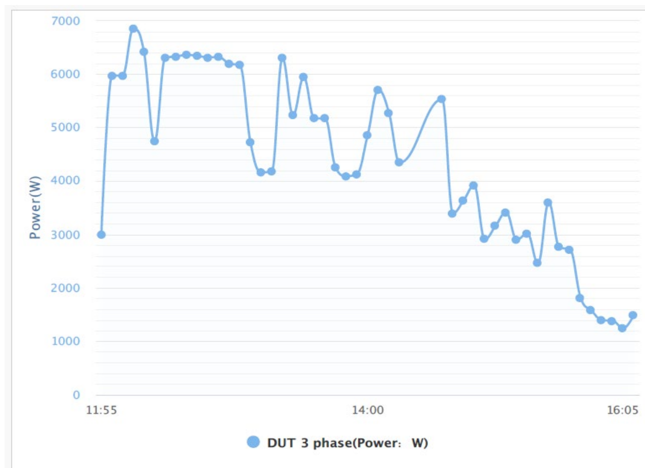

Figure 6. Shows hourly energy usage for October 2023.

Figure 7. Shows Daily & Monthly energy usage for October 2023.

Table 2: Global comparison of installed solar PV with DUT

Site Area of Installation	Capacity Installed (kW)	Energy Output (kWp/kWp-day)	Final Yield (kWp/kWp-day)	SPV Panel efficiency (%)	System efficiency (%)	Inverter efficiency (%)	PR (%)
Durban University of Technology	10	16178	4.93	13.2	12.1	96.30	83.7
Dublin (Republic of Ireland)	1.72	885.1	2.47	14.9	12.6	89.2	81.5
Morocco	5	6411.3	4.45	12.38	11.99	96.7	79
India	110	163100	3.26	-	-	-	71.6
University of Johannesburg	300	1760.40	-	19.24	12.84	98	87.1

6. Conclusion

The Solar PV system installed at the engineering building of Durban University of Technology (DUT) was analyzed using mainly the systems system's load profile and energy usage, furthermore the system was investigated in comparison to other similar existing systems to accurately analyze all the contributing factors used to measure and calculate the system's performance ratio. The performance parameters such as efficiency and performance ratio show that the performance is in a good range compared the other installed Solar PV systems across the country and globally. Future studies must demonstrate the environmental effects, grid code requirements, sensitivity analysis and systems' financial feasibility.

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Biographies

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Kayode Timothy Akindeji is currently a Senior Lecturer at the Department of Electrical Power Engineering, Durban University of Technology (DUT), Durban, South Africa where he is also the Administrative Leader for the Smart Grid Research Centre. He received his B.Sc. degree in Electronic and Electrical Engineering and M.Sc. in Electronic and Electrical Engineering from Obafemi Awolowo University, Ile - Ife, Nigeria in 2001 and 2010 respectively. He obtained his Ph.D. degree in electrical engineering from the University of Kwa-Zulu Natal (UKZN), Durban, South Africa in 2022. He is registered as Professional Engineering Technologist with the Engineering Council of South Africa (ECSA) and a Southern Africa Energy Efficiency Confederation (SAEEC) member. He is also a Member of

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