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Case Study

# Performance assessment of large-scale rooftop solar PV system: a case study in a Malaysian Public University

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**Abstract**
Adopting rooftop solar PV systems in various domestic and non-domestic sectors (including commercial, industrial, and agricultural) exhibits their commitment to green energy ventures. This study intends to evaluate the effectiveness of a grid-connected solar system that has been installed so far: a 6.9 $MW_p$ photovoltaic (PV) system implemented at University Tun Hussein Onn (UTHM) in Batu Pahat, Johor. This green energy system was installed as a part of the Self-Consumption (SELCO) program utilizing a Supply Agreement for Renewable Energy (SARE) contract. To assess the mounted energy system's efficiency, performance monitoring was carried out between December 2021 and November 2022. By evaluating the enactment of the 6.9 $MW_p$ solar system at UTHM, this present work has attempted to compile the achievement of implementation of self-consumption in terms of performance analysis and financial benefits to consumer. Based on International Electrotechnical Commission (IEC) 61724 standard, this study also investigates several performance characteristics of the PV system, such as final yield, clearness index (CI), array yield, PV module efficiency, inverter efficiency, reference yield, and capacity factor (CF) performance ratio (PR). Moreover, an assessment of Carbon Dioxide ($CO_2$) avoidance was also conducted to quantify the amount of $CO_2$ reduction achieved. In addition, the self-consumption ratio and self-sufficiency ratio pattern for solar power plant in UTHM has been assessed. The monthly clearness index at the project location from December 2021 to November 2022 ranges from 0.63 to 0.66. The PV system was monitored throughout this time and generated 8529 MWh of energy. The installed PV system has shown an efficiency of 11.86%, a final yield of 108.28%, and a PR of 0.78, respectively. Further, the installed 6.9 $MW_p$ PV system at UTHM will cut $CO_2$ emissions by 5450 tons annually. The 6.9 MWp solar PV system is also estimated to reduce 25.1 RM mil in 25 years. Making the system larger to 6.9 $MW_p$ would reduce the consumption from the grid during the week, makes it possible to achieve self-consumption levels of up to 100% and self-sufficiency of this solar plant is relatively low ranges from 22 to 35%. The research finding bridges the gap between policy makers, investors, and the public regarding acceptance of the large-scale Self-Consumption (SELCO) and strengthen the strategic collaborations between solar service provider and educational bodies to support of the government's agenda to achieve carbon emission intensity reduction in Malaysia.

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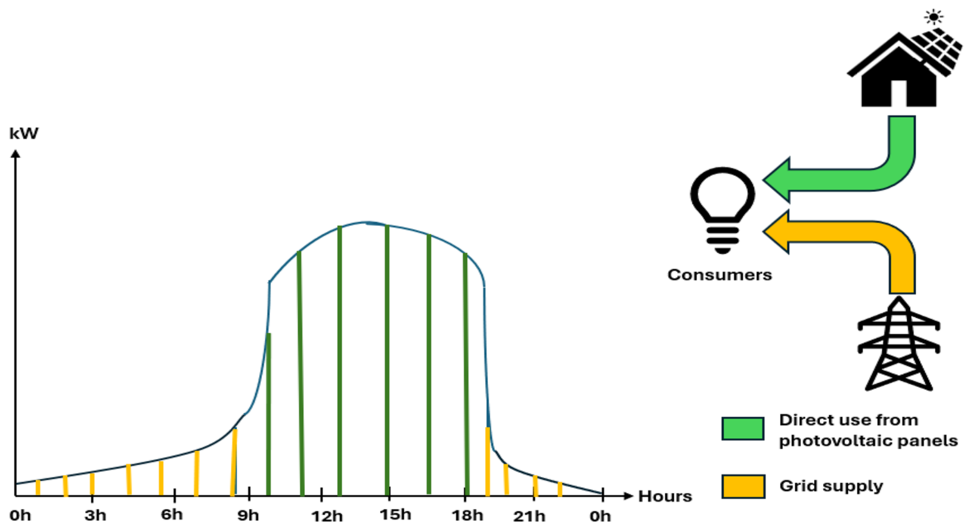
**Graphical Abstract**




**Articles** Highlights

- The study site's yearly average solar radiation of 133.83 kWh/m$^2$ indicates the area's significant potential for solar energy harvesting.
- Technical performance analysis showed that the site is very favorable for the deployment of solar PV systems, with an annual average performance ratio of 78% derived from the collected data.
- The solar PV system has considerable environmental benefits, with an estimated annual decrease of 5450 tons of $CO_2$ emissions.

**Keywords** Malaysia renewable energy initiatives · Rooftop solar systems · Performance assessment · Supply agreement of renewable energy contract · Self-consumption scheme

**Abbreviations**

| | |
|---|---|
| $CO_2$ | Carbon dioxide |
| $C_f$ | Capacity factor |
| $E_{DC}$ | Energy production |
| $G_{STC}$ | Standard test condition |
| $G_t$ | Incidence radiation |
| $Y_f$ | Final yield |
| $L_A$ | Array capture loss |
| $L_S$ | System loss |
| $SO_2$ | Sulfur dioxide |
| $Y_R$ | Reference yield |
| AC | Alternative current |
| CERE | Center for Excellence for Renewable Energy |
| $Y_A$ | Array yield |
| CI | Clearness Index |
| CUF | Capacity utilization factor |
| DC | Direct current |
| IEC | International electrotechnical commission |
| FiT | Feed in tariffs |

| | |
|---|---|
| GHG | Greenhouse gasses |
| GWh | Gigawatt hour |
| IPT | Public Institutions of Higher Learning |
| ITTHO | Institut Teknologi Tun Hussein |
| MoHE | Ministry of Higher Education |
| MWp | Megawatt peak |
| kWp | Kilowatt peak |
| kWh | Kilowatt-hour |
| NEM | Net energy metering |
| NOx | Nitrogen oxide |
| PoA | Plane of array |
| PV | Photovoltaics |
| PR | Performance ratio |
| PPA | Power purchase agreement |
| SARE | Supply Agreement with Renewable Energy |
| TEPS | Total primary energy supply |
| TNB | Tenaga Nasional Berhad |
| UNITEN | Universiti Tenaga Nasional |
| UTHM | University Tun Hussein Onn Malaysia |

## 1 Introduction

Renewable energy emerged as the obvious choice to meet the growing need for energy while reducing carbon dioxide emissions, which are the main contributor to global warming [1]. Malaysia has also started plenty of initiatives to promote the use of alternative sources of energy, like solar photovoltaic (PV), and offered a lot of demand-side incentives for RE generation. Since the subsidies' economic sustainability was lost, the government's main concern is the volatility of fuel prices. Given that Malaysia generates its energy primarily from coal and gas, an increase in the price of that commodity is inevitable [2].

The average rate increased from 33.54 sen per kWh to 38.53 sen per kWh in 2014, the year of the most recent revision to power pricing [3]. Tariff price has increased in every category since the previous tariff, with the exception of two domestic customer categories. Those who used less than 200 kWh of power per month and those who used between 201 and 300 kWh per month were included in these categories. Both represent the vast bulk of the 4.56 million domestic clients However, considering how often fuel prices fluctuate, there is no guarantee that the tariff for these two groups will remain the same.

In addition, the government plans to reform Malaysia's electrical industry, which will involve updating electricity rates. The end user tariff will remain under government control, and targeted subsidies will be provided to ensure that the tariff revision is both cheap and acceptable to the majority of the population. The first regulatory period (RP1) began in 2015 and will expire in December 2017. The years covered by the RP2 are 2018–2020, the RP3 are 2021–2023, and so on [4]. Changes in supply and demand on the world fuel market (for example, for coal and gas) determine the Base Tariff's variable component, which is included in the Average Tariff by Sectors (cent/kWh) for the Regulatory Periods (RP) 1 to 3. The Base Tariff and Base Fuel Prices set by the government during RP1 to RP3 is shown in Fig. 1:

As 2023 promises to be yet another exciting year for achieving our Net Zero 2050 goals, research by TNB reveals that the first quarter of FY23 had higher generating costs than the first quarter of FY22, as seen in A trend that is expected to continue over time as the primary price influences on electricity (such as gasoline prices and reserve power margin) keep raising prices is cause of the low awareness of significant cost reductions and a reduction in reliance on overburdened grids, as well as security against electricity prices provided by self-generated solar electricity. This shows that research showing the flexibility of installing self-generated solar energy is lacking as self-generated solar electricity can satisfy the user's electrical needs by providing a cheaper tariff and lowering the annual cost of electricity.

Table 1 Coal and gas fuel costs differed by 10% (551 million) and 13%, respectively. Future base rates in Malaysia are anticipated to grow the cost of home piped gas, which is increasing, coal, and LNG, particularly for low voltage commercial and low voltage industrial, which includes microbusinesses, small and medium-sized businesses, and residential

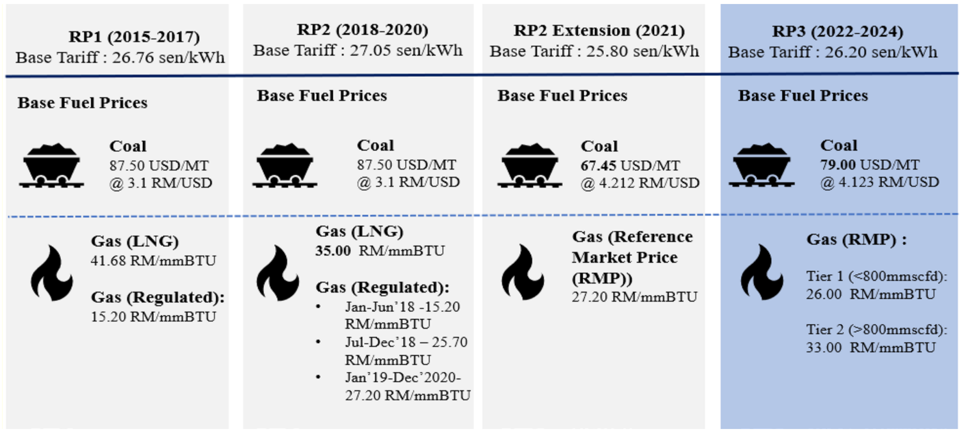



**Fig. 1** Base Tariff and base fuel prices set by the Malaysian Government from Regulatory Period (RP) 1 to RP3

**Table 1** TNB & IPP Fuel Costs for Malaysia (RM mil) [5]

| Fuel Type | TNB & IPP fuel costs for Malaysia (RM mil) | | | |
|---|---|---|---|---|
| | 1QFY23 | 1QFY22 | Variance | |
| | | | RM mil | % |
| Coal | 5589.3 | 5038.4 | 551.0 | 10.9 |
| Gas | 2940.7 | 2601.4 | 339.3 | 13.0 |
| Distillate | 37 | 209.7 | (172.8) | (82.4) |
| Oil | 1.6 | 66.4 | (64.8) | > 100.0 |
| Total | 8568.6 | 7915.9 | 652.7 | 7.6 |

customers. It is anticipated that the. Imbalance Cost Pass-Through (ICPT) surcharge will be imposed on medium- and high-voltage customers, including international enterprises.

A trend that is expected to continue over time as the primary price influences on electricity (such as gasoline prices and reserve power margin) keep raising prices is cause of the low awareness of significant cost reductions and a reduction in reliance on overburdened grids, as well as security against electricity prices provided by self-generated solar electricity. This shows that research showing the flexibility of installing self-generated solar energy is lacking as self-generated solar electricity can satisfy the user's electrical needs by providing a cheaper tariff and lowering the annual cost of electricity.

Two solar PV system programs have been made available to consumers by SEDA (Sustainable Energy Development Authority of Malaysia): the Net Energy Metering (NEM) program, which is still in operation, and the Feed-in Tariff (FiT) program, which runs from 2017 to 2020. The whole energy produced of the PV array will be exported directly to the utility grid as part of the FiT plan [6, 7]. Under the FiT system, a utility company that exports grid electricity for a period of 21 years is required to pay a Feed-in Approval Holder (FiAH) a predetermined selling price. Malaysians are in great demand for this plan's applications because of its high selling rates. The PV array's energy output is initially utilized by the residential load before any extra energy is sent to the utility grid for export, according to the NEM system, which is used to build the link. Though the FiT offers more in the way of financial incentives, the NEM is a more financially viable strategy for the government.

In order to assist the government's goal of reducing carbon emission intensity, MESTECC) has formed a variety of solar energy policies initiatives with various parties, including the residential and industrial sectors.In Malaysia, a number of studies evaluating the performance of PV installations have been conducted (see examples [8–18]). All of these studies reported on solar PV performance metrics (such as performance ratio and involved sector), which vary with solar energy legislation, as shown in Table 2. In spite of these efforts to promote environmentally friendly product usage, Malaysia has not carried out any studies to assess the large-scale self-generated solar PV system. Aspects of performance analysis and economic analysis with the SELCO programme using a SARE contract in a location blessed with a a natural tropical environment with a radiation climate that is average of 4500 kWh m-2 and plenteously of sunshine 12 h per day have not been thoroughly carried out. This paper helps close this gap with the help of a small-scale survey (N = 100) that examines the acceptance of solar energy polices especially FIT, NEM and SELCO in among domestic and non-domestic sectors

**Table 2** Solar Policies development in Malaysia

| Location | Installed capacity | Solar policies | PR (%) | Sector | References |
|---|---|---|---|---|---|
| Monash University, Selangor state of Malaysia | 232.5 kWp | FiT | 85.4 | Commercial building | [8] |
| National University of Malaysia, southwestern Malaysia | 5 kWp | FiT | 63.8–84.12 | Commercial building | [9] |
| Universiti Teknikal Malaysia Melaka building | 20 kWp | FiT | 66.46–74.79 | Commercial building | [10] |
| Kuala Terengganu | 7.8 kWp | FiT | 75.72 | Residential | [11] |
| States of Selangor and Sabah | 12 kWp | FIT | 62.63–64.67 | Residential | [12] |
| Northeast of Peninsular Malaysia | 619 kW | FiT | 77 | Commercial | [13] |
| National University of Malaysia | 5.76 kWp | FIT | 62.6–64.6 | University | [14] |
| Polytechnic Sultan Azlan Shah (PSAS) | 688 kWp | NEM 3.0 | 68–71 | Commercial | [15] |
| Changlun | 4 kWp | NEM | 79.6 | Residential | [16] |
| UCSI, University North Wing Campus | 100 kWp | FiT/NEM | 67.56–69.23 | Commercial | [17] |
| Perlis, Northern Malaysia | 5 MWp | FiT | 71.24 | Commercial | [18] |
| UTHM | 6.9 MW | SELCO | To be assessed | University | Present work |

(including commercial, industrial, and agricultural). According to survey data, only 13.1% of participants were aware of SELCO energy policies, compared to 47.8% and 60.9% who were aware of the existence of FiT and NEM solar energy policies, respectively. This survey indicates that interest rates and the number of people in Malaysia who are embracing solar PV policies, particularly SELCO, are still comparatively low.

The study of B40 households' knowledge, awareness, and acceptance of government policies through research done in Malaysia. Despite the fact that 80% of respondents possess a basic understanding of science, their awareness of solar energy technology and its application was rated as average [19]. An investigation conducted disclosed Malaysians' behavioral intentions about solar photovoltaic technology. Findings indicate that the majority of Malaysians are reluctant to invest in solar PV and are not familiar with the aforementioned schemes, which makes expanding the amount of electricity generated by solar power a difficult task. As Jayaraman et al. [20] so eloquently stated, the biggest barriers to the use of solar electricity in Malaysia are the high cost of installation and the lack of awareness and expertise among Malaysians in this field.

Previous research fails to acknowledge the significance of the Malaysian government's self-consumption (SELCO) solar incentives in bolstering and accomplishing future renewable energy objectives at Public Institutions of Higher Learning (IPT). The success of large-scale self-consumption solar PV at Public Institutions of Higher Learning (IPT) was also taken into consideration in this case study, as multiple domestic and non-domestic segments (comprising commercial, industrial, and agricultural segments) demonstrate their commitment to green energy ventures by adopting rooftop solar systems.

According to most customers, there are some obstacles preventing large-scale SELCO from spreading, such as inaccurate information about subsidized power rates, a lack of success stories, and the potential financial gain from investing in self-consumption energy policies. The above coordination has not been considered so the present work has attempted to compile the achievement of implementation of self-consumption interms of performance analysis and financial benefits to consumers. In sum, this study bridges the gap between policy makers, investors, and the public regarding acceptance of the large scale Self-Consumption (SELCO) and play a vital role in helping decision-makers to develop policies that aid in expanding and developing Malaysia's self-consumption solar PV industry.

Thus, the findings of this research will contribute to sustainable development and can potentially expand solar implementation collaboration with other educational organizations.

Hence, following are the primary contribution of this study as follows:

- To analyze results obtained from a large scale SELCO solar PV installation i.e. UTHM for a period of one year, starting from December 2021 and November 2022. The PV system is characterized with different performance parameters including Reference yield, ambient temperature, final yield, system losses, capacity factor and performance ratio
- To estimate the average $CO_2$ avoidance from the present case study that reflects the achievement of the Self-Consumption (SELCO) Scheme
- To evaluate the financial benefits to the consumers (UTHM) from this case study
- To provide detailed analysis and practical insight into the achievements of Malaysia's Renewable Energy initiatives, supporting the ongoing decarbonization efforts in the energy sector.

## 2 System description and methodology

This research methodology follows the sequence of the flowchart, which has been presented in Fig. 2. For a comprehensive performance analysis of the 6.9 $MW_p$ rooftop solar installation, the research focuses on UTHM, Batu Pahat Campus site. In achieving this study's objective, several parameters were required for analysis, namely the solar irradiance and power generation as the primary data and supported by auxiliary data related to the ambient conditions, i.e., temperature collected by measured by the sensor adjacent to the rooftop's solar panels. The assessment is further deep dive by analysing the effectiveness of the solar energy generation site under SARE programme by calculating the performance parameters of the solar PV installation includes, final yield, efficiency module, performance ratio (PR) and perform $CO_2$ avoidance calculation.

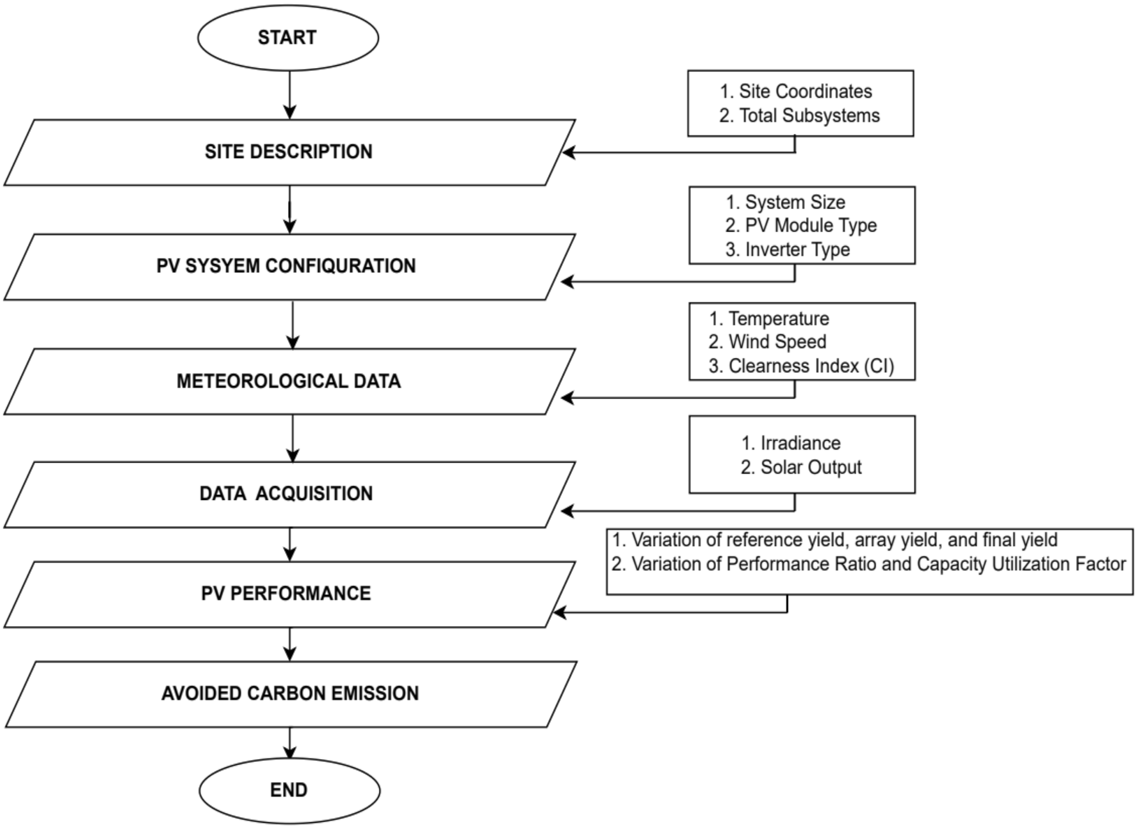



**Fig. 2** Methodology flowchart

## 2.1 Study area

UTHM (Universiti Tun Hussein Onn Malaysia), formerly known as ITTHO and KUiTTHO, is one of the public universities situated in the state of Johor, Malaysia. Its two (2) campuses are located in the districts of Batu Pahat (main campus) and Muar (satellite campus). UTHM's main campus has a total area of 2,398,337 $m^2$. Its ground floor comprises 371,756.53 $m^2$ and which is made by down eight faculties, five academic centres, a library, 70 laboratories, lecture theatres and tutorial rooms, residential colleges, a sports and recreational centre, medical facilities, a UTHM book shop, a mosque, a cafeteria, a gym & fitness centre, and religious facilities. For a comprehensive performance analysis of the 6.9 MWp rooftop solar installation, the research focuses on UTHM, Batu Pahat Campus site. Sites including Block G1 FKEE, Block G2 FKMP, Block E11, E12, E14, E15, E16, E17, FPTV, DTMI Auditorium, Cafeteria, Block FKAAB, Block F1, Block F3, FSKTM, Stadium Roof, and DSI Auditorium are included in the study's area of interest, see Fig. 3.


**Fig. 3** A satellite view of the solar PV plant at University Tun Hussein Onn Malaysia covering the study area

## 2.2 System description

TNB and UTHM have formed an innovative relationship in the field of renewable energy (RE) through the Self-Consumption Scheme using the SARE contract. The installation of a solar PV system at UTHM in Batu Pahat, Johor, with an overall installed capacity of 6.9 MWp marked the completion of this project's alignment with Malaysia's net zero emission by 2050 target and the ASEAN Plan of Action for Energy Cooperation 2016–2025, which aims to increase the contribution of Renewable energy by 23% by 2025 in the overall energy mix [21]. The system, which has been operational since November 12, 2021, is provided to UTHM without any upfront costs, and it is charged a fixed rate for energy generated that is less than the grid tariff. Additionally, the system's running costs and maintenance are covered for the duration of the contract. Academic faculties are part of the 25-building solar system installation at the UTHM campus in Parit Raja, auditoriums, a walkway, and a solar parking lot. The system is made up of PV technology: monocrystalline JINKO solar and 3-phase based inverter, Huawei model SUN2000-100KTL-M1, which was next sent straight to the state grid, and was utilized to convert DC to AC. It is put on the flat and tilted rooftop of each building at coordinates of 1° 51′ 32″ N 103° 5′ 8″ E as indicated in Fig. 4 and it is divided into 26 sub-structures as depicted in Table 3. Figure 5 demonstrates the UTHM boundary that comprises 25 solar rooftop subsystem locations.

The 300 Wp solar modules with 567 monocrystalline silicon cells were employed. For DC/AC conversion and grid connection, a three-phase Huawei SUN2000-33KTL inverter with a 30 kW rated output power was employed. Table 4 lists the technical terms of the PV module and inverter [22].

Figure 6 shows the setup configuration of the inverter for the power plant. The grid-connected solar PV systems necessitate high-power medium-voltage inverters for converting DC to AC at the correct amplitude and frequency.

## 2.3 Systems methods of data acquisition and analysis

This section discusses the features of tracking the electricity generated by a solar power system installed at Malaysia's University Tun Hussein Onn. To achieve this goal,, several parameters were required for analysis, namely the solar irradiance and power generation as the primary data and supported by auxiliary data related to the ambient conditions, i.e., temperature. All these parameters were measured by the sensor adjacent to the rooftop's solar panels. The sensors' measurements, which have been continuous since installation, are averaged at 5-min intervals and then stored in a cloud-based database via FusionSolar as shown in Fig. 7; however, the data used for this study's research was only extracted from January 2022 to December 2022.

The internal local data storage and a web server of FusionSolar are easily reachable online or across a local area network. The FusionSolar data collecting system measures the voltage and current every five minutes. The monitored solar irradiance and power output are shown in Fig. 8.

PLANT OVERVIEW – UNIVERSITI TUN HUSSEIN ONN MALAYSIA (6900 $kW_p$)


| | |
|---|---|
| **Plant Address** | : Universiti Tun Hussein Onn Malaysia |
| **Longitude and latitude** | : 1° 51'32"N 103° 5'8"E |
| **Total string capacity** | : 6.9 $kW_P$ |
| **Grid Connection date** | : 2021-11-01 |
| **Type of solar energy system** | : SELCO |
| **Plant time zone** | : (UTC+08:00) Kuala Lumpur |

**Fig. 4** Site Location (retrieved from fusion solar monitoring dashboard)

**Table 3** Details and specifications for each subsystem connection for 6.9 MWp solar PV system at UTHM

| No | Subsystems | Total panels | Total String | Approximate Area ($m^2$) | Total inverter |
|---|---|---|---|---|---|
| 1 | Electrical and Electronic Engineering Faculty (FKEE G1) | Approximately 21,200 panels | 95 | 5100 | 7 |
| 2 | Mechanical and Manufacturing Engineering Faculty (FKMP G2) | | 101 | 5500 | 7 |
| 3 | Sport Complex | | 38 | 1773 | 3 |
| 4 | Academic Management Office (PPA) | | 46 | 2455 | 3 |
| 5 | Block E16 | | 18 | 960 | 2 |
| 6 | Block E14–E15 | | 20 | 1066 | 2 |
| 7 | Block E11–E12 | | 16 | 853 | 2 |
| 8 | Workshop | | 79 | 4213 | 6 |
| 9 | Library | | 47 | 2506 | 3 |
| 10 | Technical and Vocational Education Faculty (FPTV) | | 44 | 2350 | 3 |
| 11 | Walkaway | | 26 | 1386 | 2 |
| 12 | Block E17 | | 10 | 500 | 1 |
| 13 | Tunku Mahkota Ismail Auditorium (DTMI) | | 10 | 500 | 1 |
| 14 | Development and Maintenance Office (PPP) | | 16 | 853 | 1 |
| 15 | Faculty of Civil Engineering and Built Environment (FKAAB) | | 30 | 1600 | 2 |
| 16 | Block F3 | | 19 | 1013 | 2 |
| 17 | Cafeteria | | 23 | 1226 | 2 |
| 18 | Block F1 | | 19 | 1013 | 2 |
| 19 | Faculty of Science and Technology in Computing (FSKTM) | | 30 | 1600 | 3 |
| 20 | Faculty of Technical and Vocational Education (FPTV) | | 26 | 1386 | 2 |
| 21 | Hangar | | 16 | 853 | 1 |
| 22 | Shamsuddin Research Centre for Microelectronics and Nanotechnology (Mint SRC) | | 15 | 800 | 1 |
| 23 | Block D14–D15 | | 15 | 800 | 1 |
| 24 | Stadium | | 28 | 1493 | 2 |
| 25 | Sultan Ibrahim Auditorium (DSI) | | 68 | 3626 | 4 |
| 26 | Faculty of Electrical & Electronic Engineering | | 40 | 2133 | 3 |


**Fig. 5** A 6.9 MWp solar PV system at UTHM comprises 25 subsystems

**Table 4** PV and specifications of inverter

| PV Module | | Inverter | |
|---|---|---|---|
| Parameter | Specification | Parameter | Specification |
| Type of module | Monocrystalline silicon | Model | SUN2000-60KTL-M0 |
| $P_{max}$ | 315 Wp | Input (DC) | |
| $I_{mp}$ | 9 A | Nominal power | 11600W |
| $V_{mp}$ | 35 V | Voltage range | 1100V |
| $I_{sc}$ | 8.68 A | Maximum current | 22A |
| $V_{dc}$ | 43 V | Output (AC) | |
| Temperatures coefficient of $P_{max}$ [22] | – 0.440%/°C | Voltage range (3phase) | 480V |
| Efficiency | 14% | Nominal current | 79.4A |
| | | Output apparent power | 66kVA |

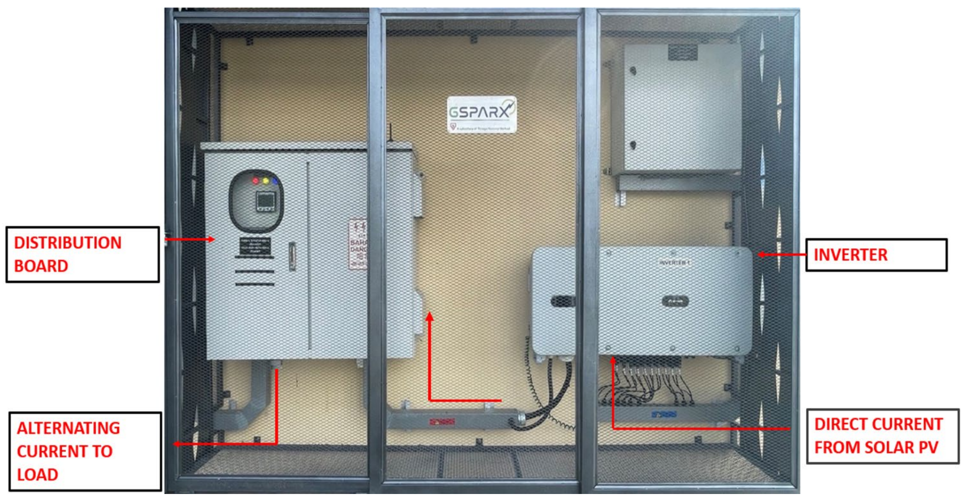



**Fig. 6** Inverters (DC) input/Output (AC)

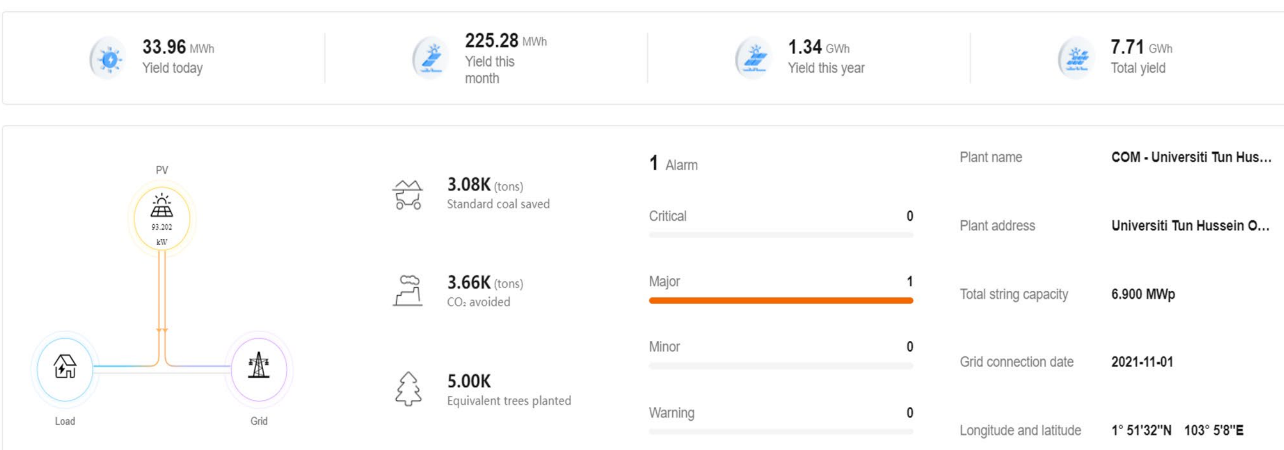



**Fig. 7** FusionSolar Smart PV control system interface

## 2.4 Wind speed

For a comprehensive performance analysis of the 6.9 $MW_p$ rooftop solar installation, the raw data on the annual wind speed was required to interrelate the clearness index at study area. Most low-level clouds in the troposphere are located

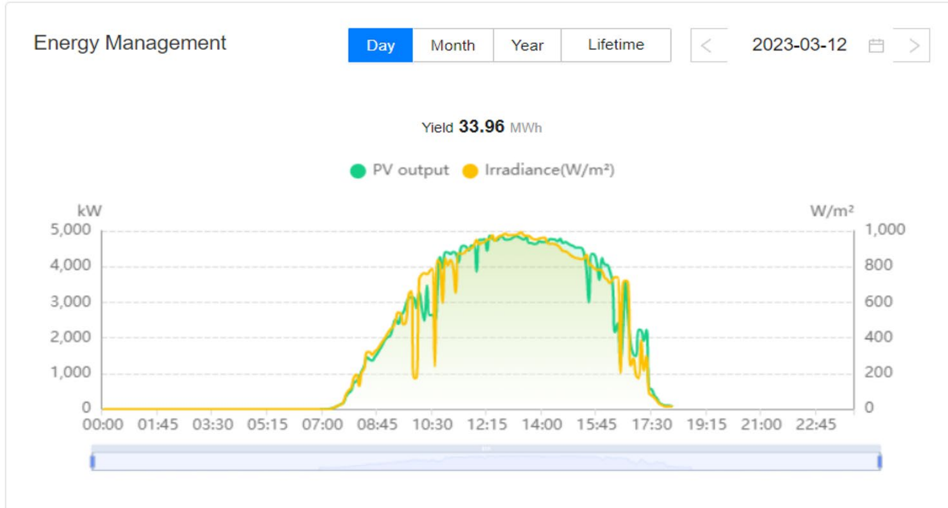



**Fig. 8** Hourly average power and irradiance per day


**Fig. 9** Meteorological Station's Location at Batu Pahat, Johor

below 2000 m, hence the current analysis was modified to include wind speed data at that altitude. The study's data was gathered during a 1-year period, beginning in December 2021, and ending on November 22, using daily average statistics. Figure 9 displays specifics about the meteorological station's location selected for this investigation.

## 3 Photovoltaic (PV) power plant characteristic parameters

PV installation evaluation criteria are laid out in the IEC (International Electrotechnical Commission) standard (IEC-61724). The PR, the $Y_R$, the $Y_a$, and the $Y_f$ are the LC, and LS The system's overall efficiency is depicted in these numbers in terms of energy output, the accessibility of solar resources, and the overall impact of PV system losses.

### 3.1 Reference yield ($Y_r$)

It is referred to as the reference irradiance-producing power $H_T$ ($kWh/m^2$) under standard test conditions ($G_{STC}$) which is (1 $kW/m^2$). It also referred as the PV system's solar resource [23]. Equation 1 illustrates the computation.

$$Y_R = \frac{H_T}{G_{STC} = \left(1kW/m^2\right)}. \tag{1}$$

### 3.2 Array yield, ($Y_A$)

It is the ratio of the installed PV array's kW ($P_O$) power productivity to the daily energy output of the PV array ($E_{DC}$). $Y_A$ value is depicted by Eq. 2.

$$Y_A = \frac{E_{DC}}{P_O} \tag{2}$$

### 3.3 Final yield, ($Y_f$)

It is demarcated as the difference amongst the installed kW capacity ($P_O$) of the PV array and the daily energy production ($E_{AC}$) of the PV plant. $Y_f$ is determined using Eq. 3

$$Y_f = \frac{E_{AC}}{P_O} \tag{3}$$

### 3.4 Performance ratio, PR

In a grid-connected photovoltaic system, the most prevalent rating for characterizing the energy transition is the performance ratio (PR). $Y_f$ divided by $Y_R$ equals PR. This measure shows the system's efficiency from the beginning of solar energy conversion through the generation of electrical energy at the end. Therefore, the PR index is affected by every component of the environment, including the effectiveness of the PV system. The PR calculation is shown in Eq. 4 [21].

$$PR = \frac{Y_f}{Y_r} \times 100\% \tag{4}$$

A system loss estimate is also made for the PV system in accordance with IEC 61724. The loss is the result of the system's parts, which also include the PV panel, inverter, cable wire, and other aspects that exacerbate the damage. The system's loss value is displayed in Eq. 5 of the IEC 61724 standard.

### 3.5 Array capture loss ($L_c$)

It is reliant on how system components like the inverter, cable, and solar panels affect the system. It is computed using an Eq. 5.

$$L_c = Y_R - Y_f \tag{5}$$

### 3.6 System loss ($L_s$)

It is the PV array loss. The difference between $Y_R$ and $Y_A$ values. It is computed using an Eq. 6.

$$L_S = Y_R - Y_A \tag{6}$$

### 3.7 Capacity factor ($C_f$)

The energy content produced if a PV system works at its regarded as output ability divided by the total the system's output of energy during a specific time period is known as the conversion factor. Equation (7) yields the value of $C_f$ [24].

$$C_f = \frac{Total\ Annual\ Energy\ Output, E_{AC}}{P_{PVrated} * 8760} \times 100\% \tag{7}$$

### 3.8 System efficiency ($\eta_{sys}$)

The expression in Eq. (8) is used to calculate the monthly efficiencies of the individual subsystems as well as the overall system efficiencies [25].

$$\eta_{sys} = \frac{E_{AC,d}}{G_t A_A} \times 100 \quad (8)$$

E (AC,d) is the system's output in AC watts, $G_t$ is incidence radiation on the array's plane (PoA), and $A_A$ is the array's area [26].

### 3.9 Clearness index, (*CI*)

It is calculated using information from the clear sky model and pyranometer data. The CI's value ranges from 0 to 1. The value 0 denotes that there is no irradiance to be received on the ground and that there is a complete cloud cover. On the other hand, number 1 denotes that the maximum potential amount will be received. The clearness index can also be derived using the relationship between the extraterrestrial horizontal insolation and the measured global solar insolation, $K = \frac{H}{H_o}$. Each month's average was computed using everyday extraterrestrial radiation on average over a month ($H_o$). A $H_o$ was intended using Eq. (9) [27].

$$H_o = \frac{24}{\pi} I_{sc}\left(w_s sin\phi \sin\delta + \cos\phi\cos\delta\sin w_s\right) d_r \quad (9)$$

where Ws is the average sunrise hour angle for the given month, $\phi$ signifies the site's latitude, $\delta$ the sun's declination, and $I_{sc}$ (=1367 $\frac{W}{m2}$) is the solar constant. The following Eqs. (10, 11, 12) can be used to calculate both $\delta$ and $W_s$ [28] In Eq. 11, n is the year's day count beginning on 1 January

$$\delta = 23.45 \sin\left[\frac{360(d+284)}{365}\right] \quad (10)$$

$$d_r = \left(1 + 0.0033 \cos\frac{360n}{365}\right) \quad (11)$$

$$w_s = cos^{-1}(-\tan(\phi)\tan(\delta)) \quad (12)$$

According to the expression in Eq. 13, it is possible to anticipate the clearness index.

$$K = \frac{H}{H_o} \quad (13)$$

### 3.10 Avoided carbon emissions

It is displayed as the difference between the baseline and project scenarios versus absolute $CO_2$ emission levels. The calculation is (baseline carbon intensity—asset carbon intensity) x energy production of the asset. Photovoltaic energy annual avoided emissions are calculated by Eq. (14) [29].

$$C_{ae,PV} = \frac{\left[EF_{elec} - EF_{PV}\right] \times EG_{f,PV}}{1000} \quad (14)$$

where $EF_{elec}$ is the *Grid electricity emission factor* ($\frac{tCO2}{MWh}$), $EF_{PV}$ is the *Photovoltaic emission factor* ($\frac{tCO2}{MWh}$), which are assumed to be 0, $EG_{f,PV}$ is the *Energy generated by photovoltaic panels* (*MWh*).

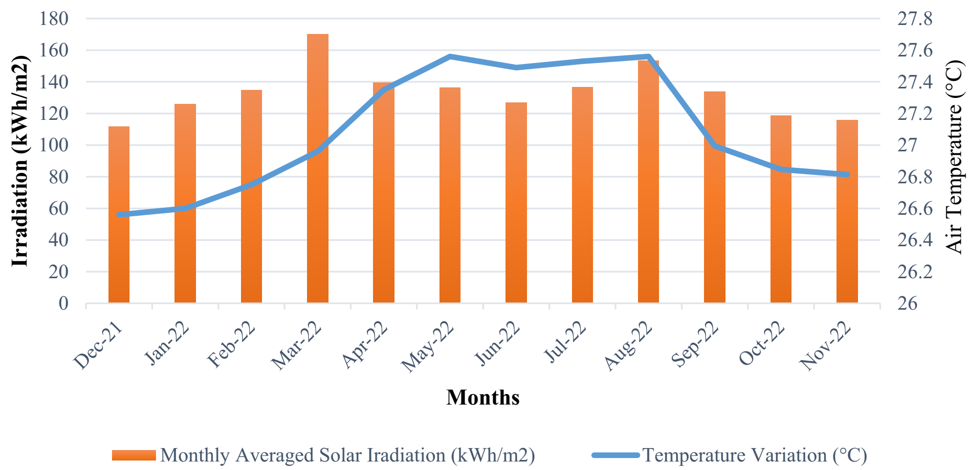



**Fig. 10** Variation of solar irradiation and air temperature

# 4 Results

## 4.1 Solar resources assessment

Figure 10 shows the monthly solar irradiance and air temperature variations retrieved by FusionSolar. In December 2021, the radiant intensity was 111.56 kWh/m; in March, it peaked at 170.03 kWh/m$^2$. Solar radiation declined during the months, reaching 126.89 kWh/ m$^2$ in June. The second peak is noted in August, swiftly tracked by a decline to the lowermost value of 115.67 kWh/m$^2$ in November 2022. The PV module's temperature is substantially influenced by the room temperature. The power of the PV module yield decreases as the module temperature rises. The study area's ambient temperature ranges from 26.56 to 27.55 °C. The typical air temperature at the plant location is comparable to the standard test conditions temperature at roughly 26 °C.

Additionally, as shown in Fig. 11, the monthly clearness index at the project location from December 2021 to November 2022 ranges from 0.63 to 0.66. It was discovered that CI has an average annual value of 0.63; its lowest and highest values are 0.60 in November 2022 and 0.66 in July 2022, respectively. It was determined that the clearness index was low in the wet seasons when there were strong winds in Dec. 2021 and from Aug. 2022 to Nov. 2022. The intensity of the clouds is typically greater during the rainy season than during the dry season. Many Malaysian cities, including Kuala Terengganu, Kuching, Kota Kinabalu, Seri Iskandar, and other districts in Johor, Malaysia, have been the subject of prior research on monthly clearness indices. Pontian, Kulai, Tangkak, Kluang, Muar, Batu Pahat, Mersing, Kota Tinggi, and Segamat have reported that it varies between 0.55 to 0.7 [28–30]. Overall, the CI of the 6.9 MWp Solar PV energy system at UTHM provides more details regarding the potential for solar energy as well as the atmospheric characteristics of solar

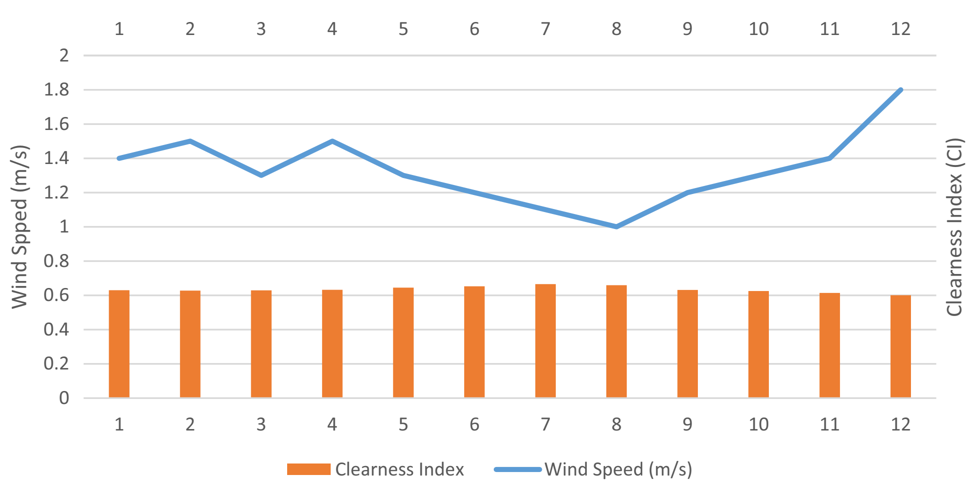



**Fig. 11** Variation of average clearness index and wind speed

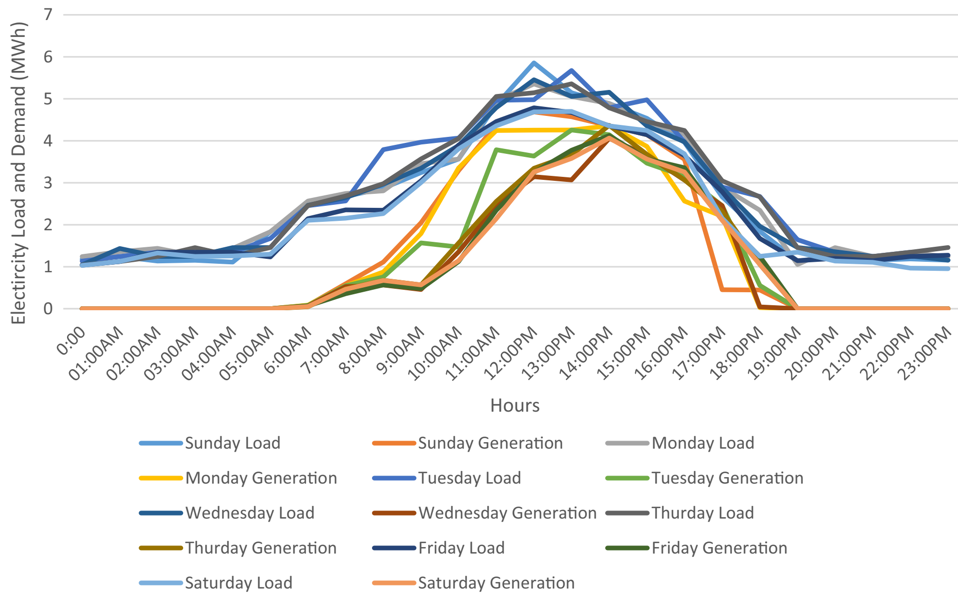



**Fig. 12** Comparison of electricity demand between weekend and weekdays

installations. It appears to be suitable for solar energy applications since it reported a clearness index of cloud that has exhibited above 0.6 every month.

### 4.2 UTHM's load demand

The model that has been introduced allows us to examine the fluctuations in the probability of specific severe power consumption events and provides a typical range of power consumption at a given time of day. Knowledge of the estimated demand is critical to calculate how much electricity is needed at UTHM within a given time period. The data indicate that there is small variation in the amount of electricity consumed on weekdays compared to weekend days, falling between 7 and 9 MWh daily, while the daily variation in power consumption is only 3.1% of the average, as demonstrated in Fig. 12.

In the case of UTHM, Johor, Saturday is the weekend, while Sundays are the first day of each week Since UTHM's days of operation are Sunday through Friday, the typical week's demand is an average demand that remains constant during the workdays. The demand was marginally lower on the weekend—the sole holiday of the week—than on other days. According to the hourly changes in power demand, the load varied little between 12 and 5 a.m., the demand rose starting at 6 a.m., and the average demand remained steady until 5 p.m. The demand further decreases from 6 p.m. to 9 p.m. during nighttime hours.

Given that university staff and students occupy the lecture halls, library, and educational offices during the week, it was anticipated that more electricity would be needed during these hours. For indoor thermal comfort, more electricity is needed, with temperature being the primary factor influencing this requirement.

The daily load profile by days for educational buildings at UTHM tends to be more similar to the solar power generation curve as shown in Fig. 13, it can be said that this feature gives educational buildings an advantage in terms of clean energy consumption effectively and reducing over-generation. This implies that educational institutes are feasible for solar PV production, especially large-scale production.

### 4.3 Results for energy production

This discussion presents the energy production results from a 6.9 $MW_p$ solar PV plant at UTHM, producing a total energy of 8529.60 MWh yearly. As shown in Fig. 14, the results highlight certain months when power production peaks. In March, the power system generated 889 MWh of energy, making it one of the months with the highest power production. August follows closely with a production of 809MWh. The power production in April also indicates the peak power generated, with recorded production of 509MWh. Moreover, the graph also depicts the lowest energy production from October to December. 651 MWh is recorded in October, and 646 MWh in November, whereas December records production of 618 MWh, making them the months with the lowest energy production.

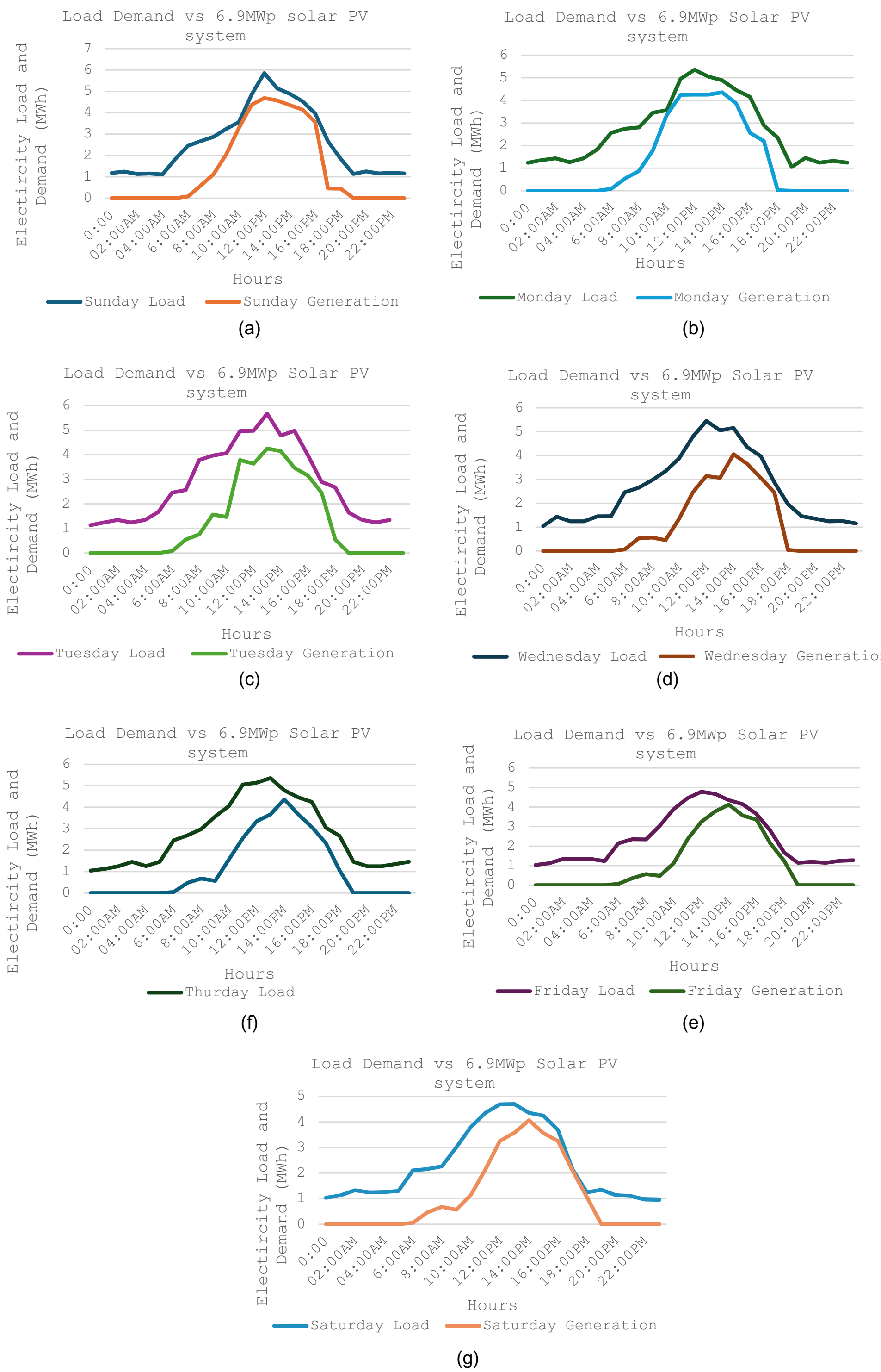



**Fig. 13** **a**–**g** Shows daily load profile compared to PV generation curve for UTHM

## 4.4 Reference yield, final yield, and array yield variations

The data shown in Fig. 15 demonstrate a drop in the array's maximum value and the final yield in March. There is a second peak that can be seen in August. The reference yield is influenced by the PV array's daily solar illumination. As solar insolation increases, the reference yield also increases. The array yield, reference yield, and final yield variation for the period of December 2021 to November 2022 are shown in Fig. 15. The monthly average final yield varies from a low

Fig. 14 Solar power production (kWh)

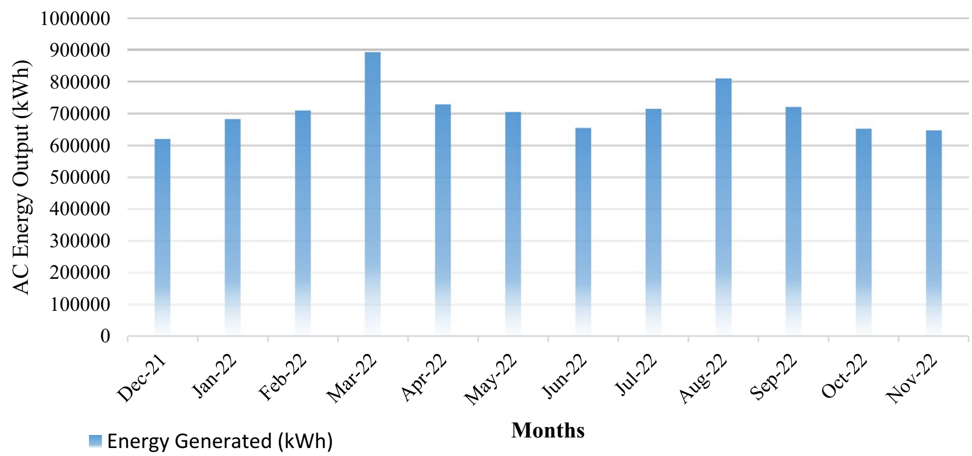



Fig. 15 Monthly variations in the array yield, reference yield, and final yield

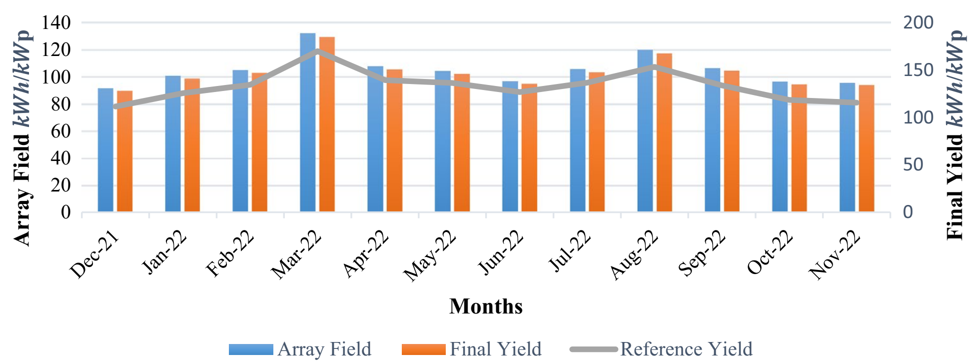
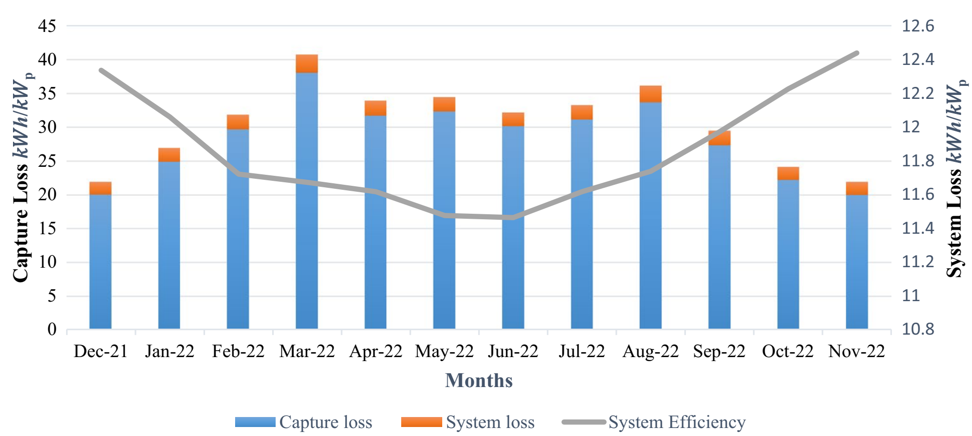



Fig. 16 Variation in energy losses and solar PV system plant efficiency month to month




of (89.64 $kWh/kW_p$-month) month in December 2021 to a maximum of (129.27 $kWh/kW_p$-month) in March 2022. From a minimum of 91.47 kWh/kWp-month in December 2021 to a maximum of 131.91 kWh/kWp-month in March 2022, the average monthly array yield varies. From a minimum of 91.47 kWh/kWp-month in December 2021 to a maximum of 131.91 kWh/kWp-month in March 2022, the average monthly array yield varies. The horizontal irradiation average for the month, which is lowest in December and highest in March, can be blamed for this variance. The ultimate yield's value increased gradually starting in December 2021 and peaked in March 2022. From March to June 2022, the final yield initially declines before gradually increasing to achieve the second peak in August 2022 (117.35 $kWh/kW_p$-month).

Numerous appropriate research studies have been conducted on the analysis of solar PV performance with respect to reference yield, array yield, and final yield. The findings of a study on the long-term efficiency and deterioration analysis of a 5 MW solar PV plant in the Andaman & Nicobar Islands were presented by researchers Pushp Rai Mishra and Shanti Rathore [31]. The findings from this study. The maximum values of 4.92, 4.08, and 3.98 kWh/kW/day were noted for the reference yield, array yield, and final yield, respectively. The efficiency evaluation of a 4.98 kWp solar photovoltaic system for isolated Indian islands was investigated in a study that examined location and orientation [32]. The results of experiments for reference yield, array yield, and final yield were reported, with values that ranged from 5.41 to 6.86 h/d, (4.03 to 5.04) h/d, and (3.82 to 4.79) h/d. Overall, research demonstrates that the UTHM PV system is more widely used for energy collecting within a certain geographic area.

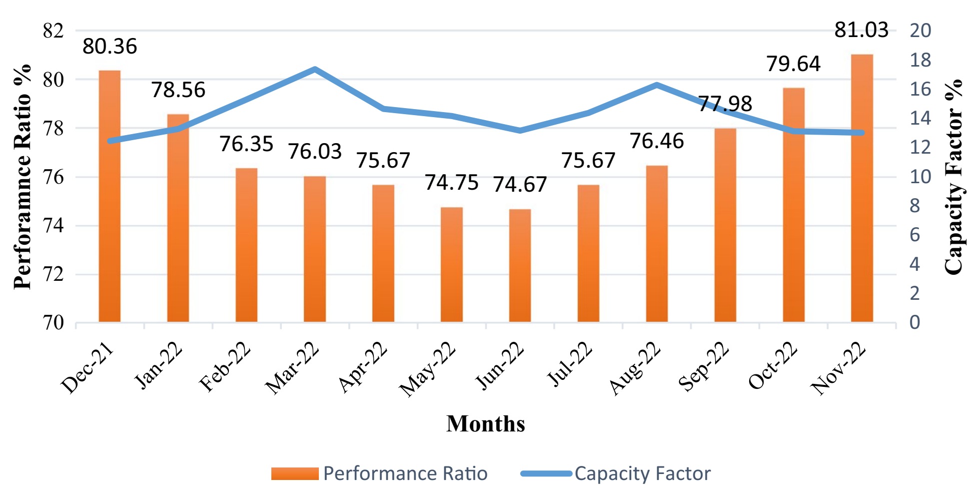
### 4.5 Energy losses

Figure 16 shows the monthly change in plant efficiency and loss characteristics (capture and system). The energy loss in a solar power plant rises to start in December (21.91 kWh/kWp), peaks in March (40.75 kWh/kWp), and then nearly stabilizes until it reaches its second peak in August 2022 (36.12 kWh/kWp). The energy loss in the solar plant is represented by the difference between the reference and final yields. Energy output is less than it would be under STC circumstances, according to the energy loss value. The primary environmental elements causing this variation are the shift in sun irradiance and site-specific ambient temperature. Compared to the capturing loss (blue colored in the graph), the system loss (seen in orange on the graph) is little. The solar power plant's energy output decreases as energy loss rises. The interaction of heat loss in power cables, interconnections, and losses from dirt mostly brings on energy losses. The estimated average energy efficiency for the solar PV facility is 11.86%.

### 4.6 Variation of performance ratio and capacity utilization factor

An acceptable operation is indicated by the average PR value of 77.26%. Figure 17 depicts the variation in PR and CF over a predetermined time frame. This variance falls between the PR and CUF range for solar PV systems in nations in Southeast Asia [33–35]. The variation in solar irradiation had no effect on the performance ratio. The month of November, which has a low solar irradiation of 115.67 kWh/m2, has the highest performance ratio (81.03%), and the month of June, which has the lowest PR (74.67%), has the maximum solar irradiation of 126.89 kWh/m$^2$. The PR value decreased because solar PV plants lost more energy in the months with higher sun irradiation. The value of CUF fluctuates between 12.45 and 17.37%, which is within the 16%–17% range of most of Malaysia's rooftop solar PV systems. The variation in CF can be explained by the value of the ultimate yield, which depends on how much electrical energy is generated. There are two peak parts in the CF of the 6.9 MWp solar PV system. The first peak was between the lowest value (12.45%) in December 2021 and the peak (17.37%) in June 2022. Because there are more days with rain (and less energy produced during these months), the CF value progressively rises from June 2022 onwards and achieves a second peak in August 2022 (16.29%). A decline follows this in CF value to fall to the lower (13.01%) in November. The ambient temperature influences the amount of energy produced, and it has been noticed that as the temperature increased, so did the volume of energy produced. The PV system's annual monthly average CUF was discovered to be 15.27%, which is greater than some other tests on rooftop PV systems conducted in Malaysia, which were only 9.27%–14.85% [8].

Fig. 17 Performance ratio and capacity utilisation factor monthly variation



### 4.7 Avoided $CO_2$ emissions

This section goes through the idea of reducing $CO_2$ emissions and how it relates to the overall amount of electrical energy Malaysia will produce in 2021. It initiates with environmental variables that must be considered while evaluating carbon dioxide emissions. In Malaysia, the $CO_2$ factor, representing the quantity of $CO_2$ released for every unit of generated electricity, is 0.639 $tCO_2/MWh$ (metric tons of $CO_2$ per megawatt-hour) on average [36]. In contrast to coal-based thermal power plants, which produce significant amounts of GHG like $CO_2$, NOx, $SO_2$, and ash, a any other renewable energy source, such as a PV system would have a positive environmental impact. Moreover, the installed 6.9 $MW_p$ solar system in UTHM is evident in its per capita carbon emissions reduction achieved by this PV system, which is estimated to be 5450 tons per year, this translates to 136,250 aged trees have been saved from being cut down. The reduction in greenhouse gas emissions is shown, along with a comparison of the acquired results with other data found in the literature. The research study performed by Muhammad Firdaus Mohd Zublie, Md. Hasanuzzaman, and Nasrudin Abd Rahim examined the rooftop solar photovoltaic system for the Net Energy Metering Scheme in Malaysia[15]. The outcomes indicate that an overall of 728,625 kg$CO_2$ of carbon emissions were lowered over time. According to a study conducted by Ilhom Ismatovich Raxmatov, 300 kW solar photovoltaic systems might prevent between 90.4 and 95.5 tons of $CO_2$ emissions from entering the region. The study evaluated the system's effectiveness in the Uzbek environment [37]. According to the report, the 6.9 MWp solar PV system at UTHM's reduction of emissions analysis is comparable to other solar power plants globally.

### 4.8 Cost analysis

Figure 18 illustrates the variance in electricity purchases and savings with individual consumption. The utility bill without PV system is estimated to be 7.1 RM mil yearly. April (0.69 mil), Sept (0.67 RM mil) and Nov (0.679 RM mil) are when peaks of utility costs in the absence of PV. The months of February (0.47 mil), June (0.407 RM mil), and July (0.512 RM mil) saw the utility costs in the absence of PV. PV savings in total with self-consumption value decreseas gradually starting in December 2021 and peaked in March achieve the highest of 0.1 RM mil. From March to June 2022, PV savings with the self-consumption initially decline before gradually increasing to achieve the second peak in August 2022 0.16 RM mil. The PV saving with self-consumption recorded 1.08 RM mil yearly. The new utility bills since the PV system was installed is 6.02 RM mil yearly. The 6.9MWp solar PV system is estimated to reduce 25.1 RM mil in 25 years.

### 4.9 Self-consumption vs self-sufficiency

Figure 19 illustrates the concept of the constant base load, showing ratio between the PV production and the portion of the PV production consumed by the loads under ambient condition in UTHM, Batu Pahat since the air is humid and carries many particles which scatter the sunlight, and the ambient temperature is quite high.

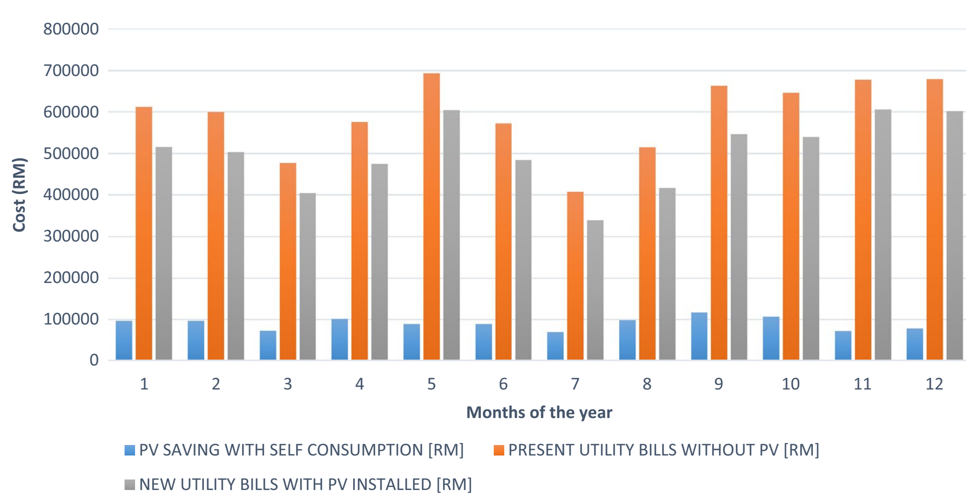



**Fig. 18** Variation in the cost of electricity and savings through self-consumption

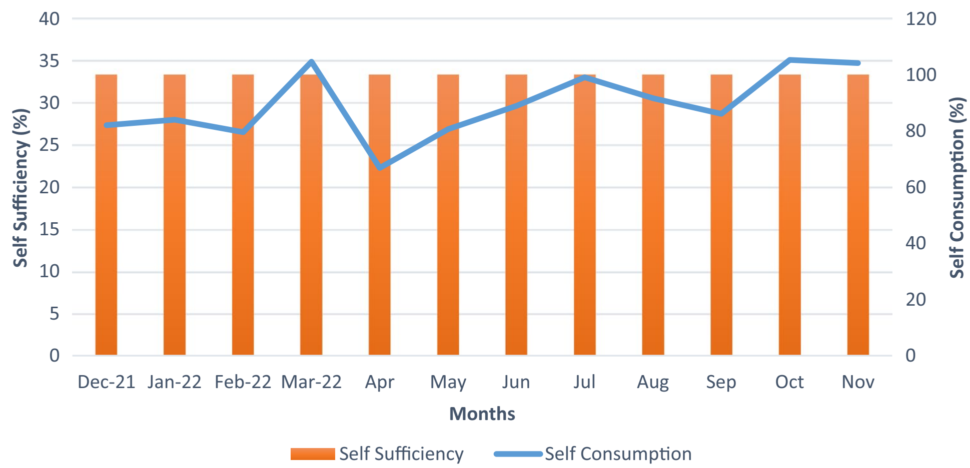



**Fig. 19** Self-sufficiency and self-consumption for 6.9 MWp grid-connected PV system at UTHM

This 6.9 MWp solar PV system at UTHM ensures that no extra electricity is wasted on the weekends and would also lower the amount of energy consumed from the grid during the week. It is feasible to reach self-consumption levels of up to 100% because every watt of electricity generated contributes to returns and none is wasted, and it is always guaranteed that no electricity will be injected into the power grid. The self-sufficiency of this solar plant is relatively low, ranging from 22 to 35% as shown in Figure 19.

The self-sufficiency rate (SSR) and the self-consumption rate (SCR) are 26.6% and 92.0%, respectively, according to Edwin Garabitos Lara's research on self-consumption with residential PV systems in the context of the Dominican Republic [38]. Furthermore, the analysis of the Solar collective self-consumption by Idiano D'Adamo and Massimo Gastaldi reveals that the distribution of self-consumption falls between 30 and 60% [39]. In the study, the government's anticipated 50% self-consumption rate (with respect to PV generation) for residential systems was evaluated, and additional proof was requested. Researchers Sugiartha et al. conducted research on solar photovoltaic systems with self-consumption in villas [40]; they reported ratios of 93.5% for self-consumption and 35.6 percent for self-sufficiency. The acceptable range of self-consumption rates was estimated to be 25–45% based on the scant evidence that was available, and a purposefully high number of 45% was selected to "encourage those installations that make the most use of the renewable electricity generated" (DECC, 2015a, p. 31) [41]. Finding all this evidence suggested the safe operation of the 6.9MWp solar system in UTHM, Batu Pahat.

## 5 Discussion

### 5.1 Comparative performance indices of PV system

The results from similar studies in various places able to compare operating results from different PV systems, the specific yield in $\frac{kWh}{kW_p}/year$ is calculated as well as the performance ratio. Table 5 shows performance parameters for different building mounted PV systems. The annual average daily final yield of the PV system in this study was 4.23 $\frac{kWh}{kW_p}/day$ which was higher than those reported in Germany, Poland, Northern Ireland and India. Although it was less than the reported yields in Brazil and Malawi, it is equivalent to those from some regions of Thailand. When compared to the other systems, the PV system had the highest performance ratio, system efficiency, and PV module efficiency. The test site's low ambient temperature and high wind velocity made it ideal for PV systems.

An examination of the performance of a rooftop solar PV power plant at Kamuzu International Airport, Malawi, was conducted by Banda et al. [42]. The average efficiencies of the array, inverter, and overall system were 15.3%, 95.2%, and 14.6%, respectively. A 17.7% yearly capacity factor and a 79.5% average performance ratio were recorded on average. As was previously said, these outcomes are comparable to the UTHM solar PV facility and proved to be

**Table 5** Performance parameters for different grid-connected PV systems

| Location | PV type ($kW_p$) | Energy output ($kWh/kW_p$) | Final yield ($kWh/kW_p$-$day$) | Module efficiency (%) | System efficiency (%) | Inverter efficiency (%) | Performance ratio (%) | References |
|---|---|---|---|---|---|---|---|---|
| Crete, Greece | 171.36 | 1336.6 | 1.96 to 5.07 | – | – | – | 67.36% | [45] |
| Dublin, Ireland | 1.72 | 885.1 | 2.4 | 14.9 | 12.6 | 89.2 | 81.5 | [26] |
| Brazil | 2.2 | 1685.5 | 4.6 | | | | 82.9 | [46] |
| Malaga, Spain | 2.0 | 1339 | 3.7 | 8.8–10.3 | 6.1–8.0 | 85–88 | 64.5 | [47] |
| Northern Ireland | 13 | 616.9 | 1.7 | 7.5–10 | 6.0–9.0 | 87 | 60–62 | [48] |
| Warsaw, Poland | 1 | 830 | 2.3 | 4.5–5.5 | 4.0–5.0 | 92–93 | 60–80 | [49] |
| Jaen, Spain | 200 | 892.1 | 2.4 | 8.9–10.1 | 7.8 | 88.1 | 62.7 | [50] |
| Thailand | 500 | 766.54 | 2.9–4.0 | 9–12 | | 92–98 | 70–90 | [34] |
| Cochin Airport, India | 12,000 | 1984.10 | | | | | 86.56 | [51] |
| Kamuzu Airport in Malawi | 830 | 1551.25 | 4.3 | 15.3 | 14.6% | 95.2% | 79.50 | [42] |
| UTHM | 6900 | 1236.1 | 4.23 | 14% | 11.86% | | 77.26% | Present case study |

Table 6 Energy per area ($kWh/m^2$) for different grid-connected PV systems

| Location | Capacity (kWp) | Annual GHI (kWh/$m^2$) | PV electricity generation (kWh) | Module area ($m^2$) | Energy per area (kWh/$m^2$) | References |
|---|---|---|---|---|---|---|
| Kenya | 600 | 1712 | 735,000 | 3740 | 196.52 | [52] |
| Brazil | 2.2 | 1825 | 3708.2 | 14 | 264.91 | [46] |
| Thailand | 325 | 1742 | 452,920 | 2156 | 210 | [53] |
| Northern India | 5kWp | 1787 | 7175.4 | 34 | 211.04 | [54] |
| Ireland | 1.72 $kW_p$ | 1724 | 1522.364 | 10.3 | 147.802 | [26] |
| South Africa | 3.2 kWp | 1797 | 5757 k | 28 | 205.607 | [55] |
| India | 11.2 | | 14,960 | 70.35 | 212.64 | [56] |
| UTHM | | 1746 | 8,529,656 | 39,567 | 215 | Present study |

nearly identical. Similar findings to this analysis have been reported by other researchers who have examined the operation of grid-tied PV systems [43, 44].

According to many academic sources, including Attari et al. [35], Ayompe et al., Adebiyi et al. [24], and Mensah et al. [20], the average capacity utilization factor ranges between 5and 20.1% (see Table 5). This demonstrates that the PV system at UTHM is reliable and performs at levels consistent with expectations [22, 26, 44].

### 5.2 Energy per area ($kWh/m^2$)

Similarly, the energy per area ($kWh/m^2$) of a solar PV array in relation to the deployment of solar PV in South India, North India, Kenya, Brazil, Thailand, and Ireland shown in Table 6. The highest and lowest values energy conversion rate is observed to be 147.802 $kWh/m^2$ and 264.91 $kWh/m^2$. The thorough comparison of PV systems shows that UTHM's 6.9MWP solar PV systems achieve the highest energy-per-area ratio in the area. This research site benefits from an ample supply of solar energy, which raises the overall energy production.

### 5.3 Comparative performance ratio and capacity utilization factor (CUF) of PV system

The performance ratio and capacity utilization factor (CUF) achieved were compared (Table 7) with those reported solar PV systems at different places that were employing similar solar PV technology of Mono-SI PV in order to solidify the rationale for placing the solar PV panel at the UTHM. In comparison to PV arrays installed in Ireland, Ifran, Spain, and Krishanagar, the PR and CF of solar PV is superior for the place under consideration. As a result, the performance indices for the monocrystalline silicon solar PV cell technology at UTHM are both superior and comparable to those found globally, suggesting that the location under consideration is suitable for the deployment of solar PV.

## 6 Conclusion

In Malaysia, PV plants are expected to generate a certain range of power based on standard test conditions. However, in practice, the average generated power rarely equates to anticipated outputs and doesn't meet load demand that is intended to cover. Consequently, 6.9 MWp solar pv system at UTHM offers self-generated solar electricity at public

Table 7 Performance parameters for employing similar solar PV technology of Mono-SI PV

| Location | Solar PV technologies | CF | PR | References |
|---|---|---|---|---|
| Ireland | Mono-Si PV | 10.1 | 81.5 | [26] |
| Ifran, Morocco | Mono-Si PV | – | 84.25 | [57] |
| Spain | Mono-Si PV | – | 69.5 | [58] |
| Krishanagar | Mono-Si PV | 16 | 77.5 | [59] |
| UTHM | Mono-Si PV | 15.27%, | 77.26 | Present study |

university. In this context, understanding self-consumption and self-sufficiency, to demonstrate the energy independence from national grid is important. Thus, the 6.9 MWp grid-connected PV system at UTHM, supported by the SARE contract under the SELCO scheme analyzed according to performance indices of IEC 61724 standards. The annual mean PR is determined to be 0.78, which is greater than the PR values reported in similar case studies conducted in other Southeast Asian nations, including Thailand, Vietnam, and Indonesia. The PV system's 108.28 MWh/MWp yearly average final yield shows superior performance to other solar PV systems evaluated in Malaysia in terms of final yield. The overall system efficiency is computed to be 11.86%, indicating the effective conversion of solar energy into electricity. 100% solar self-consumption 6.9 MWP solar PV Power plant indicated that all produced PV energy is consumed by the loads. The self-sufficiency of this solar plant is relatively low ranges from 22 to 43%. The 6.9 MWp PV system installation at UTHM has reduced the $CO_2$ emissions by approximately 5450 tonnes per year, thereby contributing to environmental sustainability and support Malaysia's efforts toward clean and green energy production. The 6.9 MWp solar PV system is estimated to reduce 25.1 RM mil in 25 years. Furthermore, the limitations pertaining to this study are lacks sensitivity analysis to assess the effects of different operating circumstances and system design characteristics. Furthermore, the study does not take the system's ohmic losses into account. This omission affects the 6.9 MWp solar PV system's total efficiency by ignoring possible inefficiencies in energy transit from the generating source to the load. Consequently, it is recommended that future research evaluate how aging factors affect solar PV performance, including efficiency, material deterioration, overheating, mismatching, and attaining sustainable management and operation of solar energy systems. Furthermore, the best way to evaluate design and orientation factors for the long-term expansion of rooftop solar PV system installations is through performance analysis. Future research on the impact of several tracking systems—one, two, azimuth, and seasonal tilt—on the functionality and energy efficiency of the system is crucial in this regard. Future studies ought to concentrate on investigating the issues around the shading effect and the impact of dust on the photovoltaic (PV) systems' efficiency at UTHM.

### 6.1 Recommendations and limitations

The characteristics of radiation from the sun itself are the primary constraints on PV generation. It fluctuates significantly throughout the day and over the seasons and has a poor power density. The main constraints for PV generating are the characteristics of solar radiation itself. It has a low power density and ranges greatly during the day and the seasons. It is essential to establish energy storage technologies that are both economical and efficient to preserve excess energy created during peak times for use during times when the output of renewable energy is low.

Furthermore, limitations pertaining to PV systems include unresolved issues with properly describing degradations, the impacts of hotspots, dust, and shade, and enhancing material efficiency. Performing under varying climatic circumstances, photochemical, thermomechanical, and chemical stressors on PV panels have an impact on their overall performance and ability to produce energy. Corrosion, encapsulant material delamination, browning of cell material, burn marks on the rear of modules, milky patterns, cracks in top facing glass, and solar cell flaws were the most common plant problems discovered.

Emphasis on creative solutions and strategic planning is crucial to overcoming obstacles and optimizing solar power in the 6.9 MWP solar PV system. Here are a few crucial methods:

- Technological Advancements: Continued research and development are essential to improving solar panel efficiency, durability, and cost-effectiveness. Advancements such as perovskite solar cells, smart grid integration, and energy storage innovations will enhance solar power's viability in the region.
- Policy and Regulatory Support: Governments and regulatory bodies play a crucial role in fostering a favourable environment for solar energy. Implementing supportive policies, incentivizing solar installations, and streamlining the permitting process can accelerate the adoption of solar power and reduce associated costs.
- Collaborative Partnerships: Collaboration between public and private sectors, academia, and international organizations can drive knowledge sharing, capacity building, and investment in solar energy infrastructure. Joint initiatives can help overcome financial barriers and leverage expertise for efficient project implementation.

**Author contributions** L.G—contributes on collection of data & analysis and interpretation of result; draft manuscript preparation M.M and M.A—contributes on implementation of installation of solar PV plant and configuration on data monitoring dashboard All authors reviewed the results and approved the final version of the manuscript.

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## Declarations

**Competing interests** The authors have no competing interests to declare that are relevant to the content of this article.



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