Performance assessment of three grid-connected photovoltaic systems with combined capacity of 6.575 kWp in Malaysia

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A B S T R A C T

This research aims to evaluate the performance of grid-connected photovoltaic systems based on three PV technologies along with a composite PV system installed at the rooftop of the engineering tower building, University of Malaya, Kuala Lumpur, Malaysia. The grid-connected PV systems are based on poly-crystalline (p-si), mono-crystalline (m-si), and thin-film (amorphous silicon (a-si)) technologies. The performance evaluation is based on the monthly and annual data that is monitored from January 2016 to December 2019. A comprehensive analysis is conducted on eleven performance parameters such as; performance ratio, capacity factor, array yield, final yield, PV array efficiency, PV system efficiency, inverter efficiency, AC energy, array losses, system, and the overall losses. Results show that p-si based PV system performs better with high annual average (array yield (1309.7 h), array efficiency (12.17%), and system efficiency (11.33%)) accompanied by less degradation in eleven parameters as compared to a-si and m-si PV systems.

Moreover, the performance ratios of p-si and a-si PV systems are found higher than the values reported in some of the existing literature studies, subjected to similar and different climatic conditions. The results also indicate that environmentally the composite PV system has the potential to avoid 28143.7 kg of CO2 emissions in four years. This research is expected to deliver valuable statistics to individuals and organizations about the real performance of grid-integrated PV systems in Malaysia, including other tropical climate regions in the world.

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1. Introduction

A spike in modern technology has triggered an exponential rise in the demand for electrical energy. Among different types of energy, electrical energy has a significant contribution to the society. The primary fossil fuel sources used for the generation of electrical energy are coal, oil, and natural gas. The extensive usage of these sources has put a real threat to their life. The approximate life of coal, gas, and oil reserves is 107, 37, and 35 years respectively (Akhter et al., 2019). On the other hand, excessive usage of fossil fuels creates an alarming condition for global warming due to pollution created from greenhouse gas (GHG) emissions (Adaramola et al., 2014). To deal with this energy crisis and climate issues, solar energy has attained prime importance among governments, decision-makers, sponsors, industrialists, and climate researchers, in contrast to other renewable energy sources (Clayton et al., 2015).

Solar energy has immense potential for electrification in both rural and decentralized areas (Halabi et al., 2017). The PV systems have attained global acceptance due to their massive potential for
The performance of PV systems mainly depends upon solar cell technology, solar radiation, and other climate factors. Therefore, proper monitoring of PV systems is required to define the behavior of PV modules against different meteorological parameters for accurate performance evaluation (Khalid et al., 2016). The purpose of monitoring the PV systems is to facilitate a means to ascertain and extract valuable information regarding operational problems to avoid similar issues in the future, and also to keep the PV system in continuous functional status with improved performance (Brecl et al., 2016).

Electrical output parameters are recorded at sampling times of 5, 15, and 30 min. The obtained data is checked and summarized for the analysis. Besides, at least one-year data is collected for analysis, although it has a provision for a sampling rate of 15 and 30 min data. Based on the adequately monitored data analysis, the prediction of inverter performance using the MPPT method can be executed (van Sark et al., 2017).

Table 1 describes the recent literature analyzing the performance of different PV technologies in various parts of the world to decide the optimum PV technology under a specified condition. To attain the optimum PV system for Malaysia, certain studies are described in the literature as well. The performance of two grid-linked PV systems was presented at Bangi. Malaysia (Humađa et al., 2016): one was mono-crystalline (m-si), and the other was copper indium—selenide (CIS) based modules. It was observed that the maximum monthly PR in a year for CIS and m-si was 84.1% and 79.1%, respectively. It indicates that CIS modules performed better than m-si under tropical atmospheric conditions. However, the performance of CIS as compared to p-si and a-si had not been evaluated. Furthermore, the efficiency of inverter (\( \eta_{\text{inv}} \)) and the PV system (\( \eta_{\text{sys}} \)) were also not assessed in this study. Another study (Kumar et al., 2019) was conducted at Universiti Malaysia Pahang (UMP). The performance of three PV technologies is evaluated in this study, which are CdTe, c-si, and CIS. The CdTe modules performed better with PR of 76.20%–77.36% as compared to the other two modules. Similar to the previous study, this study did not evaluate the performance of p-si and a-si under the tropical weather of Malaysia. Also, this study did not consider the analysis on several other performance parameters, i.e., \( Y_A, \eta_{\text{PV}}, \eta_{\text{sys}} \) and \( \eta_{\text{inv}} \).
A techno-economic study (Yatim et al., 2017) was performed on a 3.3 kW residential BIPV system with HIT, m-si, p-si, and thin-film modules in Penang, Malaysia. It was found that thin-film modules performed better than the other three modules. The annual energy produced was 4723 kWh, 4749.3 kWh, 4999.6 kWh, and 5179 kWh for HIT, m-si, p-si, and thin-film modules, respectively. However, detailed performance analysis was not conducted in this study. In Kuala Lumpur, a comparative study (Zain et al., 2013) was performed between grid-connected p-si and m-si PV structures. It was observed that the PR of p-si was 3% higher than the PR of m-si. However, a-si PV system was not presented in this study. Another common shortcoming of these four studies is that the performance analysis was conducted on only one-year data, hence the impact of degradation in the performance parameter had not been incorporated in these studies.

It is evident from these similar climate studies that there is no single best technology for the tropical climate of Malaysia. Therefore, it is necessary to assess various technologies over a long period within the same environment to obtain better information with regards to the performance deviations of a particular region for different environmental patterns. So far from the author’s knowledge, no study in Kuala Lumpur provides a detailed analysis based on several performance parameters for p-si, a-si, and m-si PV structures. It is observed that the PR of p-si was 3% higher than the PR of m-si. However, a-si PV system was not presented in this study. Another common shortcoming of these four studies is that the performance analysis was conducted on only one-year data, hence the impact of degradation in the performance parameter had not been incorporated in these studies.

The objective of this research is to evaluate the performance of grid-connected Photovoltaic systems based on three PV technologies along with a composite PV system installed at the rooftop of the engineering tower building, UM, Kuala Lumpur, Malaysia. The paper presents the monthly and annual evaluation based on eleven different performance indices such as the capacity factor, performance ratio, PV array efficiency, system efficiency, inverter efficiency, array yield, final yield, AC energy generated, array losses, system and the overall losses. The data employed for estimating the PV system performances were collected between January 2016 and December 2019. Furthermore, the paper compares the analysis results with those reported in some of the previous studies under similar and different climates. Furthermore, the contribution of the composite PV system to the environment is also examined in terms of Greenhouse gases (CO₂, SO₂, NOₓ, and Ash) reduction. This study provides an insight into the need to observe the PV system performance and extract valuable information regarding possible operational problems, to keep the PV system in continuous operational conditions with improved overall performance.

The remaining paper is planned as follows: The methodology is discussed in section 2; the results and discussions, including the comparison of results with the previous studies, are presented in section 3; a comprehensive summary of results is presented in section 4; the environmental impact of composite PV power system is elaborated in section 5, while, the results are concluded in section 6.

2. Methodology

In this section, the data analysis methods are discussed, using the PEARL’s grid-linked rooftop PV system, at the University of Malaya, Kuala Lumpur, Malaysia as a case study.

2.1. Description of the grid-connected PV system at PEARL lab

The PV system is installed at latitude and longitude of 3.07°N and 101.39°E, respectively, about 66 m above the sea level. It has three types of modules. Mono-crystalline PV array (SHELL/SQ75 model) has an installed capacity of 1.875 kWp for 25 modules, with 75WP capacity for each module. Poly-crystalline PV array (MITSUBISHI/PV-AE125MF5N model) has an installed capacity of 2.0 kWp for 16 modules, with 125 WP capacity for each module. PV array based on amorphous silicon technology (SHARP/NS-F135G5 model), has an installed capacity of 2.7 kWp for 20 modules, with 135 WP for each module. Therefore, the overall capacity of the composite PV system is 6.575 kWp. The individual PV structures were installed at a proper distance according to IEC 61730 standards which are being followed by Sustainable Energy Development Authority (SEDA) (Authority and Malaysia, 2013). SEDA is responsible for monitoring renewable energy projects in Malaysia. In Kuala Lumpur, there is no winter season. Therefore, the shading effect is minimum. However, there are two main seasons; sunny and rainy seasons. An optimum tilt angle of 10° for this PV system is also a key factor in reducing the shading effect (Saadatian et al., 2013).

All modules are fixed and oriented towards true south at azimuth and tilt (inclination) angle of 0° and 10° respectively. For a
fixed configuration, the angle of inclination is determined as an angle of PV modules from the horizontal level, while the azimuth angle is specified as an angle of PV modules relative to the southwards direction. Both angles are considered optimal. The Liu and Jordan model (1962) is used for the optimization of these angles (Khatib et al., 2015). Research in (Saadatian et al., 2013) reported that the solar radiation received at a tilt angle of 10° was maximum for PV panels in Kuala Lumpur. The PV panels have less shading effects and dust accumulation at this angle. In Malaysia, true south-facing (Azimuth 0°) is an optimum orientation at which PV systems have maximum annual average PV yield due to its location in the northern hemisphere (Ahmed et al., 2019). The phenomenon of natural cooling is adopted in the installation of this PV system by mounting the modules with an open back. Fig. 1 indicates the main parts of the rooftop fixed system. An overview of PEARL’s grid-connected PV system at the Faculty of Engineering, UM, Malaysia, is presented in Fig. 2.

PEARL’s grid-linked PV system was commissioned for use in October 2015. However, the results calculated in this study are based on data measured between January 2016 and December 2019. The data was recorded by a web server integrated with the inverter for 5-min intervals, from which related performance parameters are calculated at hourly, daily, monthly and yearly intervals by using relative mathematical formulas. The two inverters for p-si and m-si PV arrays have rated power of 1600W each. The third inverter for a-si PV array has a rated power of 2500W. Table 2 and Table 3 describes the technical specifications of the PV modules and inverters, respectively.

The SMA SUNNY SENSOR BOX is used to measure wind speed, solar irradiance, ambient, and PV module temperature. The SMA power injector is used to power the sensor box and is connected with SMA SUNNY WEBBOX through a communication bus. The Sunny Web box is used to record all the data from sensors and grid-connected inverters. The Sunny Web box is connected with local networks and desktop computers to save and monitor the data measurements. The data can be downloaded with a resolution of 5, 15 and 30 min, depending upon the requirement. The data for the previous 12 months remains available and can be downloaded at any time.

2.2. Performance analysis

For evaluating the performance of the PEARL’s grid-linked system, the following parameters are used: total AC (EAC) and DC energy (EDC) outputs (kWh), performance yields (reference yield (YR), array yield (YA), and final yield (YF)) (kWh/kWp), system efficiencies (inverter efficiency, array efficiency, and system efficiency) (%), CF (%), system losses (array losses, system losses, and overall losses) (Ls) (kWh/kWp) and PR (%). The analysis of the PV system is performed based on these parameters and can be compared with similar rooftop grid-tied systems regardless of capacity and location.

Fig. 1. Main parts of the rooftop fixed system (a) Photo of the installed three technologies PV systems (b) Grid-connected inverters.
2.2.1. AC energy output

The alternating current (AC) energy produced over a certain time by the system is called the energy output of the system. The total hourly ($E_{AC,h}$), daily ($E_{AC,d}$), monthly ($E_{AC,m}$) and yearly ($E_{AC,y}$) energy of the PV system are defined as follows (de Lima et al., 2017):

$$E_{AC,h} = \sum_{t=1}^{t=60} (E_{AC,t})$$  \hspace{1cm} (1)

$$E_{AC,d} = \sum_{h=1}^{h=24} (E_{AC,h})$$ \hspace{1cm} (2)

Fig. 2. An overview of PEARL’s grid-linked PV system at Faculty of Engineering, UM, Malaysia.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Technical specifications of PV modules.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>NS-F135G5</td>
</tr>
<tr>
<td>Maker</td>
<td>SHARP</td>
</tr>
<tr>
<td>Cell type</td>
<td>Thin film</td>
</tr>
<tr>
<td>Peak power, $P_{mp}$ (W)</td>
<td>135</td>
</tr>
<tr>
<td>$V_{mp}$ (V)</td>
<td>47</td>
</tr>
<tr>
<td>$I_{mp}$ (A)</td>
<td>2.88</td>
</tr>
<tr>
<td>$V_{oc}$ (V)</td>
<td>61.30</td>
</tr>
<tr>
<td>$I_{sc}$ (A)</td>
<td>3.41</td>
</tr>
<tr>
<td>Temperature coefficients</td>
<td></td>
</tr>
<tr>
<td>power, $P_{mp}$ (K/%)</td>
<td>$-0.30$</td>
</tr>
<tr>
<td>$V_{oc}$ (K/%)</td>
<td>$-0.24$</td>
</tr>
<tr>
<td>$I_{sc}$ (K/%)</td>
<td>$+0.07$</td>
</tr>
<tr>
<td>Mechanical specifications</td>
<td></td>
</tr>
<tr>
<td>Dimensions: Length X Width X Thickness (mm)</td>
<td>$1402 \times 1001 \times 24$</td>
</tr>
<tr>
<td>Weight (Kg)</td>
<td>26</td>
</tr>
<tr>
<td>Number of modules</td>
<td>20</td>
</tr>
</tbody>
</table>
The EAC energy becomes the input of an inverter. The daily (EDC) energy created by the PV system is known as DC energy output.

While EAC is the AC generated energy (in minutes). The yields represent the pragmatic action of PV array comparative to its rated capacity. There are three types of system yields, which are reference, array, and final yields. The ratio of DC energy output to the rated power of the PV system for a specific time is known as the array yield. It points out the number of PV array operating hours at its rated capacity to generate the equal DC energy, as measured. It is defined as (Attari et al., 2016):

\[ E_{AC,m} = \sum_{d=1}^{N} (E_{AC,d}) \] (3)

\[ E_{AC,y} = \sum_{m=1}^{P} (E_{AC,m}) \] (4)

The EACt is the AC generated energy (in minutes). While EACh, EACd, EACm, and EACy are the hourly, daily, monthly, and yearly AC generated energies. N and P are the number of days and number of months in equations (3) and (4), respectively. The energy created by the PV system is known as DC energy output. This DC energy becomes the input of an inverter. The daily (EDCd), monthly (EDCm), and yearly (EDCy) energy produced by the PV system is shown as:

\[ E_{DC,h} = \sum_{t=1}^{t=60} (E_{DC,t}) \] (5)

\[ E_{DC,d} = \sum_{h=1}^{h=24} (E_{DC,h}) \] (6)

\[ E_{DC,m} = \sum_{d=1}^{N} (E_{DC,d}) \] (7)

\[ E_{DC,y} = \sum_{m=1}^{P} (E_{DC,m}) \] (8)

**Table 3**

Technical specifications of inverters used in the PV system.

<table>
<thead>
<tr>
<th>Model</th>
<th>Sunny Boy 1600 TL</th>
<th>Sunny Boy 2500 HF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maker</td>
<td>SMA</td>
<td>SMA</td>
</tr>
<tr>
<td>No of units</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>DC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V_{max} (V)</td>
<td>600</td>
<td>700</td>
</tr>
<tr>
<td>V_{rated} (V)</td>
<td>400</td>
<td>530</td>
</tr>
<tr>
<td>V_{min} / V_{initial} (V)</td>
<td>125/150</td>
<td>175/220</td>
</tr>
<tr>
<td>I_{max} (A)</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>I_{ac} (A)</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>MPP inputs/strings per MPP input</td>
<td>1/1</td>
<td>1/2</td>
</tr>
<tr>
<td>AC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{rated} (W)</td>
<td>1600</td>
<td>2500</td>
</tr>
<tr>
<td>F_{mp} (VA)</td>
<td>1600</td>
<td>2500</td>
</tr>
<tr>
<td>V_{ac} (V)</td>
<td>220/230/240</td>
<td>220/230/240</td>
</tr>
<tr>
<td>V_{nominal} (V)</td>
<td>180–260</td>
<td>180–280</td>
</tr>
<tr>
<td>f (Hz)</td>
<td>50Hz/60Hz</td>
<td>50Hz/60Hz</td>
</tr>
<tr>
<td>PF</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Maximum efficiency (%)</td>
<td>96</td>
<td>96.3</td>
</tr>
<tr>
<td>European efficiency (%)</td>
<td>96</td>
<td>95.3</td>
</tr>
<tr>
<td>Dimensions: Length X Width X Thickness (mm)</td>
<td>440 × 339 X 214</td>
<td>348 × 580 X 145</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>16</td>
<td>17</td>
</tr>
</tbody>
</table>

2.2.2. System yields

The daily, monthly, and yearly array yield is given as:

\[ Y_{A} = \frac{E_{DC}}{P_{pv\text{-}rated}} \] (9)

\[ Y_{A,d} = \frac{E_{DC,d}}{P_{pv\text{-}rated}} \] (10)

\[ Y_{A,m} = \frac{E_{DC,m}}{P_{pv\text{-}rated}} \] (11)

\[ Y_{A,y} = \frac{E_{DC,y}}{P_{pv\text{-}rated}} \] (12)

The ratio of AC output energy to the PV rated power at standard test conditions (STC) for a specific time is called the final yield. It denotes the number of PV array operating hours at its rated capacity to generate the equivalent AC energy, as measured. It is given as (Adaramola, 2015):

\[ Y_{F} = \frac{E_{AC}}{P_{pv\text{-}rated}} \] (13)

\[ Y_{F,d} = \frac{E_{AC,d}}{P_{pv\text{-}rated}} \] (14)

\[ Y_{F,m} = \frac{E_{AC,m}}{P_{pv\text{-}rated}} \] (15)

\[ Y_{F,y} = \frac{E_{AC,y}}{P_{pv\text{-}rated}} \] (16)

The ratio of overall in-plane solar radiation (kWh/m²) to PV reference irradiance (1 kW/m²) over a given period is called reference yield. Peak sun hours are calculated from this yield. The reference yield is shown as:
The performance ratio is the ratio of final yield to reference yield. PR shows the familiarity of the system to its actual performance during real operation and provides the comparison of different PV systems irrespective of nominal rated power capacity, tilt angle, and location (de Lima et al., 2017). PR explains the effect of losses on the PV output power due to module temperature and the imperfect use of solar radiation. It is represented as (Kumar and Sudbakar, 2015):

$$PR = \frac{Y_F + 100}{Y_R} = 1 - \left( \frac{L_A + L_s}{Y_R} \right) \%$$

(23)

Where $Y_f$, $Y_r$, $L_A$, $L_s$, and PR are the final yield, reference yield, array losses, system losses, and performance ratio, respectively.

3. Results and discussions

3.1. Temperature effect on PV current and voltage

Fig. 3 and Fig. 4 describe the module temperature effect on PV voltage and current for one type of PV module at several intensities of solar irradiances. The maximum module temperature was 61.36 °C, which occurred at solar irradiance of 884.8 W/m². The maximum difference between a module and ambient temperatures was 22.58 °C. In Kuala Lumpur, the average daily ambient and module temperatures were 31.3 °C and 37.2 °C, respectively, for the examined period. The monthly average module temperature changed from 33.7 °C in November to 40.7 °C in March. While the monthly average ambient temperature changed from 29.8 °C in November to 33.1 °C in March.

It can be perceived from Fig. 3 that the PV voltage decreases slightly with the rise of module temperature at a certain solar irradiance level. While, the PV current is observed to increase with the increase in module temperature at the same solar irradiance level, as revealed in Fig. 4. At solar irradiance of 700W/m², the PV voltage decreases from 218.3 V to 209.5 V, and PV current rises from 9.38 A to 9.94 A as module temperature rises from 41.2 °C to 55.3 °C. It indicates almost no power loss due to a rise in temperature.

The PV voltage is decreased from 221.4 V to 206.8 V, and PV current has a rise from 2.02 A to 12.4 A at solar irradiance levels ranging from 100 W/m² to 900 W/m² respectively. An increase in PV module temperature is observed at solar irradiance levels between 600 W/m² and 900 W/m². 75% of overall in-plane solar irradiance is below 600 W/m² with the highest module temperature of 42.4 °C, which indicates a little effect of high module temperature on PV voltages and currents to acquire the maximum output power. The MPPT is also available in each inverter to track the maximum power point throughout the entire monitored period.

3.2. AC energy output

The monthly average and annual AC energy output are depicted in Figs. 5 and 6 respectively for all PV systems over the observed period of four years. The solar radiation is ranging from 100.7 kWh/m² in November to 130.4 kWh/m² in March, showing a strong relationship with AC energy produced. The monthly average AC energy generated is ranging from (239.7–319.3) kWh, (181.3–229.6) kWh, (105.7–105.7) kWh and (526.4–677.9) kWh, from November to March for a-si, p-si, m-si, and composite PV system respectively. The monthly average AC energy is perceived to be high for all three PV systems, from December to April, due to high solar radiation in these months. However, it is found low for all three PV systems; from May to November, due to less solar radiation in the rainy season.

The annual average AC energy generated is 3293.2 kWh, 2435.8 kWh, 1425.6 kWh, and 7179.5 kWh for a-si, p-si, m-si, and composite PV system respectively. The annual average AC energy of a-si based PV system (3293.2 kWh) is higher than yearly average AC energy of p-si (2435.8 kWh) and m-si (1425.6 kWh) modules based PV systems. The yearly average AC energy generated in m-si is about 56.7% and 41% less than that of a-si and p-si respectively because m-si array annual average array efficiency is 40% and 21.8% respectively.
lower than that of p-si and a-si PV systems respectively. The module hierarchy in the present study agrees with that reported in Penang, Malaysia (Yatim et al., 2017) in which a-si has also highest annual average AC energy (5179 kWh) followed by p-si (4999.6 kWh), m-si (4749.3 kWh) and HIT (4723 kWh).

Fig. 6 indicates that annual AC energy decreases slightly for the period (2016–2017), while it remains almost constant for the period (2017–2018) for all three PV systems. However, annual AC energy for a-si PV systems drops rapidly than the other two PV systems. The yearly AC energy has a variation of (3715–2808.9) kWh, (2547.6–2457.2) kWh, and (1600–1302.4) kWh during the monitored period (2016–2019) for a-si, p-si and m-si modules based PV systems respectively. The difference between the maximum AC energy in 2016 and the minimum AC energy in 2019 gives the total degradation in AC energy for the whole monitored period. Therefore, the degradation calculated in AC energy is 906.1 kWh, 90.4 kWh, and 297.6 kWh for a-si, p-si, and m-si modules PV systems, respectively, over the monitored duration.
Hence, a-si modules based PV system has a higher annual average AC energy generated than p-si and m-si PV systems, while the reduction in generated AC energy is found less for p-si (90.4 kWh) than that for a-si (906.1 kWh) and m-si (297.6 kWh) over four years.

3.3. System yields

Fig. 7 shows monthly average array and reference yield of different PV systems for the given period. The monthly average array yield has variation of (94.4–125.7) h, (97.5–123.8) h, (60.7–73.9) h, and (110.3–85.7) h, from November to March for a-si, p-si, m-si, and composite PV systems respectively. The monthly array yield for all three PV systems is observed to increase slightly with reference yield from January to March, while a decreasing trend is observed from March to June due to reduced solar radiation. In July, the monthly array yield for p-si is slightly above reference yield. It may happen due to improved array performance as a result of lower operating temperatures for this month. All three PV systems have followed the same trend as reference yield from August to December.

The monthly array yield for all three PV systems is observed high in sunny season (December–April) due to high solar radiation, with maximum value in March, while it is found low during the rainy season (May–November) due to low solar radiation, with the minimum value in November.

The annual array yield has a variation of (1462.7–1104.2) h, (1369.6–1321.4) h, and (912.8–749) h for a-si, p-si, and m-si modules based PV systems respectively, for 2016–2019. The difference between the maximum (2016) and minimum (2019) annual array yield gives the degradation in array yield over four years monitored period. Therefore, the degradation in array yield is 358.5 h, 48.2 h, and 163.8 h for a-si, p-si, and m-si modules PV systems, respectively. The degradation in array yield is higher for a-si (358.5 h) than p-si (48.2 h) and m-si (163.8 h) over four years period. Therefore, p-si modules based PV system has a high annual average array yield and less degradation than the other two systems.

Figs. 8 and 9 show the monthly average and annual final yield relative to reference yield for different PV systems, respectively, over the given data period. The a-si and p-si modules based PV system are generating final yield close to the reference yield, as shown in the figure. The variation of monthly average final yield is (88.7–118.3) h, (90.6–114.8) h, (56.3–68.8) h, and (103.1–80.1) h, from November to March, for a-si, p-si, m-si, and composite PV systems respectively. The monthly average final yield of a-si modules is higher than that of the other two modules from January to April due to high solar radiation, while from May to December, it is almost the same for both p-si, and a-si PV systems. However, m-si modules have the lowest monthly average final yield for all months due to poor array performance. For all three PV systems, the monthly average final yield is observed high in the sunny season due to high solar radiation, while it is found low due to less solar radiation in the rainy season.

The annual average final yield is 1219.7 h, 1217.9 h, 760.3 h, and 1088.1 h for a-si, p-si, m-si, and composite PV systems, respectively. The results demonstrate that the annual average final yield for a-si modules system is almost equal to p-si and higher than m-si modules based PV systems for a given period. The final yield for a-si modules is better than p-si and m-si from 2016 to 2018, but it is inferior than p-si modules for 2019. The annual average final yield
for m-si is low because the yearly average AC energy generated in m-si is about 56.7% and 41% less than that in a-si and p-si modules, respectively, due to poor PV array performance. The degradations in final yields are 335.6 h, 45.2 h, 158.75 h, and 196.8 h for a-si, p-si, m-si, and composite PV system, respectively, over four years. Based on these statistics, p-si is better than the other two PV systems with less degradation in the final yield over four years.

Moreover, the daily average final yields of a-si (3.34 h) and p-si (3.34 h) based PV systems in the present study are better than daily final yields of a-si (3.08 h), p-si (3.1 h) in Ghana (Quansah et al., 2017) and p-si (3.12 h) in Singapore (Wittkopf et al., 2012), which have a similar tropical humid climate like Malaysia. In (Wittkopf et al., 2012), p-si modules have the same manufacturer (Mitsubishi) as p-si modules in the present study. While, in comparison with different climate studies, p-si modules have daily average final yield (3.34 h) better than 3.32 h in India (Pundir et al., 2016), 2.55 h in Norway (Adaramola et al., 2015) and 1.45–2.44 h in India (Sharma and Chandel, 2013). Table 4 describes all these studies.

3.4. Capacity factor

The monthly average CF for three PV systems, together with a
The monthly average array efficiency for three PV systems, together with a composite system for the recorded period, is shown in Fig. 11. The array efficiency varies from 11.9% in February, March, October, and November to 13% in July for the p-si modules system, while it varies from 6.8% in March to 7.9% in July for m-si modules system. For a-si modules system, array efficiency varies from 9.3% in October and November to 9.8% in July for all three PV systems. The monthly average array efficiency is seen better in the showery season than that in the sunny season due to better array yield. The monthly average array efficiency is shown in Table 4. p-si modules (Mitsubishi) have better CF (15.7%) than p-si modules (Mitsubishi) (12.9%) in the present study. While, comparison with similar climate studies shown in Table 4, p-si modules (Mitsubishi) have better CF (13.5%) than p-si modules (Mitsubishi) (12.9%) in the present study. While, in comparison with different climate studies in Table 4, p-si modules in this study have CF (13.9%) better than 13.85% in India (Pundir et al., 2016), 10.56% in Norway (Adaramola et al., 2015) and 9.27% in India (Sharma and Chandel, 2013). The monthly average array efficiency is shown in Table 4. p-si modules (Mitsubishi) have better CF (15.7%) than p-si modules (Mitsubishi) (12.9%) in the present study. While, in comparison with different climate studies shown in Table 4, p-si modules in this study have CF (13.9%) better than 13.85% in India (Pundir et al., 2016), 10.56% in Norway (Adaramola et al., 2015) and 9.27% in India (Sharma and Chandel, 2013).

### 3.5. System efficiencies

The monthly average array efficiency for three PV systems, together with a composite system for the recorded period, is shown in Fig. 11. The array efficiency varies from 11.9% in February, March, October, and November to 13% in July for the p-si modules system, while it varies from 6.8% in March to 7.9% in July for m-si modules system. For a-si modules system, array efficiency varies from 9.3% in October and November to 9.8% in July. For all three PV systems, the monthly average array efficiency is shown in Table 4. p-si modules (Mitsubishi) have better CF (15.7%) than p-si modules (Mitsubishi) (12.9%) in the present study. While, in comparison with different climate studies shown in Table 4, p-si modules in this study have CF (13.9%) better than 13.85% in India (Pundir et al., 2016), 10.56% in Norway (Adaramola et al., 2015) and 9.27% in India (Sharma and Chandel, 2013).
The annual average array efficiency is 12.17%, 9.34%, 7.3%, 9.6% for p-si, a-si, m-si, and composite PV systems respectively. P-si modules system has higher annual average array efficiency than a-si and m-si modules system for the whole monitoring period. The degradations in array efficiencies are 1.46%, 1.94%, 1.44% for p-si, m-si, and a-si, respectively, over the monitored period (2016–2019). Degradation in array efficiency for p-si is almost the same as in a-si but lower than m-si.

Furthermore, the annual average array efficiency of the p-si modules (12.17%) based PV system is better than the p-si array efficiency (11.5%) found in a study at Kuala Lumpur (Zain et al., 2013). While, in comparison with different climate studies around the world, annual average array efficiency of p-si (12.17%) modules in the present study is better than 11.07% in India (Tripathi et al., 2014), (9.5–10.8) % in Japan (Tahri et al., 2018), 12.7% in Norway (Quansah et al., 2017), 11.34% in India (Yadav and Bajpai, 2018), 10.93% in Lesotho (Mpholo et al., 2015) and 9.45% in Turkey (Eke et al., 2013), for the same p-si module. The a-si modules have better annual average efficiency (9.34%) than 6.56% in India. Table 4 describes the performance of all these studies.

The monthly average and annual system efficiencies for three types of PV systems, together with the composite system for the observed period (2016–2019), are shown in Figs. 12 and 13 respectively. The system efficiency fluctuates from 10.9% in January and March to 12.2% in July for p-si, while it varies from 6.3% in March to 7.4% in July for m-si modules system. For a-si modules system, the system efficiency varies from 8.5% in September and October to 9.1% in July. In the rainy season, the monthly average system efficiency is found higher than that in the sunny season, for all three PV systems due to better array performance as a result of low operating temperature (Adaramola et al., 2015). The monthly average system efficiency for p-si modules is higher than the other two systems for the whole period.

The annual average system efficiency is 11.33%, 8.8%, 6.8%, 9% for p-si, a-si, m-si, and composite PV systems respectively. The annual average system efficiency for m-si is so different from p-si because the AC energy generated in m-si is about 41% less than AC energy in p-si due to poor array performance of m-si. The annual average system efficiency depends on AC energy, in-plane solar radiation, and the area of the PV module. Solar radiation is the same for all types of PV systems, and the area is fixed for each PV array. Therefore, the AC energy generated is the key factor that affects system efficiency. The degradation in system efficiency is 0.5%, 1.42%, and 2.42% for p-si, m-si, and a-si, respectively, over the monitored period. Therefore, p-si is superior to both a-si and m-si systems due to the high yearly average value and less degradation.
Moreover, the p-si modules in the current study have annual average system efficiency (11.33%) better than 11.2% in Singapore (Wittkopf et al., 2012) and 10.41% in Thailand (Chimtavee and Ketjoy, 2012). In (Wittkopf et al., 2012), p-si modules have the same manufacturer (Mitsubishi) as p-si modules in the present study. While, in comparison with different climate studies around the world, annual average system efficiency of p-si (11.33%) modules in the present study is better than 10.52% in India (Tripathi et al., 2014), 10.24 to 10.7% in Japan (Tahri et al., 2018), 8.7% in India (Pundir et al., 2016), 10.02% in India (Yadav and Bajpai, 2018) and 9.58% in Lesotho (Mpholo et al., 2015), for the same p-si module. The a-si modules also have better annual average system efficiency (8.8%) than 6.06% in India (Tripathi et al., 2014). Table 4 describes all these studies.

Fig. 13 shows the monthly average inverter efficiency for three PV systems together with a composite system over the monitored period (2016–2019). The inverter efficiency of a-si is better as compared to the inverter efficiencies of the other two PV systems. The inverter efficiency varies from 94% in May and June to 94.3% in September and November for a-si modules system, while it varies from 92.8% in November to 93.3% in February for m-si modules system and from 92.7% in March to 93.2% in July for the p-si modules system.

An increasing trend is observed in inverter efficiency from March to April because the drop in AC generated energy is found lower as compared to the decline in DC energy due to a decrease in solar radiation at the early start of rainy days. The inverter efficiency for p-si and m-si is observed almost equal from April to December except for the first four months, while a-si has better inverter efficiency than the other two modules. The monthly average inverter efficiency is found almost equal in both sunny (December–April) and the rainy seasons (May to November), for all the PV systems.

The annual average inverter efficiencies are 93%, 93.1%, 94.1%, 93.5% for p-si, m-si, a-si modules and composite PV systems, respectively. The annual average inverter efficiency for a-si modules PV system is greater than that for the other two PV systems over the whole period. In comparison with similar climate studies, the p-si modules in the present study have an annual average inverter efficiency (93%), equal to 93% (Chimtavee and Ketjoy, 2012) and better than (87.9–89.2%) (Chimtavee et al., 2011) both in Thailand. While comparing with different climate studies around the world, annual average inverter efficiency of p-si (93%) modules in the present study are better than (89.1–89.2%) in Japan (Tahri et al., 2018), 89.8% in India (Sharma and Goel, 2017), 8.7% in India (Pundir et al., 2016), 88.8% in Norway (Quansah et al., 2017), 88.4% in India (Yadav and Bajpai, 2018), 87.8% in Lesotho (Mpholo et al., 2015) and 88.1% in South Africa (Okello et al., 2015), for the same p-si module. Table 4 describes the performance of all these studies.

### 3.6. Array and system losses

The monthly average array and system losses for three types of PV systems, along with the composite system for the observed duration (2016–2019), are displayed in Fig. 17. The array losses vary...
from 5.3 h in July to 4.9 h in February for p-si and from 33.3 h in July to 56.5 h in March for m-si PV system, while they vary from 1.6 h in July to 7.3 h in October for a-si PV systems. For all three PV systems, a gradual decrease in annual array losses is observed from March to July due to the decline in solar radiation and an increase in PV array efficiency during these months. However, these losses are increased gradually from July to October due to the rise in solar radiation and a decrease in PV array efficiency. However, monthly average array losses are found higher in a sunny season than in the rainy season due to poor array performance for all three PV systems.

The annual average array losses are 24.7 h, 517.8 h, 38.7 h, and 171.7 h for p-si, m-si, a-si modules based and composite PV systems. The annual average array losses for m-si PV systems are higher than the other two PV systems. The reason is that the yearly average array yield of m-si PV systems is 37.6% and 37% lower than p-si and a-si, respectively, due to poor m-si array performance. The annual average array efficiency of m-si PV systems is also 40% and 21.8%
The negative values of array losses (array capture gain) in a few months for p-si and a-si modules PV system, caused higher PR and array efficiency. The reason is that solar radiation is lowest with high humidity in June and July due to heavy rains. The drops of water remain on the PV module as a result of heavy rains and humid environment, which keep the module cool by transferring its heat into ambient by evaporation. The array performance is enhanced as a result of this cooling effect due to high humidity in these rainy months (June and July) (Adaramola et al., 2015). The overall average array losses for p-si modules based PV systems are lower than that for the other two systems.

The monthly system losses have variations of (6.7–9) h, (4.4–5.1) h, and (5.7–7.4) h, from November to March, for p-si, m-si, and a-si modules respectively. The system losses are higher in the sunny season than in the rainy season due to poor array performance and lower system efficiency. The annual average system losses are 91.7 h, 56.1 h, 76 h, and 75.1 h for p-si, m-si, a-si, modules based and composite PV systems. The m-si modules based composite PV systems have lower yearly system losses than the other two PV systems.

The overall annual losses (array losses + system losses) for three types of PV systems, along with the composite system, are depicted in Fig. 18. The overall annual average losses 116.4 h, 574 h, 115.3 h, 246.15 h for p-si, m-si, a-si, and composite PV systems, respectively. The overall annual losses for a-si based PV system are negative in 2016 due to enhanced array performance in rainy months as a result of low operating temperatures (Adaramola et al., 2015). The annual average overall losses of a-si and p-si modules are almost the same and less than the m-si PV system over the monitored period (2016–2019).

### 3.7 Performance ratio

The monthly average and annual PRs for three types of PV systems along with composite PV system over the observed duration (2016–2019) are revealed in Figs. 19 and 20, respectively. The average monthly PR varies from 88% in January and March to 98.1% in July for p-si modules, while it varies from 53% in March to 62.8% in July for m-si modules. However, for a-si modules, the average monthly PR is ranged from 88% in October to 95.7% in July. The a-si modules have better PR than the other two modules from January to April, while for the remaining eight months, p-si has higher PR than the other two. For all three PV systems, the average monthly PR is observed low from December to April due to high reference yield and overall losses during the sunny season. However, it is found high from May to November during the rainy season due to low reference yield and overall losses.

The annual average PR is 91.3%, 91.3%, 57.2% and 81.6% for p-si, a-si, m-si, and composite PV systems respectively. The annual PR is found to drop rapidly for a-si than p-si and m-si PV systems over the duration (2017–2019). It is due to high overall losses in a-si during that period. While the m-si PV system is observed to have lower average yearly PR than a-si and p-si, because the yearly average final yield of m-si modules is about 37.6% and 37.7% lower than that of p-si and a-si modules respectively. The PR degradation for a-si modules (24.2%) is higher than p-si (3.9%) and m-si modules (12.1%) for the monitored period. Therefore, the p-si modules based PV system is superior to both a-si and m-si modules based PV system due to less PR degradation, even though the PR of p-si and a-si is equal.

Table 4 describes the comparison of the present study with similar and different climate studies. In comparison with similar studies, the annual average PR of a-si (91.3%) and p-si (91.3%) based PV systems in the present study are better than PR of a-si (75.8%) in Ghana (Quansah et al., 2017), p-si (76.3%) in Ghana (Quansah et al., 2017), p-si (80%) in Kuala Lumpur (Zain et al., 2013), p-si (84%) in Singapore (Wittkopf et al., 2012) and p-si (73.45%) in Thailand (Chimtavee and Ketjoy, 2012). In (Wittkopf et al., 2012), p-si modules have the same manufacturer (Mitsubishi) as p-si modules in the present study. The m-si has comparatively less annual average PR (57.2%) than (59.9%–79.1%) (Humada et al., 2016) and 77.28% (Farhoodnea et al., 2015) in Malaysia. Comparing with different climate studies, p-si modules in the present study have average PR (91.3%) better than (80.8%–86.5%) in Japan (Tahri et al., 2018), 78.48% in India (Ramanan and Karthick, 2019), 78% in India (Sharma and Goel, 2017), 63.7% in India (Pundir et al., 2016), 83.03% in Norway (Adaramola et al., 2015), 74% in India (Sharma and Chandel, 2013), 77% in India (Yadav and Bajpai, 2018), 70% in Lesotho (Mpholo et al., 2015), 72% in Turkey (Eke et al., 2013), 84.3% in South Africa (Okello et al., 2015), 85% in India (Vasisht et al., 2016) and 67.36% in Greece (Kymakis et al., 2009). While, a-si modules have PR (91.3%) better than 70.8% in India (Tripathi et al., 2014), (68%–75%) in Mauritania (Sidi et al., 2016) and 79.5% in India (Shukla et al., 2016).
4. Summary

The a-si modules based PV system have shown better annual performance parameters than the other two PV systems except for the array efficiency, system efficiency, and array yield over three-year period (2016–2018). However, in 2019, the performance of a-si becomes worse than p-si due to less value of generated DC and AC energies as a result of poor array performance. The m-si PV system is observed to have a lower annual average PR than the a-si and p-si because the yearly average final yield of the m-si PV system is about 37.6% and 37.7% lower than that of p-si and a-si PV systems, respectively. The annual average final yield and CF for m-si are lowest because the yearly average AC energy generated in m-si is about 56.7% and 41% less than that in a-si and p-si, respectively. It is due to poor m-si array annual average array efficiency, which is 40% and 21.8% lower than that of p-si and a-si PV systems, respectively.
The yearly average array yield of m-si PV systems is also 37.6% and 37% lower than p-si and a-si, respectively, due to poor array performance. Therefore, the overall annual losses (array + system) of m-si are found higher than that of a-si and p-si PV systems, respectively. However, the m-si modules have less annual average system losses (561.1 h) than p-si (913 h) and a-si (76 h) PV system. While the yearly average inverter efficiency of m-si (93.1%) modules is slightly better than that of p-si (93%) but less than that of a-si (94.1%).

The monthly average (PR, array, and system efficiencies) are found lower in sunny season (November–April) than in the rainy season (May–October) due to poor array performance and higher overall losses for all three PV systems. While, monthly average (DC energy, AC energy, array yield, final yield, CF, and overall losses) are found higher in the sunny season than in the rainy season, as a result of higher solar radiation. However, monthly average inverter efficiency is observed almost equal in both seasons.

The PV systems based on p-si and a-si modules have an equal annual average (PR, CF, final yield, and overall losses). However, the yearly average (array yield, array, and system efficiency) of p-si based PV system is better as compared to the other two PV systems for the monitored period (2016–2019). While the degradations in almost all these performance parameters are found less in p-si than a-si and m-si modules based PV systems for the entire monitored period. Therefore, poly-crystalline based PV systems are the more suitable choice for the site considered due to high array yield, array and system efficiencies along with less degradation in almost all the considered performance parameters as compared to other two (a-si, m-si) PV systems for the monitored period (2016–2019).

5. Environmental impacts of composite PV power system

The clean energy generated by the PV has an encouraging impression on the atmosphere. A considerable amount of greenhouse gases (CO2, SO2, NOx, and Ash) are released by the coal thermal power plants. It is estimated that composite PV system (6.575 kWp) has caused a total reduction of 28143.7 kg CO2 (Kumar and Systems, 2016; Sharma and Goel, 2017), 35.64 kg SO2, 74.4 kg NOx, and 1952.9 kg Ash (Tarigan and Kartikasari, 2015) in four years. The annual average reduction is 7035.9 kg CO2, 8.9 kg SO2, 18.6 kg NOx, and 488.2 kg Ash. The annual reduction of GHG emissions by composite (6.575 kWp) PV system is presented in Table 5. The formula for calculating GHG (CO2, SO2, NOx, Ash) emission reduction is given as follows: [Produced electricity (kWh)] x [Factor for GHG (CO2, SO2, NOx, Ash) avoided (kg/kWh)] = avoided (CO2, SO2, NOx, Ash) in kg. For example for 2016 the avoided CO2 (kg) = [7862.6 (kWh)] x [0.980 (kg/kWh)] = 7705.35 kg.

Table 5

<table>
<thead>
<tr>
<th>Reference</th>
<th>GHG</th>
<th>Emission (kg/kWh)</th>
<th>Total annual reduction (KG) every year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kumar and Systems, 2016</td>
<td>CO2</td>
<td>0.980</td>
<td>7705.35</td>
</tr>
<tr>
<td>Sharma and Goel, 2017</td>
<td>SO2</td>
<td>0.0124</td>
<td>9.75</td>
</tr>
<tr>
<td>Tarigan and Kartikasari, 2015</td>
<td>NOx</td>
<td>0.0259</td>
<td>20.4</td>
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<tr>
<td>Tarigan and Kartikasari, 2015</td>
<td>Ash</td>
<td>0.068</td>
<td>534.7</td>
</tr>
</tbody>
</table>

Based on the technical analysis of these performance parameters, it is concluded that p-si based PV systems are the most suitable choice. In contrast, m-si based PV system is the least appropriate choice for the site considered. Further study can be conducted in the future to analyze the performance of the system from an economic perspective to determine the most cost-effective PV modules for this tropical climate.

6. Conclusions

This study is conducted for three grid-linked PV systems along with the composite system (6.575 kW) installed at the UM, Kuala Lumpur, Malaysia, for the monitored data period (2016–2019). The findings of this research can be summarized as follows:

- The annual average AC energy is 3293.2 kWh, 2435.8 kWh, 1425.6 kWh, and 7172.3 kWh for a-si, p-si, m-si, and composite PV systems, respectively.
- The p-si modules based PV system has a higher annual average array yield (1309.7 h) than a-si (1295.7 h) and m-si (816.4 h) based PV systems, with a yearly average array yield of 1166.1 h for the composite PV system.
- The p-si modules based PV system has an annual average final yield (1217.9 h), almost equal to a-si (1219.7 h) and higher than m-si modules (760.3 h), with a yearly average final yield of 1091 h for the composite PV system.
- The annual average CF is 13.9%, 13.9%, 8.7% and 12.43% for a-si, p-si, m-si, and composite PV systems respectively.
- The annual average (array, system) efficiencies are (12.17%, 11.33%), (9.34%, 8.8%), (7.3%, 6.8%), and (9.63%, 8.96%) for p-si, a-si, and m-si modules based and composite PV systems respectively. The p-si modules PV system has the highest array and system efficiencies than the other two PV systems.
- The annual average inverter efficiency is 94.1%, 93%, 93.1% and 93.5% for a-si, p-si, m-si, and composite PV systems respectively.
- The annual average overall losses are 115.3 h, 116.4 h, 574h, and 241.95 h for a-si, p-si, m-si, and composite PV systems, respectively.
- The annual average PR for a-si and p-si modules based PV systems is equal (91.3%) and is greater than that for m-si modules (57.22%) based PV systems, with annual average PR of 81.6% for the composite system. Moreover, the PRs of p-si and a-si based PV systems are higher than PRs reported in 25 literature studies with similar and different climates, as shown in Table 4.

While lesser degradations have been observed in almost all the performance parameters for p-si than a-si and m-si PV systems for the whole period.

It is estimated that being a source of clean energy, the composite PV system (6.575 kWp) has significant potential to clean the environment from pollution by avoiding 28143.7 kg CO2 in four years with an annual average of 7035.9 kg CO2.

CRediT authorship contribution statement

Muhammad Naveed Akhter: Resources, Formal analysis, Writing - original draft. Saad Mekhilef: Resources, Formal analysis,
Declarations 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.

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