Bulletin of Electrical Engineering and Informatics
Vol. 12, No. 4, August 2023, pp. 1993~2004
ISSN: 2302-9285, DOI: 10.11591/eei.v12i4.5072

Comparative analysis of grid-connected bifacial and standard mono-facial photovoltaic solar systems

Nor Hidayah Abdul Kahar[1], Nurul Hanis Azhan[2], Ibrahim Alhamrouni[2], Muhammad Nubli Zulkifli[2], Tole Sutikno[3], Awang Jusoh[4]
[1]Intelligent Embedded Research Laboratory (IERL), Electrical Engineering Section, Universiti Kuala Lumpur British Malaysian Institute, Selangor, Malaysia
[2]Renewable Energy Research Laboratory (RENERAL), Electrical Engineering Section, Universiti Kuala Lumpur British Malaysian Institute, Selangor, Malaysia
[3]Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[4]Department of Power Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia

Article Info

Article history:

Received Oct 24, 2022
Revised Dec 12, 2022
Accepted Feb 23, 2023

Keywords:

Bifacial
Large-scale solar
Mono-facial
Return on investment
Solar power

ABSTRACT

This paper describes the design of a solar photovoltaic (PV) system using simulation of PVsyst software. This work involves the simulation of bifacial and mono-facial PV solar in a large-scale solar system. For a bifacial system, the yearly total energy to the grid is 1699.6 MWh, with an average of 4.57 kWh/kWp/day. For a mono-facial system, the total energy to the grid over the year is 1645.3 MWh, with an average of 4.05 kWh/kWp/day. The average collection losses obtained for bifacial and mono-facial modules were 0.33 kWh/kWp/day and 0.82 kWh/kWp/day, respectively, with system losses of 0.15 kWh/kWp/day (bifacial) and 0.18 kWh/kWp/day (mono-facial). The average performance ratio for bifacial and mono-facial was 0.904 and 0.801, respectively. The bifacial PV system was able to generate profit in terms of Return on investment (ROI), around 357%, and reach a breakeven around 7 years. The payback period for a mono-facial PV system was around 8.1 years, with an ROI of 290.4%. This work mainly focuses on a comparative analysis of bifacial and mono-facial photovoltaics, emphasizing the effectiveness and the implementation suitability of bifacial photovoltaics over mono-facial PV solar systems.

Corresponding Author:

Nurul Hanis Azhan
Renewable Energy Research Laboratory (RENERAL), Electrical Engineering Section
Universiti Kuala Lumpur British Malaysian Institute
Batu 8, Jalan Sungai Pusu, Gombak, 53100 Selangor, Malaysia
Email: nurulhanis@unikl.edu.my

1. INTRODUCTION

Solar energy for electric energy generation is an important source of green and renewable energy, experiencing remarkable expansion in recent years [1]. According to Lewis [2], solar energy can satisfy the energy demand satisfactorily because it is abundant in nature and a free energy source, making it very attractive for power generation. Solar energy is harnessed through various technologies, for example, solar photovoltaic (PV), thermal electricity, solar heating, solar architecture, solar fuels, and artificial photosynthesis [3]–[6]. However, PV technology has dominated the renewable market, with the installations reaching the capacity of 183 GW in total by the end of 2021 [7]. The interest is due to the advantages of PV technology that can be built as standalone systems, as well as continuous support from the government, cost reduction, reliability, and limited supply of non-renewable sources [8], [9]. PV system have numerous technological applications, including reverse osmosis plants [10], [11], solar home systems [12], [13], power generation [14], [15], water pumping [16], [17], remote buildings [18], [19] and other applications [20], [21]. Therefore, the demand for a PV system is increasing every year, and the analyst has revised its outlook for 2022, expecting a new PV system may total between 204 and 252 GW [7].

In the past few years, the PV industry has made significant efforts to develop highly efficient solar cells capable of producing greater electricity power [22]. There has been growing market interest in bifacial PV module types, which are expected to be the next breakthrough technology in the field [23], [24]. Currently, bifacial PV modules correspond to approximately 20% of the market share of PV technologies, which is expected to increase up to 35% by 2030 [25]. The growing interest arises from developing solar cells with rear-side metallization, and their integration into glass–glass modules enable the utilization faces of the bifacial PV module to be used for generating electricity. By taking advantage of this bifaciality, more significant amounts of energy can be produced compared to mono-facial module PV panel, which utilizes solar from only one side [26]–[28]. Depending on the installation, about 20% more energy can be produced by bifacial PV modules side by side compared to equivalent mono-facial modules. Moreover, bifacial PV modules cost the same as conventional mono-facial modules with the same front surface [29].

Previously, various solar plants were proposed for evaluating the performance of bifacial and mono-facial PV systems. Tina *et al.* [30] proposed and compared the performance of bifacial PV and mono-facial modules in floating power plants. Gallegos *et al.* [31] have analysed the performance of bifacial and traditional PV modules in terms of cost-effectiveness. Perera and Wen [32] proposed a performance analysis of a 10 kW grid-connected solar power system with a comparison in the integration of bifacial PV systems versus mono-facial PV systems. Perera and Wen [32] focused on smaller solar power stations and only on the solar panel's efficiency. Hundreds of companies worldwide are involved in producing PV modules with varying efficiencies and limitations. Additionally, the installation costs for solar PV vary depending on the system and the project. The expected increase in energy yield is strongly influenced by various factors such as ground reflection properties, module orientation, mounting height, number and distance of surrounding modules, geographical location, climate, and others. Thus, the PV system cannot be predicted in a general way with simple estimations, and it is crucial for the researcher to evaluate the implementation of the PV system in a specific location.

This research aims to provide the performance and economic feasibility of an investment project to determine whether there is any potential for PV project implementation. Malaysia is a country that heavily promotes renewable energy because of its tropical location. The country receives an average monthly solar irradiation of 400-600 MJ/m^2 and thus has the potential to build large-scale solar (LSS) power plants [33]. In this study, the focus is on the northern state of Malaysia, which is Perlis. The state has the advantage of receiving an average of 12 hours of sunlight per day, making it the hottest state in Malaysia with the highest level of solar radiation [33]. Malaysia has developed a high electricity demand as a developing country on the verge of economic development. To reduce greenhouse gas emissions, the government has approved a LSS scheme to support the national electricity grid and contribute to developing an environmentally friendly energy source in the country [34]. This programme allows the LSS farm to generate electricity, which will then be sold to the national Tenaga Nasional Berhad (TNB) grid. Other government incentives for renewable energy utilisation include the self-consumption (SELCO) and net energy metering (NEM) schemes. However, the SELCO scheme applies when electricity is generated for personal use only, and any excess is not permitted to be exported to the grid. In contrast, the NEM scheme allows only excess electricity to be exported to the grid after the solar PV installation has been consumed [35], [36].

In this work, PVsyst was proposed to determine the performance of the bifacial and mono-facial PV systems widely used in Malaysia's LSS projects. The simulated results for both PV modules for the LSS power plant were compared and discussed. The yearly mean normalized performance indices such as array yield (Ya), reference yield (Yr), final yield (Yf), performance ratio (PR), array capture loss (LC) and system loss (LS) was evaluated using International Electrotechnical Commission (IEC) Standard 61724 [37]. It is the industry-standard method for performing technical analysis on a solar PV array, and it has been used by several researchers in their studies [38]–[43]. In the financial analysis part, the return on investment (ROI), including project payback times, was calculated where annual production, financial performance, and the results of the investments also had been investigated. Finally, the implementation suitability of bifacial PV over mono-facial PV for LSS power plants is highlighted in this paper.

2. METHOD

2.1. Tested system

The proposed site is in Perlis, Malaysia with longitude and latitude of 6.4406° N and 100.1984° E, respectively. By using the standard test conditions (STC), which are given by 1000 W/m^2 irradiance, 25 °C temperature and AM 1.5 spectrum, the estimated total power output of a mono-facial solar power plant is 1.16 MW [44]. However, the bifacial solar power plant has an estimated total power output of around 1.507 MW which is around 23% more than a mono-facial solar power plant. Both types of PV systems were set to have the same ground albedo of 20%, tilt angle of 15° and azimuth angle of 0° [45]. Table 1 shows the specifications of the modules for bifacial solar and mono-facial solar modules.

Table 1. PV modules specifications

Components/parameters	Bifacial solar modules	Mono-facial solar modules
Name of module	JKM400M-72H-BDVP	NU-JC370
Type of module	Monocrystalline silicon	Monocrystalline silicon
Modules per string (unit)	28	28
Number per string (unit)	88	88
Number of PV modules (unit)	2464	2464
Total *Pnom* (kW$_p$)	986	999
Pmax (W$_p$)	400.00	370.00
Imp (A)	9.76	10.75
Vmp (V)	41.00	34.42
Isc (A)	10.24	11.54
Voc (V)	48.80	40.81

Table 2 shows the specifications for the selected inverter used in bifacial and mono-facial LSS systems. This study uses 5 units of 175 kW$_{ac}$ to get 875 kW$_{ac}$. The output is set to 800 V at 50 Hz for grid compatibility in Malaysia. The inverter is required for any grid-connected system to convert direct current (DC) to alternating current (AC). Several factors influence inverter performance, including voltage range, configuration (series or parallel), and others.

Table 2. Details of inverter

Components	Specifications/parameters
Manufacturer	Huawei technologies
Model	SUN2000-185KTL-H1
Unit nom. power (kW$_{ac}$)	175
Number of inverters	5 unit
Pnom total (kW$_{ac}$)	875
Pnom ratio (W$_p$)	1.126
Operating voltage (V)	550-1500

2.2. Performance analysis

2.2.1. System yields

Reference yield: it is the total energy of the system when operating at nominal efficiencies. The reference yield, Y_r, is given in (1) and can be expressed as [43]:

$$Y_r = \frac{H_t}{G_o} \tag{1}$$

Where H_t and G_o are the total irradiance on a horizontal plane and the global irradiance at STC, respectively. Array yield: the array field, Y_a in (2) represents the DC energy generated from the PV array and can be demonstrated as [46], [47]:

$$Y_a = \frac{E_{DC}}{P_o} \tag{2}$$

Where P_o and E_{DC} are the nominal power and DC energy output of the PV array at STC. The value of E_{DC} can be calculated in (3):

$$E_{DC} = V_{DC} \times I_{DC} \times t \tag{3}$$

Where V_{DC} and I_{DC} are the DC output voltage and current of the PV array, respectively, while t refers to the time in hours. Final system yield: this parameter refers to the amount of energy injected into the grid. The final system yield, Y_f is given in (4) and can be expressed as [48], [49]:

$$Y_f = \frac{E_{AC}}{P_P} \tag{4}$$

where E_{AC} is the AC energy output of the PV system, and P_P is the peak power of the PV array at STC.

2.2.2. System array and energy losses

The losses parameters, in addition to the yield parameter, influence the performance of a PV system, where the losses are feasible in every component used in the design of a grid-connected PV system. There are primarily two types of loss parameters: array capture and system losses. Array capture losses: several factors cause this loss, such as PV cell temperature rise, partial shade, dust accumulation on PV array, and mismatching. Array capture loss, L_C is given in (5) and can be expressed as [44]:

$$L_C = Y_r - Y_a \tag{5}$$

Where Y_r and Y_a are the reference yield and array yield, respectively. System losses: system losses are created by the inverter system and other electrical components required for grid integration. The equation for system loss, $L_{S,}$ is given in (6) and expressed as [40]:

$$L_S = Y_a - Y_f \tag{6}$$

where Y_a and Y_f is the array and final system yield, respectively.

2.2.3. PV efficiency

Performance ratio: the PR, PR, can be calculated by determining the ratio of final system yield to reference yield or by dividing the grid energy by the nominal power [45], [46]. The mathematical expression for PR is given in (7) and can be written as:

$$\mathrm{PR} = \frac{Y_f}{Y_r} = \frac{E\_Grid}{GlobInc} \tag{7}$$

Where Y_f is the calculated final system yield in (4), and Y_r is the reference yield. The *E_Grid* is the energy injected into grid (MWh), and *GlobInc* is global incident irradiation.

2.2.4. Investment and cost

The profitability of the system can be summarised based on three important results expressed in (8)-(10) [47]. Payback period: the years required to recover the net investment cost defined in the installation and operating costs section. The payback period is unknown if the system is not profitable (more expenses than income). The following formula is used to calculate the amount recovered each year [47]:

$$\begin{aligned}\text{The recovered amount for year}_\mathrm{t} &= \text{Net balance of year}_\mathrm{t} + \text{Self} - \text{consumption saving for year}_\mathrm{t}\\ &+\text{Redemption part of the loan for year}_\mathrm{t}\end{aligned} \tag{8}$$

Where the net balance of the year equals the after-tax profit minus any dividend payments. The redemption part of the loan is the capital repayment of the borrowed amount (annuity excluding interest). The SELCO saving is the energy consumed from own production multiplied by the consumption tariff. Net present value (NPV): the difference in the present value of cash inflows and cash outflows over time. The mathematical expression for *NPV* is given in (9) and can be written as [47]:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{9}$$

Where R_t is the net balance for the year (t), *i* is the discount from alternative investments, $\mathrm{E_t}$ is the electricity production of the year, and the system's lifetime is denoted by *n*. ROI: this parameter measures the profitability of the system and can be calculated using (10) as shown [47]:

$$\text{ROI ratio} = \text{Net benefit at the end of lifetime/Total investment} \tag{10}$$

where negative ROI indicates that the system is not profitable.

2.3. Proposed method

The PVsyst software tool is used to simulate the simulation model of a planned PV system consisting of PV modules, inverters and a grid interface network [47]. This software enables the design of the system and allows the amount of energy generated to be calculated. The sizing of the PV system will affect the output performance, which is heavily influenced by the geographical location. The outcomes may include several simulation variables, which can be demonstrated in hourly, daily or monthly values [48], [49]. The simulation procedure adopted for analysis is explained below:

- Step 1: defining the project. A grid-connected PV system project is created in the project design menu by specifying meteorological data and the geographical location where the solar farm is to be implemented.
- Step 2: creating the system variant. The relevant plant design data is specified. The data includes PV module type and orientation, PV plant installation data, load power and inverter data from the PVsyst database.
- Step 3: simulating and analyzing. After all the necessary data has been specified, successive variants are added, and simulation is performed. The simulation generates various graphs and reports to analyse and further evaluate the PV system.

3. RESULTS AND DISCUSSION

The simulated results for the bifacial PV system are shown in Table 3. The data for global horizontal radiation and ambient temperatures were taken from Meteonorm 8.0, provided in PVsyst software. From Table 3, the input of the system is given by the yearly global horizontal radiation, which is 1837.4 kWh/m^2. The maximum global horizontal solar irradiance in March was 186.7 kWh/m^2, with the highest ambient temperature of 28.49 °C. The minimum global horizontal solar irradiance is in November with 131.6 kWh/m^2 and an ambient temperature of 26.90 °C. Annual global incident energy that is irradiation incident on the collector plane is 1845.9 kWh/m^2. The total effective global irradiance, GlobEff, is the remaining irradiation reaching the collector area given by 1743.3 kWh/m^2. Variations in PV energy production can be caused by solar irradiance and ambient temperature changes. According to Table 3, the maximum DC energy of the PV array is produced in March for the considered location, which is 170.7 MWh. The months of June and August have the lowest DC energy output of 123.7 MWh. The total mean DC energy generated from the PV array over the year is 1699.6 MWh. Overall, the yearly total AC energy to the grid is 1645.3 MW, with the maximum energy generated in March (166.0 MWh) and minimum energy in June (116.6 MWh).

Table 3. Main results of bifacial LSS

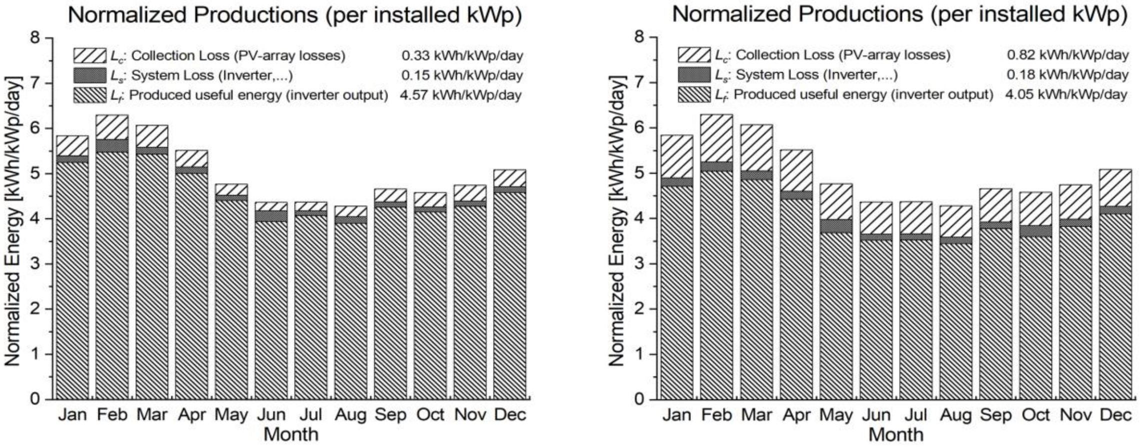
Parameters and month	GlobHor (kWh/m^2)	T_Amb (°C)	GlobInc (kWh/m^2)	GlobEff (kWh/m^2)	EArray (MWh)	E_Grid (MWh)
January	163.1	27.41	181.0	171.7	164.9	160.4
February	170.7	28.19	182.6	173.6	164.7	156.6
March	186.7	28.49	188.2	178.2	170.7	166.0
April	172.8	28.17	165.4	156.2	152.2	148.1
May	159.9	28.38	147.8	138.7	138.3	134.7
June	144.0	27.59	130.9	122.6	123.7	116.6
July	147.6	27.72	135.4	126.9	127.7	124.4
August	139.8	27.57	132.7	124.8	123.7	119.3
September	141.8	26.89	139.8	131.7	129.4	126.0
October	137.8	27.05	142.0	134.4	130.3	126.8
November	131.6	26.90	142.3	135.1	130.0	126.4
December	141.5	27.20	157.6	149.5	144.0	140.0
Year	1837.4	27.63	1845.9	1743.3	1699.6	1645.3

The main results for the mono-facial PV system are shown in Table 4. The input to the system for mono-facial PV is also taken from Meteonorm 8.0, where the data for global horizontal radiation and ambient temperature are constant. From Table 4, the maximum DC energy output of the mono-facial PV array was 156.4 MWh in March, while the lowest DC energy output was 109.6 MWh in June. Compared to the results in Table 4 with Table 3, the annual DC energy of the PV array for mono-facial PV systems is 1543.8 MWh, which is less than bifacial PV, which produced 1699.6 MWh. Therefore, less total energy was obtained from the mono-facial PV system for load/grid over the year, which is 1477.2 MWh, with the maximum energy generated in March (150.5 MWh) and minimum energy in June (105.5 MWh). Furthermore, the findings show that mono-facial LSS lowered monthly and annual global efficiency compared to bifacial LSS.

Table 4. Main results of mono-facial LSS

Parameters and month	GlobHor (kWh/m^2)	T_Amb (°C)	GlobInc (kWh/m^2)	GlobEff (kWh/m^2)	EArray (MWh)	E_Grid (MWh)
January	163.1	27.41	181.0	171.3	151.7	145.9
February	170.7	28.19	182.6	173.2	152.1	146.2
March	186.7	28.49	188.2	177.8	156.4	150.5
April	172.8	28.17	165.4	155.8	137.9	132.7
May	159.9	28.38	147.8	138.3	123.3	114.1
June	144.0	27.59	130.9	122.2	109.6	105.5
July	147.6	27.72	135.4	126.5	113.4	109.2
August	139.8	27.57	132.7	124.4	111.2	106.7
September	141.8	26.89	139.8	131.3	117.5	113.1
October	137.8	27.05	142.0	134.0	119.1	111.5
November	131.6	26.90	142.3	134.8	119.4	114.7
December	141.5	27.20	157.6	149.2	132.2	127.0
Year	1837.4	27.63	1845.9	1738.7	1543.8	1477.2

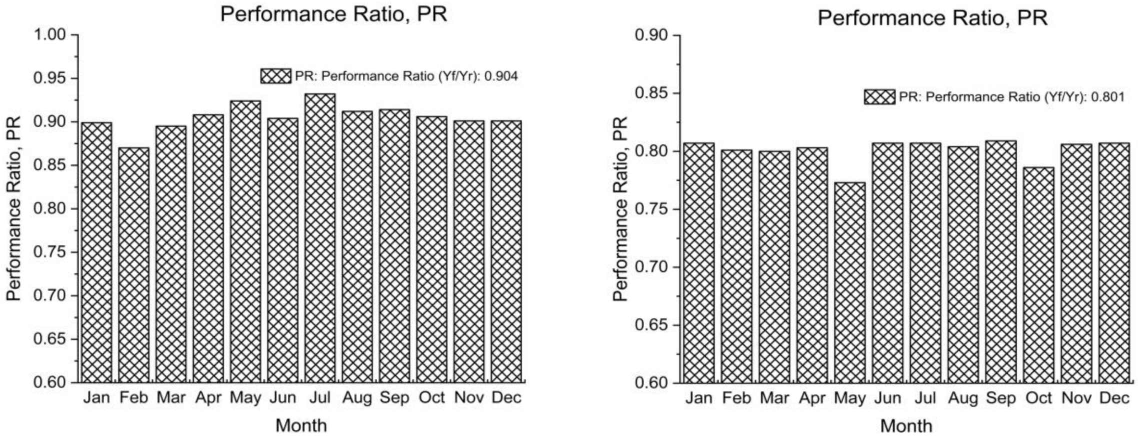
The results for bifacial and mono-facial LSS normalized productions for 12 months are shown in Figure 1. The IEC Standard 61724 [50] defines normalized outputs as standardised variables for evaluating PV system performance. Comparing Figure 1(a) with Figure 1(b), the average losses in the bifacial PV array are 0.33 kWh/kWp/day, which is lower than the mono-facial PV array, which has losses of 0.82 kWh/kWp/day. This is because the bifacial PV panels can collect incident light from both front and back sides, allowing more irradiation from the rare side to penetrate the PV panel. This will increase the energy yield, resulting in increased useful energy injected into the grid. As a result, the bifacial LSS inverter can produce an average of 4.57 kWh/kWp/day of energy, which is higher than the mono-facial LSS inverter, which only produced 4.05 kWh/kWp/day. The loss in the system is due to system components which in our case is inverter [51]. The average bifacial LSS system loss is 0.15 kWh/kWp/day, which is lower compared to the mono-facial LSS system, with the loss in the system being 0.82 kWh/kWp/day. From the table, it also can be seen that there is big difference in term of collection loss or PV array loss while only small difference in term of system loss for both systems. This is because both systems have almost identical design with same type of inverter except for the type of solar panels used. So, most of the loss in mono-facial system came from the PV array including thermal, module quality, mismatch and incident angle modifier (IAM) losses, shading, and other inefficiencies.



(a) (b)

Figure 1. Energy output throughout the year; (a) bifacial LSS and (b) mono-facial LSS

The performance of the PV plant can be evaluated based on the PR, as shown in Figure 2. For the bifacial system, the annual PR is between 0.870 to 0.932 and shows the average PR for a year is 0.904. For the mono-facial system, the annual PR is found between 0.773 to 0.809 and shows the average PR for a year is 0.801. This is due to the higher amount of solar irradiance received by the bifacial PV panel compared to the mono-facial PV panel. These findings proved that a bifacial PV module is more efficient than a mono-facial PV module. According to the European PV guidelines, a good PR value ranges between 0.8–0.85 and a value below 0.75 indicates a problem [52], [53]. For most of the months of the year, the PR for bifacial and mono-facial systems is almost constant with less than a 1% difference between maximum and minimum values, which is satisfactory. Figures 2(a) and 2(b) show PR performance for each month, demonstrating a variation in PR throughout the year for both bifacial and mono-facial LSS. It is be due to the thermal fluctuations of the ambient temperature affecting the PV modules. The PR diminishes because of the PV array's higher operating temperature, leading to higher temperature losses [54], [55].



(a) (b)

Figure 2. Performance ratio; (a) bifacial and (b) mono-facial LSS

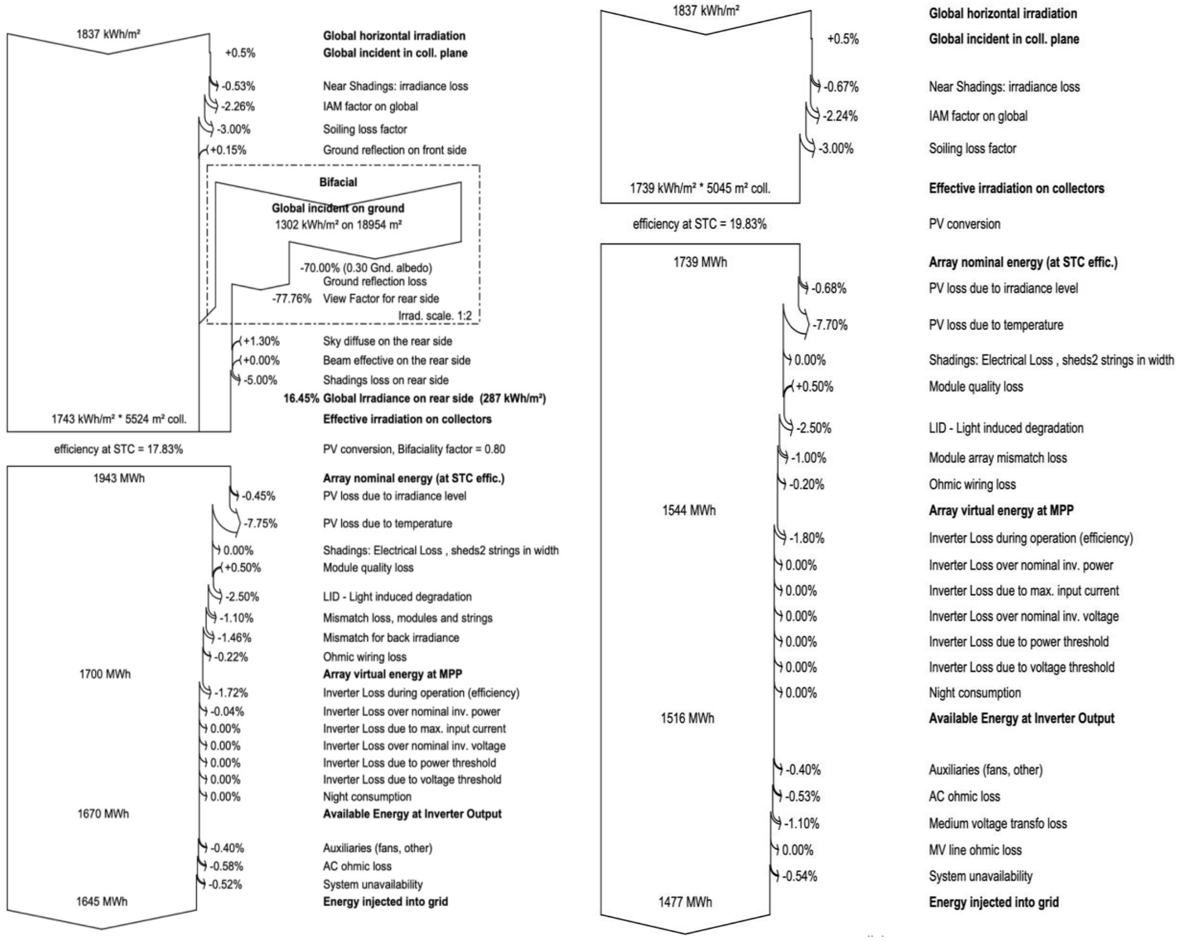
Figure 3 depicts the output energy to the load over the year after several loss corrections, where different stages of simulation can be visualized through the Sankey diagrams below. From Figures 3(a)-(b), the top of the diagram is referred to the input energy, which is the horizontal global irradiation. The diagram starts with 1837 kWh/m^2 for both bifacial and mono-facial LSS. The increase of +0.5% for a global incident in the coil plane is referred to as the transposition factor from horizontal global irradiation (GlobHor) to global incident irradiance (GlobInc). Following this increase, losses due to near shading, IAM and soiling are shown as energy loss arrows. Each arrow value represents a relative loss of the remaining energy at the previous stage. Based on both figures, the diagrams show that the final irradiation on the collector for bifacial LSS is 1743 kWh/m^2 multiplied by a total collector area of 5524 m^2, and mono-facial LSS is 1739 kWh/m^2 multiplied by a total collector area of 5045 m^2 for getting total luminous energy available on the collectors.

In Figure 3(a), a bifacial diagram adds the energy incident on the PV array after reflected from the ground. The additional irradiation is taken into account before the electrical losses are considered. The diagram shows irradiation on ground reflection, which is 1309 kWh/m^2 with an area of 18954 m^2. However, there is -70% ground reflection and -77.76% view factor for rear side losses when the ground albedo is 0.30. The incident solar energy on the bifacial PV module varies with the value of ground reflectance (albedo), where higher albedo will increase the amount of solar irradiation reflected on the backside of the bifacial PV module [56], [57]. There is also 16.45% irradiation on the rear side, which is 1309 kWh/m^2 with -5% shading loss, on which the values are dependent.

The solar energy is then converted into electrical energy by multiplying the nominal efficiency of the modules at STC. From the diagrams, the nominal energy of the array after bifacial and mono facial PV conversion is 1943 MWh and 1739 MWh, respectively. The next two losses, which are irradiance level and temperature, are since PV modules do not work at STC. The PV loss due to the irradiance level is caused by the low-light relative efficiency and may be lower during sunny weather conditions. The PV loss due to the temperature is the notable decrease of efficiency where the loss may be very high in hot climates [55]. Other array losses like the light-induced degradation, the module quality, the mismatch between modules and the ohmic wiring losses will decrease the array power further [58]. Finally, the array of virtual energy obtained at maximum power point (MPP) was given by 1700 MWh and 1544 MWh, available at the input of the bifacial and mono-facial inverter.

Then, there are several losses at the inverter level. The inverter loss during operation is also known as efficiency loss [59], wherein in this case, -1.72% for the bifacial inverter and -1.80% for the mono-facial inverter. The diagrams also show that a bifacial PV system has an extra -0.04% of losses due to power clipping at the nominal power of the inverter due to an undersized inverter [60]. Subsequently, the available energy at inverter output is reduced to 1670 MWh and 1516 MWh for bifacial and mono-facial, respectively.

Additionally, other losses occur in the AC circuit, further decreasing the energy injected into the grid [61]. Finally, the total electrical energy injected into the grid for the bifacial and mono-facial systems is 1645 MWh and 1477 MWh, respectively.



(a) (b)

Figure 3. Yearly Sankey diagrams for; (a) bifacial and (b) mono-facial LSS

Table 5 display the final economic evaluation for LSS. It displays that for bifacial LSS, the starting cost or capital cost is much higher at approximately RM10 million, while mono-facial is at approximately RM 9 million. This is because the bifacial solar panels used by bifacial LSS are more expensive than mono-facial solar panels. The feed-in tariff of both systems is the same because both systems have identical operating locations.

Table 5. Bifacial and mono-facial economic evaluation

Parameters		Bifacial LSS	Mono-facial LSS
Financing			
Own funds		10312412.67 MYR	9049390.91 MYR
Electricity sale			
A tariff on feed-in	Peak	1.1400 MYR/kWh	
	Off-peak	0.9120 MYR/kWh	
Tariff warranty duration		20 years	
Annual connection tax		0.00 MYR/kWh	
Annual tariff changes		0.0%/year	
Feed-in tariffs reduce warranty		50.00%	
Return on investment			
Payback period		7 years	8.1 years
Net present value		36816139.49 MYR	26279489.35 MYR
Return on investment		357.0%	290.4%

For return-on-investment analysis, bifacial LSS will reach the payback period or breakeven period much sooner at seven years, while mono-facial LSS takes around 8.1 years. This is because bifacial solar panels are more effective than mono-facial solar panels and help generate more income for the company. For bifacial LSS, the ROI and NPV were also calculated, resulting in 357% and RM 36816139.49, respectively. These values are higher than mono-facial LSS, which was calculated to have 290.4% and RM 26279489.35 for ROI and NPV, respectively. Therefore, the results show that any investment made into bifacial LSS will profit more than mono-facial LSS in the long run. Based on the results achieved by the economic feasibility provided, it can be stated that the bifacial solar panels are viable since it offers excellent financial savings in the medium and long term.

4. CONCLUSION

This work demonstrated bifacial solar panel efficiency compared to the mono-facial solar panel. This goal was achieved by simulating two different LSS systems with a total capacity of 1 MW that have almost identical parameters except for the type of solar panels used. According to the simulation, the bifacial PV system can produce 1645.3 MWh/year of electricity to the grid with specific production on a daily basis per installed kWp is 4.57 kWh/kWp/day. The energy is higher than the mono-facial PV system, which only produced 1477.2 MWh/year with specific production is 4.05 kWh/kWp/day. The maximum energy injected into the grid was in March, where bifacial LSS injected 166.0 MWh compared to mono-facial, which only injected 150.5 MWh. The least electricity energy generated was in June, where bifacial LSS produced 116.6MWh while mono-facial produced only 105.5 MWh. Besides, the PR of a bifacial PV system is higher, which is 90.44%, compared to the mono-facial PV system, which has a lower PR of 80.1%. Therefore, the increment of the bifacial LSS compared to the mono-facial LSS is around 10.34%. These findings proved that a bifacial PV module is more efficient than a mono-facial PV module. This is due to the higher amount of solar irradiance received by the bifacial PV panel compared to the mono-facial PV panel. In this case, the bifacial system has additional irradiation on ground reflection of 1309 kWh/m^2 with an area of 18954 m^2 and 16.45% irradiation on the rear side which is 1309 kWh/m^2. Based on the economic evaluation for both systems, bifacial systems have higher starting costs with approximately RM10 million, while mono-facial is at approximately RM 9 million. However, in the long run, the bifacial PV system was able to generate more profit in terms of ROI, around 357%, and reach a breakeven point even sooner, around seven years. The payback period for a mono-facial PV system was around 8.1 years, with an ROI of 290.4%. Based on the economic feasibility analysis, it can be stated that the bifacial solar panels are viable since it offers excellent financial savings in the medium and long term. Therefore, the comparative analysis between bifacial and mono-facial PV systems showed the effectiveness and the implementation suitability of bifacial PV over mono-facial PV solar systems for LSS systems.

REFERENCES

[1] A. O. M. Maka and J. M. Alabid, "Solar energy technology and its roles in sustainable development," *Clean Energy*, vol. 6, no. 3, pp. 476–483, 2022, doi: 10.1093/ce/zkac023.

[2] N. S. Lewis, "Toward cost-effective solar energy use," *Science*, vol. 315, no. 5813, pp. 798–801, 2007, doi: 10.1126/science.1137014.

[3] G. Wheatley and R. I. Rubel, "Design improvement of a laboratory prototype for efficiency evaluation of solar thermal water heating system using phase change material (PCMs)," *Results in Engineering*, vol. 12, pp. 1–15, 2021, doi: 10.1016/j.rineng.2021.100301.

[4] D. M. N. Mahmood and I. M. A. Aljubury, "Experimental investigation of a hybrid photovoltaic evaporative cooling (PV/EC) system performance under arid conditions," *Results in Engineering*, vol. 15, pp. 1–11, 2022, doi: 10.1016/j.rineng.2022.100618.

[5] Q. Duan, Y. Feng, and J. Wang, "Clustering of visible and infrared solar irradiance for solar architecture design and analysis," *Renewable Energy*, vol. 165, pp. 668–677, 2021, doi: 10.1016/j.renene.2020.11.080.

[6] F. He and H. Fathabadi, "Novel standalone plug-in hybrid electric vehicle charging station fed by solar energy in presence of a fuel cell system used as supporting power source," *Renewable Energy*, vol. 156, pp. 964–974, 2020, doi: 10.1016/j.renene.2020.04.141.

[7] S. Enkhardt, "BloombergNEF says global solar will cross 200 GW mark for first time this year, expects lower panel prices," *PV Magazine*, 2022. https://www.pv-magazine.com/2022/02/01/bloombergnef-says-global-solar-will-cross-200-gw-mark-for-first-time-this-year-expects-lower-panel-prices/ (accessed Aug. 01, 2022).

[8] B. Parida, S. Iniyan, and R. Goic, "A review of solar photovoltaic technologies," *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 1625–1636, 2020, doi: 10.1016/j.rser.2010.11.032.

[9] M. Gul, Y. Kotak, and T. Muneer, "Review on recent trend of solar photovoltaic technology," *Energy Exploration and Exploitation*, vol. 34, no. 4, pp. 485–526, 2016, doi: 10.1177/0144598716650552.

[10] A. Sanna, B. Buchspies, M. Ernst, and M. Kaltschmitt, "Decentralized brackish water reverse osmosis desalination plant based on PV and pumped storage-technical analysis," *Desalination*, vol. 516, p. 115232, 2021, doi: 10.1016/j.desal.2021.115232.

[11] Y. Zahraoui *et al.*, "Self-healing strategy to enhance microgrid resilience during faults occurrence," *International Transactions on Electrical Energy Systems*, vol. 31, no. 12, pp. 1–16, 2021, doi: 10.1002/2050-7038.13232.

[12] D. Cho and J. Valenzuela, "A scenario-based optimization model for determining the capacity of a residential off-grid PV-battery system," *Solar Energy*, vol. 233, pp. 478–488, 2022, doi: 10.1016/j.solener.2022.01.058.

[13] N. Mukisa, M. S. Manitisa, P. Nduhuura, E. Tugume, and C. K. Chalwe, "Solar home systems adoption in Sub-Saharan African countries: household economic and environmental benefits assessment," *Renewable Energy*, vol. 189, pp. 836–852, 2022, doi:

10.1016/j.renene.2022.03.029.

[14] S. Assawaworrarit, Z. Omair, and S. Fan, "Nighttime electric power generation at a density of 50 mW/m2 via radiative cooling of a photovoltaic cell," *Applied Physics Letters*, vol. 120, no. 14, p. 143901, 2022, doi: 10.1063/5.0085205.

[15] T. J. Abodunrin and C. J. Ofulue, "Micro-electricity generation using solar thermal design and modelling thermosiphon applications from waste recycled materials," *Results in Engineering*, vol. 13, pp. 1–11, 2022, doi: 10.1016/j.rineng.2022.100369.

[16] A. M. Al-Falahat *et al.*, "Energy performance and economics assessments of a photovoltaic-heat pump system," *Results in Engineering*, vol. 13, pp. 1–11, 2022, doi: 10.1016/j.rineng.2021.100324.

[17] M. A. Jones, I. Odeh, M. Haddad, A. H. Mohammad, and J. C. Quinn, "Economic analysis of photovoltaic (PV) powered water pumping and desalination without energy storage for agriculture," *Desalination*, vol. 387, pp. 35–45, 2016, doi: 10.1016/j.desal.2016.02.035.

[18] A. Abotaleb and A. Abdallah. "Performance of bifacial-silicon heterojunction modules under desert environment" *Renewable Energy,* vol.127, pp. 94-101, 2018, doi: 10.1016/j.renene.2018.04.050.

[19] B. Ghaleb and M. Asif, "Assessment of solar PV potential in commercial buildings," *Renewable Energy*, vol. 187, pp. 618–630, 2022, doi: 10.1016/j.renene.2022.01.013.

[20] S. Susan and D. Wardhani, "Building integrated photovoltaic as GREENSHIP'S on site renewable energy tool," *Results in Engineering*, vol. 7, pp. 1–9, 2020, doi: 10.1016/j.rineng.2020.100153.

[21] S. El Himer, M. Ouaissa, M. Ouaissa, and Z. Boulouard, "General parametric of two micro-concentrator photovoltaic systems for drone application," *Studies in Computational Intelligence*, vol. 45, no. 2, pp. 275–289, 2021, doi: 10.1007/978-3-030-97113-7_16.

[22] G. K. Singh, "Solar power generation by PV (photovoltaic) technology: a review," *Energy*, vol. 53, pp. 1–13, 2013, doi: 10.1016/j.energy.2013.02.057.

[23] T. Uematsu *et al.*, "Development of bifacial PV cells for new applications of flat-plate modules," *Solar Energy Materials and Solar Cells*, vol. 75, no. 3–4, pp. 557–566, 2003, doi: 10.1016/S0927-0248(02)00197-6.

[24] Z. Younes, I. Alhamrouni, S. Mekhilef, and M. R. B. Khan, "Blockchain applications and challenges in smart grid," in *2021 IEEE Conference on Energy Conversion (CENCON)*, 2021, pp. 208–213, doi: 10.1109/CENCON51869.2021.9627297.

[25] Y. Zahraoui, M. R. Basir Khan, I. Alhamrouni, S. Mekhilef, and M. Ahmed, "Current Status, Scenario, and Prospective of Renewable Energy in Algeria: A Review," *Energies*, vol. 14, no. 9, p. 2354, 2021, doi: 10.3390/en14092354.

[26] J. Libal and R. Kopecek, *Bifacial photovoltaics: technology, applications and economics*. United Kingdom: The Institution of Engineering and Technology, 2018, doi: 10.1049/PBPO107E.

[27] I. Alhamrouni, Ibrahim, Firdaus Ramli, Mohamed Salem, Bazilah Ismail, Awang Jusoh, and Sutikno Tole. "Optimal power scheduling of renewable energy sources in micro-grid via distributed energy storage system" *TELKOMNIKA Telecommunication, Computing, Electronics and Control*, vol. 18, no. 4, pp. 2158-2168, 2020, doi: 10.12928/telkomnika.v18i4.15159

[28] J. Jang and K. Lee, "Practical performance analysis of a bifacial PV module and system," *Energies*, vol. 13, no. 17, pp. 1–13, 2020, doi: 10.3390/en13174389.

[29] H. P. Yin *et al.*,"Optical Enhanced Effects on the Electrical Performance and Energy Yield of Bifacial PV Modules," *Solar Energy*, vol. 217, pp. 245-252, 2021, doi: https://doi.org/10.1016/j.solener.2021.02.004.

[30] G. M. Tina, F. Bontempo Scavo, L. Merlo, and F. Bizzarri, "Comparative analysis of monofacial and bifacial photovoltaic modules for floating power plants," *Applied Energy*, vol. 281, p. 116084, 2021, doi: 10.1016/j.apenergy.2020.116084.

[31] C. D. Rodríguez-Gallegos, M. Bieri, O. Gandhi, J. P. Singh, T. Reindl, and S. K. Panda, "Monofacial vs bifacial Si-based PV modules: which one is more cost-effective?," *Solar Energy*, vol. 176, pp. 412–438, 2018, doi: 10.1016/j.solener.2018.10.012.

[32] H. D. M. R. Perera and H. Wen, "Power generation and performance analysis of Bi-facial vs Mono-facial 10kW photovoltaic power station," in *2019 18th International Conference on Optical Communications and Networks (ICOCN)*, 2019, pp. 1–3, doi: 10.1109/ICOCN.2019.8934305.

[33] S. Mekhilef, A. Safari, W. E. S. Mustaffa, R. Saidur, R. Omar, and M. A. A. Younis, "Solar energy in Malaysia: current state and prospects," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 386–396, 2012, doi: 10.1016/j.rser.2011.08.003.

[34] Energy Commission, *Guidelines on large scale solar photovoltaic plant for connection to electricity networks*. Putrajaya, Malaysia: Suruhanja Tenaga Energy Commission, 2018.

[35] K. H. A. Rahman, S. J. H. M. Yusof, and K. S. K. Ismail, "Renewable energy: the past and the future," in *Renewable Energy from Bio-resources in Malaysia*, Singapore: Springer, 2022, pp. 213–234, doi: 10.1007/978-981-16-9314-4_10.

[36] H. Zainuddin, H. R. Salikin, S. Shaari, M. Z. Hussin, and A. Manja, "Revisiting solar photovoltaic roadmap of tropical malaysia: Past, present and future," *Pertanika Journal of Science and Technology*, vol. 29, no. 3, pp. 1567–1578, 2021, doi: 10.47836/pjst.29.3.25.

[37] "Photovoltaic system performance-part 3: energy evaluation method corrigendum 1," *IEC-International Electrotechnical Commission*, 2018. https://standards.globalspec.com/std/10273520/IEC TS 61724-3.

[38] A. Al Mehadi, M. A. Chowdhury, M. M. Nishat, F. Faisal, and M. M. Islam. "Design, simulation and analysis of monofacial solar pv panel based energy system for university residence: a case study." *In IOP Conference Series: Materials Science and Engineering*, vol. 1045, no. 1, 2021, doi: p. 012011. IOP Publishing.

[39] V. Thakur and S. S. Chandel, "Maximizing the solar gain of a grid-interactive solar photovoltaic power plant," *Energy Technology*, vol. 1, no. 11, pp. 661–667, 2013, doi: 10.1002/ente.201300118.

[40] P. Ramanan, K. M. K., and A. Karthick, "Performance analysis and energy metrics of grid-connected photovoltaic systems," *Energy for Sustainable Development*, vol. 52, pp. 104–115, 2019, doi: 10.1016/j.esd.2019.08.001.

[41] J. D. Mondol, Y. Yohanis, M. Smyth, and B. Norton, "Long term performance analysis of a grid connected photovoltaic system in Northern Ireland," *Energy Conversion and Management*, vol. 47, no. 18–19, pp. 2925–2947, 2006, doi: 10.1016/j.enconman.2006.03.026.

[42] D. A. Quansah, M. S. Adaramola, G. K. Appiah, and I. A. Edwin, "Performance analysis of different grid-connected solar photovoltaic (PV) system technologies with combined capacity of 20 kW located in humid tropical climate," *International Journal of Hydrogen Energy*, vol. 42, no. 7, pp. 4626–4635, 2017, doi: 10.1016/j.ijhydene.2016.10.119.

[43] M. S. Adaramola and E. E. T. Vågnes, "Preliminary assessment of a small-scale rooftop PV-grid tied in Norwegian climatic conditions," *Energy Conversion and Management*, vol. 90, pp. 458–465, 2015, doi: 10.1016/j.enconman.2014.11.028.

[44] S. K. Yadav and U. Bajpai, "Performance evaluation of a rooftop solar photovoltaic power plant in Northern India," *Energy for Sustainable Development*, vol. 43, pp. 130–138, 2018, doi: 10.1016/j.esd.2018.01.006.

[45] Y. Zahraoui, I. Alhamrouni, S. Mekhilef, M. R. Basir Khan, B. P. Hayes, and M. Ahmed, "A novel approach for sizing battery storage system for enhancing resilience ability of a microgrid," *International Transactions on Electrical Energy Systems*, vol. 31, no. 12, pp. 1–19, 2021, doi: 10.1002/2050-7038.13142.

[46] A. A. Adebiyi, I. J. Lazarus, A. K. Saha, and E. E. Ojo, "Performance analysis of 8 kW grid-tied solar photovoltaic power plant in

Durban, South Africa,” *International Journal of Advanced Research in Engineering and Technology*, vol. 10, no. 4, pp. 140–153, 2019, doi: 10.34218/IJARET.10.4.2019.017.

[47] “PVSyst-logiciel photovoltaïque,” *PVSyst-Photovoltaic Software*, 2022. https://www.pvsyst.com/ (accessed Jul. 28, 2022).

[48] S. Oliveira-Pinto and J. Stokkermans, “Assessment of the potential of different floating solar technologies – overview and analysis of different case studies,” *Energy Conversion and Management*, vol. 211, p. 112747, 2020, doi: 10.1016/j.enconman.2020.112747.

[49] I. Alhamrouni, N. Zainuddin, M. Salem, N. H. A. Rahman, and L. Awalin, “Design of single phase inverter for photovoltaic application controlled with sinusoidal pulse width modulation,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 15, no. 2, pp. 620–630, 2019, doi: 10.11591/ijeecs.v15.i2.pp620-630.

[50] IEC, *Photovoltaic system performance monitoring – guidelines for measurement, data exchange and analysis*. Switzerland: International Electrotechnical Commission, 20108.

[51] S. Ekici and M. A. Kopru, “Investigation of PV system cable losses,” *International Journal of Renewable Energy Research*, vol. 7, no. 2, pp. 807–815, 2017, doi: 10.20508/ijrer.v7i2.5660.g7062.

[52] A. Woyte, M. Richter, D. Moser, S. Mau, N. Reich and U. Jahn, “Monitoring of Photovoltaic System: Good Practices and Systematic Analysis,” in *Proc. 28th European Photovoltaic Solar Energy Conference*, 2013, pp. 3686-3694.

[53] A. M. Khalid, I. Mitra, W. Warmuth, and V. Schacht, “Performance ratio – crucial parameter for grid connected PV plants,” *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 1139–1158, 2016, doi: 10.1016/j.rser.2016.07.066.

[54] M. Dhimish, “Thermal impact on the performance ratio of photovoltaic systems: a case study of 8000 photovoltaic installations,” *Case Studies in Thermal Engineering*, vol. 21, pp. 1–5, 2020, doi: 10.1016/j.csite.2020.100693.

[55] K. Kawajiri, T. Oozeki, and Y. Genchi, “Effect of temperature on PV potential in the world,” *Environmental Science and Technology*, vol. 45, no. 20, pp. 9030–9035, 2011, doi: 10.1021/es200635x.

[56] B. Marion, “Measured and satellite-derived albedo data for estimating bifacial photovoltaic system performance,” *Solar Energy*, vol. 215, pp. 321–327, 2021, doi: 10.1016/j.solener.2020.12.050.

[57] A. S. Aziz, M. F. N. Tajuddin, M. R. Adzman, and M. A. M. Ramli, “Impacts of albedo and atmospheric conditions on the efficiency of solar energy: a case study in temperate climate of Choman, Iraq,” *Environment, Development and Sustainability*, vol. 23, no. 1, pp. 989–1018, 2021, doi: 10.1007/s10668-019-00568-1.

[58] M. K. da Silva, M. S. Gul, and H. Chaudhry, “Review on the sources of power loss in monofacial and bifacial photovoltaic technologies,” *Energies*, vol. 14, no. 23, pp. 1–29, 2021, doi: 10.3390/en14237935.

[59] M. S. Mahmud et al., "Solar Highway in Bangladesh Using Bifacial PV," *2018 ieee international conference on system, computation, automation and networking (icscan)*, Pondicherry, India, 2018, pp. 1-7, doi: 10.1109/ICSCAN.2018.8541253.

[60] H. X. Wang, M. A. Muñoz-García, G. P. Moreda, and M. C. Alonso-García, “Optimum inverter sizing of grid-connected photovoltaic systems based on energetic and economic considerations,” *Renewable Energy*, vol. 118, pp. 709–717, 2018, doi: 10.1016/j.renene.2017.11.063.

[61] A. Takami, S. Arimoto, H. Morikawa, and S. Hamamoto, “Evaluation of the different losses involved in two photovoltaics systems,” in *Twelfth European Photovoltaic Solar Energy Conference*, 1994, pp. 859–862.

BIOGRAPHIES OF AUTHORS

Nor Hidayah Abdul Kahar received her Ph.D degrees in Electrical Engineering and Electronics from Brunel University London in 2020, M.Sc. degree (Hons.) in Electrical Power from Newcastle Univ., United Kingdom in 2013 and Bachelor of Engineering Technology (first class) in Electrical from Universiti Kuala Lumpur-British Malaysian Institute, Malaysia in 2012. From 2018-2020, she worked as a graduate teaching assistant at Brunel University, London. From February 2021 to February 2022, she was a postdoctoral research fellow at the Photonics Research Centre, Universiti Malaya, Malaysia. Currently, she is a lecturer in Power System and a program coordinator for electrical engineering degree course with the Universiti Kuala Lumpur British Malaysian Institute, Malaysia. Her research interests include power system harmonics, power quality, compensation of reactive power and optimization. Dr. Abdul Kahar is a registered graduate engineer and technologist with Board of Engineers Malaysia (BEM). Also, she is an associate fellow of higher education academy (AFHEA), U.K and a member of IEEE Standards Association. She can be contacted at: norhidayahabdulkahar@um.edu.my.

Nurul Hanis Azhan is a senior lecturer in Electrical Engineering section, Universiti Kuala Lumpur British Malaysian Institute, Malaysia, where she has been a faculty member since 2017. Currently, she is the Head of Section for the section. She belongs to Renewable Energy Research Laboratory (RENERAL), experienced in teaching Renewable Energy and Electronic Devices courses. She received her Dr.Eng. degree in Science and Technology (Electrical and Electronics Engineering) from Tokai University, Japan in 2017 and M.Eng. degree in Electrical and Electronic Systems from the same university in 2014. She studied Japanese Associate Degree (JAD) 3+2 twinning programme from 2007 and graduated with a first-class honour B.Eng. in Electrical and Electronics from Tokai University, Japan in 2012. Her research interests include renewable & sustainable energy power generation and technology, advanced materials, and nanotechnology. She is a registered graduate engineer with Board of Engineers Malaysia (BEM). Also, she is an ASEAN Energy Management Scheme (AEMAS) certified Energy Manager and Surface Science Society of Japan certified Surface Science Engineer. She can be contacted at: nurulhanis@unikl.edu.my.

Ibrahim Alhamrouni received his B.Eng. degree in electrical engineering from Elmergib University, Al Khums, Libya, in 2008. The M.Sc. degree in electrical power engineering from Universiti Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Johor, Malaysia, in 2011. In 2015, he has been awarded his Ph. D degree from Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), Malaysia. Currently, he is a senior lecturer and researcher at the British Malaysian Institute, University of Kuala Lumpur, Malaysia. His research interest includes power system planning and operation, deregulation and restructuring of power system and power lines maintenance. He’s currently working on micro-grid technologies and the application of power electronics in power system. He can be contacted at email: ibrahim.mohamed@unikl.edu.my.

Muhammad Nubli Zulkifli has a mix industrial and academic experience. He was a failure analysis engineer at AIC Semiconductor Sdn. Bhd. and On Semiconductor on 2006 and 2009, respectively. Currently, he is a senior lecturer at Electrical Engineering Section, Universiti Kuala Lumpur (UniKL). His research interest includes semiconductor failure analysis and reliability, electronic packaging, ZnO nanogenerator, piezoelectric and thermoelectric materials, nanoindentation, nano-characterization, finite element analysis, microstructure-mechanical-electrical properties relation to name a few. He can be contacted at email: mnubliz@unikl.edu.my.

Tole Sutikno is a lecturer in Department of Electrical Engineering at the Universitas Ahmad Dahlan (UAD), Yogyakarta, Indonesia. He received his B.Eng., M.Eng. and Ph.D. degrees in Electrical Engineering from Universitas Diponegoro, Universitas Gadjah Mada and Universiti Teknologi Malaysia, in 1999, 2004 and 2016, respectively. He has been an associate professor in UAD, Yogyakarta, Indonesia since 2008. He is currently an Editor-in-Chief of the TELKOMNIKA since 2005, and the Head of the Embedded Systems and Power Electronics Research Group since 2016. His research interests include the field of industrial applications, industrial electronics, industrial informatics, power electronics, motor drives, renewable energy, FPGA applications, embedded system, image processing, artificial intelligence, intelligent control, digital design and digital library. He can be contacted at email: tole@te.uad.ac.id.

Awang Jusoh was born in Terengganu, Malaysia in 1964. He received his B.Eng. degree from Brighton Poly-technic, U.K., in 1988. He obtained his M.Sc.and Ph.D. degrees from the University of Birmingham, U.K., in1995 and 2004, respectively. He is currently an associated professor in the Department of Power Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), Johor, Malaysia. His research interests are in DC-DC converter, renewable energy, and control of power electronics systems. He can be contacted at email: awang@fke.utm.my.