ASEAN Engineering Journal

Full Paper

COMPARATIVE ANALYSIS OF FLOATING MONOFACIAL AND BIFACIAL MODULES IN EQUATORIAL AREA: WEST SUMATERA

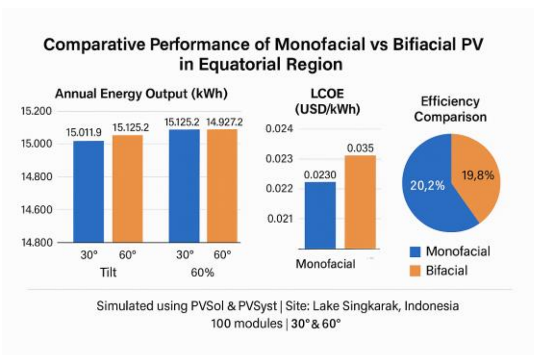
Adam Rasyid Sidiqi*, Ricky Maulana, Citra Dewi, Ali Basrah Pulungan, Hamdani

Department of Electrical Engineering, Faculty of Engineering, Universitas Negeri Padang, 25131, Padang, West Sumatera, Indonesia

Article history
Received
01 February 2025
Received in revised form
02 May 2025
Accepted
08 July 2025
Published online
28 February 2026

*Corresponding author
adamsidiqi@ft.unp.ac.id

Graphical abstract



Abstract

This study conducts a comparative performance and economic analysis of monofacial and bifacial floating solar photovoltaic (FSPV) systems in West Sumatra, Indonesia, using PVSol and PVSyst simulation tools. Simulations were performed at two tilt angles (30° and 60°) using LG450S2W-U6 (monofacial) and LG340N1T-V5 (bifacial) modules. Key performance indicators analyzed include energy yield, system efficiency, bifacial gain, and Levelized Cost of Electricity (LCOE). Results show that monofacial modules produce slightly higher energy yields (average 15,125.2 kWh/year) and lower LCOE (USD 0.0230/kWh) compared to bifacial modules (14,927.2 kWh/year, USD 0.0235/kWh). Although bifacial modules offer potential gains in high-albedo environments, their higher capital cost limits financial competitiveness under standard equatorial conditions. The findings provide stakeholders with quantitative insights for selecting optimal PV configurations in equatorial floating installations, balancing energy output and economic feasibility.

Keywords: Floating PV, Monofacial, Bifacial, Equatorial Climate, Energy Yield, LCOE, PVSol, PVSyst

1.0 INTRODUCTION

Global efforts to combat climate change have intensified the transition towards sustainable energy systems. Solar photovoltaic (PV) technologies have emerged as a leading solution, offering scalable, low-emission alternatives to fossil fuels [1]. Among these, floating solar photovoltaic (FSPV) systems are gaining attention due to their ability to conserve land, enhance energy yield through water-based cooling, and leverage existing hydrological infrastructure [2].

In the context of FSPV development, module selection **is** critical. Two major types of PV modules dominate the market: monofacial, which captures sunlight on one surface, and bifacial, which harvests light from both the front and rear sides [3]. While bifacial modules promise higher yields under reflective conditions (e.g., snow, sand, water), they come with higher capital costs and performance sensitivity to site conditions such as albedo and tilt angle [4].

Equatorial regions like West Sumatra, Indonesia, offer consistent solar irradiation, minimal seasonal fluctuation, and abundant water bodies ideal conditions for FSPV deployment [5]. However, limited studies have addressed the comparative performance and economics of monofacial and bifacial modules under such tropical, high-humidity, and high-diffuse-radiation environments [6]. Specifically, research gaps remain in:

- Quantifying energy yield differences under equatorial irradiance and water-reflected albedo;
- Evaluating system-level economic performance through Levelized Cost of Electricity (LCOE);
- Determining optimal tilt angles for each module type in FSPV configurations.

Several recent studies have demonstrated the potential performance advantages of bifacial modules in various global locations, particularly when deployed with optimized tilt and in reflective environments [7]. However, conflicting findings exist regarding their cost-effectiveness, especially when compared to monofacial modules in moderate-albedo conditions [8]. Moreover, existing literature rarely focuses on tropical equatorial climates where weather and albedo interactions may differ substantially from temperate regions.

This study addresses these gaps by conducting a detailed simulation-based analysis of monofacial and bifacial FSPV systems in Lake Singkarak, West Sumatra. Utilizing both PVSol and PVSyst tools, the research models energy yield, system efficiency, and economic viability (via LCOE), using real climate data and standardized design parameters [9]. The results aim to guide policymakers, developers, and investors in selecting optimal PV module configurations for equatorial FSPV systems, balancing energy output and long-term economic sustainability [10].

The growing emphasis on renewable energy sources as a solution to climate change and energy security has led to significant advancements in solar photovoltaic (PV) technology. Among these advancements, floating solar photovoltaic (FSPV) systems have emerged as a promising alternative due to their unique advantages such as reduced land usage, increased energy efficiency, and potential for integration with existing water infrastructure. Table 1 shows the findings of floating solar photovoltaic, monofacial, and bifacial studies.

Several studies have compared the energy yield and levelized cost of electricity generation (LCOE) between monofacial and bifacial solar panels under different conditions. [11] revealed that bifacial modules with optimized tilt angles achieved a 23.7% reduction in LCOE and a 13.6% increase in energy yield compared to monofacial modules.

A global analysis conducted by [12] on the yield potential and cost-effectiveness of solar PV farms, comparing monofacial fixed-tilt and tracker installations with their bifacial counterparts. The study highlighted that bifacial-1T installations increased energy yield by 35% and achieved the lowest LCOE levels for most of the world’s land area, indicating a significant advantage in adopting bifacial technology.

Simulation tools play a crucial role in predicting the performance of bifacial PV systems. A simulation tool developed by [13] to model the annual energy yield of bifacial modules in various geographical locations. Their results demonstrated that fixed bifacial modules generally outperformed tracked monofacial modules, especially in regions with high ground albedo coefficients. Furthermore, vertically mounted bifacial modules were found to achieve higher annual energy yields than south-facing monofacial modules at higher latitudes.

[14] assessed the prediction accuracy of simulation tools for bifacial technology by comparing simulated results with measured data. They concluded that deviations were minimal, typically within ±2% for tilt angles between 30° and 45°, suggesting that bifacial yield modeling is becoming increasingly reliable. Empirical studies have further validated the superior performance of bifacial PV modules under specific conditions. [15] evaluated the outdoor performance of bifacial PV modules under different ground reflection conditions, finding that monthly average bifacial gains ranged from 6.1% to 13.8% under 21% ground reflection and from 26.0% to 45.1% under 79% ground reflection. These results underscore the importance of ground albedo in maximizing the energy yield of bifacial systems. [16] emphasized the potential market impact of bifaciality, predicting that increased confidence from the financing sector could lead to widespread adoption. They observed energy gains ranging from 10% to 30% under various system configurations and ground reflection conditions, highlighting the economic advantages of bifacial systems.

Research specific to regions with high solar potential, such as West Sumatra, Indonesia, remains limited. However, studies like those conducted by [17] and [18] provide valuable insights. [17] demonstrated a 20% increase in output power for bifacial modules with a white reflective reflector, while [18] compared the performance of tracker system bifacial and monofacial panels, finding that bifacial systems were more advantageous in terms of energy production. [19] compared monofacial and bifacial solar modules, highlighting that bifacial modules generate more electricity due to their ability to utilize albedo radiation effectively. Bifacial photovoltaic modules have shown to produce higher short-circuit current density and power compared to monofacial modules in simulations. Their results indicated that bifacial modules produced more short-circuit current density and power, reinforcing the benefits of bifacial technology.

Recent research has also focused on the implementation of monofacial and bifacial PV modules in FSPV systems. [20] evaluated the performance of bifacial FSPV systems in California, USA. Their study showed that bifacial FSPV systems exhibited 10-20% higher energy yield than monofacial counterparts due to increased reflection from water surfaces. [21] analyzed bifacial FSPV systems on a mine pit lake in Korea. They reported a 15% higher energy production for bifacial FSPV systems compared to monofacial FSPV systems. This performance gain was attributed to the enhanced reflectivity and cooling effects provided by the water surface.

The literature consistently demonstrates the superior performance and cost-effectiveness of bifacial PV modules compared to monofacial modules, particularly in high-albedo environments and regions with significant solar potential. This study aims to build on existing research by providing a detailed comparative analysis of monofacial and bifacial FSPV systems in the tropical region of West Sumatra. By leveraging advanced modeling tools and real-time data, this research will offer practical insights into optimizing PV module selection for FSPV installations in equatorial climates, ultimately contributing to the broader adoption of renewable energy solutions in such regions.

Table 1 Key Findings of FSPV

Study	Location(s)	Year	Key Findings
[11]	China	2023	Bifacial modules with optimized tilt reduce LCOE by 23.7% and increase energy yield by 13.6% compared to monofacial modules.
[12]	Global	2023	Bifacial-1T installations can increase energy yield, with a fixed ground-mounted inclined bifacial PV system gaining 12% over monofacial, and bifacial with tracker gaining 8.9% over monofacial with tracker.
[13]	Malaysia	2022	Fixed bifacial modules outperform tracked monofacial modules, especially in regions with high ground albedo coefficients.

Study	Location(s)	Year	Key Findings
[14]	USA and Germany	2020	Simulation deviations were within ±2% for 30° to 45° tilt angles, indicating reliable bifacial yield modeling.
[15]	Varying ground reflection conditions	2023	Monthly average bifacial gains varied from 6.1% to 13.8% under 21% ground reflection and from 26.0% to 45.1% under 79% ground reflection.
[16]	Various system configurations	2022	Findings of energy gains ranging from 10% to 30% under different conditions, emphasizing the economic benefits and potential market impact of bifacial PV technology.
[17]	-	2022	Using a reflective white painted ground led to a significant improvement in the panels' performance, increasing the power gain by approximately 20%.
[18]	Multan	2023	Compared monofacial and bifacial solar PV modules for over-canal and overground installations, finding that monofacial modules for over-canal installation and bifacial modules for overground installation were the most suitable options.
[19]	-	2022	Compared monofacial and bifacial solar modules, highlighting that bifacial modules generate more electricity due to their ability to utilize albedo radiation effectively.
[20]	California, USA (Floating PV)	2021	Bifacial floating PV systems showed up to 10-20% higher energy yield than monofacial counterparts due to increased reflection from water surfaces.
[21]	Korea (Mine pit lake, Floating PV)	2022	Bifacial FSPV systems on mine pit lakes had 15% higher energy production compared to monofacial FSPV systems.

2.0 METHODOLOGY

This study employs a comprehensive approach to evaluate and compare the performance and cost-effectiveness of monofacial and bifacial floating solar photovoltaic (FSPV) systems in West Sumatra, Indonesia. This study adopts a simulation-based modeling design using PVSol and PVSyst to assess the energy and economic performance of monofacial and bifacial floating PV systems. Key input data include location-specific meteorological conditions (irradiation, temperature, wind speed) and component specifications (modules, inverters). Simulations were configured to reflect local environmental conditions at Lake Singkarak, and performance was measured using indicators such as energy yield, system efficiency, and LCOE.

2.1 Software Selection and Simulation Purpose

To ensure comprehensive performance modeling, two simulation tools are utilized in this study: PVSol and PVSyst.

- PVSol is used to design the floating PV layout, simulate user energy consumption profiles, and assess visual energy flow for residential demand assumptions.
- PVSyst provides a more in-depth irradiance and bifacial gain analysis, allowing detailed modeling of rear-side radiation, albedo effect, and accurate year-round energy yield prediction.

The use of both tools complements each other and enhances result reliability. PVSol enables accurate consumption-based sizing, while PVSyst delivers performance validation against meteorological and albedo factors.

2.2 Simulation Setup

The performance of floating PV systems in Lake Singkarak, West Sumatra, is assessed in this study using a simulation-based methodology with PV*Sol and PVSyst software. With the use of these software tools, real-world weather conditions can be modeled, enabling precise estimation of photovoltaic performance in various scenarios. In order to closely mimic actual operating conditions, the simulations include parameters like solar irradiation, temperature fluctuations, and system losses. The 100 PV modules in the simulation models are split equally between bifacial (LG340N1T-V5) and monofacial (LG450S2W-U6) panels, and they are examined at tilt angles of 30° and 60°. The following is the structure of the simulation setup.

2.3 Simulation Workflow and Stages

- Site and data acquisition: Meteorological data were retrieved using Meteonorm 8.1, including annual irradiation, ambient temperature, humidity, and wind velocity at Lake Singkarak.
- System configuration: A total of 100 floating modules were modelled 50 monofacial and 50 bifacial—analyzed at two tilt angles (30° and 60°).
- Performance simulation: Usable energy output and monthly generation were simulated across two tilt configurations per module type.
- Economic modeling: The Levelized Cost of Electricity (LCOE) was calculated using system lifetime cost assumptions and total generated output over 25 years.
- Comparative analysis: Output, efficiency, and economic indicators were compared across monofacial vs bifacial modules at both tilt angles. Deviation analysis was conducted to quantify bifacial gain.

2.4 Mathematical Model

Energy Output (E)

$$E=G_t \times A \times \eta \times PR$$

The total solar energy received per unit area over a specific time period is represented by incident solar radiation (G_t). It is expressed in kWh/m2, which is a unit of measurement that encompasses both direct and diffuse radiation. Geographical location, meteorological conditions, and seasonal fluctuations all affect the PV system's overall capacity to generate energy.

The photovoltaic module's actual size is denoted by the panel area (A). More sunlight can be captured over a larger area, which increases the amount of energy produced.

The PV module's efficiency (η) indicates how well it transforms sunlight into electrical energy. The overall amount of energy produced is impacted by the different efficiencies of different module technologies, such as monofacial and bifacial panels.

The performance ratio (PR) takes into consideration losses brought on by things like changes in temperature, dust buildup, shade, and inefficient systems. With normal values between 0.7 and 0.9, it acts as a gauge of the PV system's overall efficacy.

Bifacial Gain (BG)

$$BG=(E_{bifacial}-E_{monofacial})/E_{monofacial} \times 100\%$$

Bifacial gain represents the additional energy generated by bifacial PV modules compared to monofacial modules. Unlike monofacial panels, bifacial modules can absorb sunlight from both their front and rear surfaces, capturing reflected and scattered radiation from surrounding surfaces. This gain is particularly significant in floating PV applications, where water bodies provide a high albedo effect, increasing the amount of light reaching the rear side of the module.

Several factors influence bifacial gain, including:

- Ground Reflectivity (Albedo): Surfaces like water, snow, or white-painted roofs reflect more sunlight, enhancing rear-side energy absorption.
- Module Height and Tilt Angle: Raising bifacial panels increases their exposure to reflected light, optimizing energy capture.
- Shading and Surrounding Environment: Objects casting shadows or obstructing reflected light can reduce bifacial performance.

In this study, bifacial gain is analyzed under different tilt angles (30° and 60°) to assess its effectiveness in improving energy output. The results provide insights into whether bifacial technology is advantageous in equatorial floating solar applications.

Levelized Cost of Electricity (LCOE)

The Levelized Cost of Electricity (LCOE) is a crucial financial metric used to assess the cost-effectiveness of PV systems over their operational lifetime. It is defined as:

$$LCOE=\sum C_t/\sum E_t$$

C_t represents the total cost incurred in year, including:

- Capital Expenditure (CAPEX): Initial costs of PV modules, inverters, mounting structures, and installation.
- Operational Expenditure (OPEX): Maintenance, cleaning, and potential repair costs over the system's lifetime.
- Financing Costs: Loan interest or investment costs, if applicable.

E_t is the total energy generated by the system in year t, measured in kilowatt-hours (kWh).

LCOE is expressed in cost per kWh (e.g., USD/kWh) and helps compare different PV technologies on an economic basis. A lower LCOE indicates a more cost-effective system.

For bifacial PV modules, LCOE is influenced by:

- Increased energy yield due to rear-side reflection.
- Higher initial costs compared to monofacial modules.
- Potentially lower degradation rates, extending system lifespan.
- Additional structural or tracking system costs to optimize bifacial performance.

This study evaluates the LCOE of monofacial and bifacial floating PV systems to determine their financial viability in equatorial regions.

2.5 Site Details

The selected site for this study is located in Lake Singkarak West Sumatra, Indonesia, an equatorial region known for its high solar irradiation and consistent daylight hours throughout the year. This site is strategically chosen due to its favorable climatic conditions, which are ideal for solar energy generation. West Sumatra experiences an average solar irradiation of approximately 5.0 kWh/m² per day, with minimal seasonal variation. The average annual temperature is around 26°C, with relative humidity levels ranging between 70% and 90%, which provides a stable environment for solar panel performance.

The specific location for the floating solar PV installation is a large, calm water body within the region, which offers several advantages for the deployment of FSPV systems. The water surface helps in cooling the PV panels, potentially enhancing their efficiency by reducing the operating temperature. Additionally, the high albedo effect of water surfaces can increase the energy yield of bifacial modules by reflecting more sunlight onto the rear side of the panels.

Geographical coordinates of the site are approximately 0.6193° S, 100.5409° E, providing a near-ideal angle for solar exposure. The site is also chosen for its accessibility and proximity to existing electrical infrastructure, facilitating easy integration of the generated solar power into the local grid. Environmental factors such as wind speed, water temperature, and potential shading from surrounding vegetation or structures are also considered in the simulation to ensure accurate and realistic performance assessments.

By leveraging these site-specific details, the simulation aims to provide a thorough analysis of the energy yield, efficiency, and economic viability of both monofacial and bifacial FSPV systems under the unique conditions present in West Sumatra. This comprehensive site analysis ensures that the results will be relevant and applicable to similar equatorial regions globally. The location of the site is presented in figure 1.

Figure 1 Highlight of the site location, Lake Singkarak, West Sumatera, Indonesia

2.6 Meteorological Data

The meteorological data for this study is crucial for accurately modeling and simulating the performance of monofacial and bifacial floating solar photovoltaic (FSPV) systems in West Sumatra, Indonesia. The data includes key environmental parameters such as solar irradiation, average temperature, humidity, wind velocity, and precipitation, all of which influence the efficiency and energy yield of solar PV systems. Table 2 the meteorological data that is needed for this research.

Table 2 Meteorological Data

Location	Lake Singkarak, West Sumatera, Indonesia
Latitude & Longitude	0.6193° S, 100.5409° E
Annual Solar Irradiation	1842 kWh/m2
Average Temperature	26.7 °C
Wind Velocity	1.1 m/s

Among the various meteorological parameters, solar irradiance and ambient temperature are the most significant in determining the efficiency of solar PV systems. Increases in temperature can have both positive and negative effects on solar panel performance. Higher temperatures can reduce panel efficiency by increasing electrical resistance, leading to energy losses and lower output voltage. However, some solar technologies are designed to be more resilient to higher temperatures. To mitigate negative impacts, cooling mechanisms and regular maintenance are implemented to maintain optimal operating temperatures, ensuring long-term performance of the solar energy systems. Figure 2 shows the Monthly temperature at Singkarak.

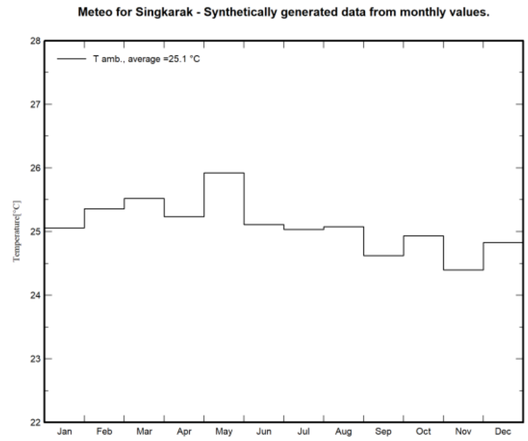


Figure 2 Ambient Temperature at Lake Singkarak

Solar irradiance, especially Global Horizontal Irradiance (GHI) and Horizontal Diffuse Irradiance, also plays a key role in the performance of solar panels. GHI represents the total solar energy received on a horizontal surface, including both direct sunlight and diffuse light scattered by the atmosphere. While the direct component contributes to achieving higher voltages and currents at the maximum power point (MPP), the diffuse component provides a more stable output under variable conditions, such as cloud cover or shading. Achieving an optimal balance between direct and diffuse irradiance is essential for maximizing the energy yield of solar panels. This balance can be achieved through appropriate panel positioning, orientation, and the use of tracking systems. Understanding both GHI and Horizontal Diffuse Irradiance is crucial for designing efficient solar energy systems and maximizing electricity generation. Figure 3 below plots the direct irradiation and diffuse irradiation.

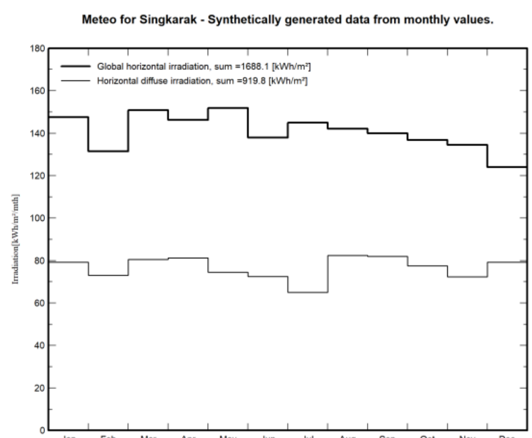


Figure 3 Direct Irradiation and diffuse irradiation comparison

Wind velocity is another important factor influencing the performance of solar PV systems. At Lake Singkarak, the average wind velocity is relatively moderate at 1.1 m/s. Figure 4 shows the wind velocity throughout the year. Wind plays a dual role in solar PV efficiency: on one hand, higher wind speeds can enhance the cooling of PV panels, potentially improving their performance by reducing thermal losses. On the other hand, excessively high wind speeds can pose risks to the structural integrity of solar installations, particularly for floating systems. Therefore, understanding wind patterns is crucial not only for optimizing cooling effects but also for ensuring the stability and durability of the solar PV setup.

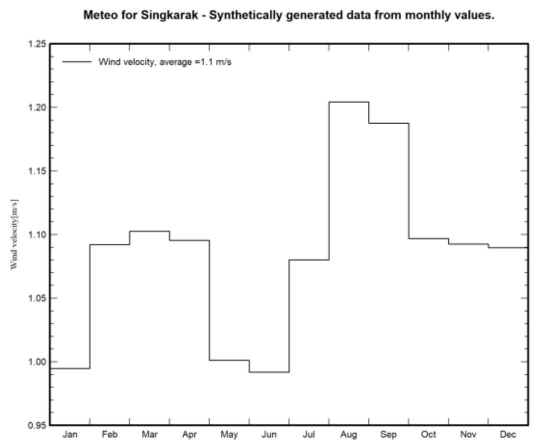


Figure 4 Wind Velocity

In regions like West Sumatra, which receive substantial rainfall with annual precipitation exceeding 3,000 mm, the frequent rains help in naturally cleaning the solar panels. This reduces the buildup of dust, bird droppings, and other debris that can accumulate on the surface of the panels, which in turn helps maintain their efficiency. Clean panels allow for better light absorption, which is crucial for optimal performance.

While rainfall aids in cleaning, it also presents challenges. FSPV systems must be designed with robust waterproofing to prevent water ingress into electrical components. Additionally, effective drainage solutions are required to ensure that excess water does not pool on the panels or the platform, which could add weight and strain on the system. Proper sealing of electrical junctions and the use of corrosion-resistant materials are critical to withstand the moist environment.

The buoyancy and stability of floating structures can be affected by heavy rain. Adequate design adjustments, such as ensuring that pontoons or other floating devices are not overwhelmed by the added weight of water, are essential. Regular maintenance checks are necessary to inspect for potential water damage and to adjust if needed.

The albedo effect refers to the reflectivity of a surface, in this case, the water surface of Lake Singkarak. Water bodies typically reflect a significant amount of sunlight. This reflected light can be utilized by bifacial solar panels, which are designed to absorb light from both the front and the back sides of the panel.

The albedo effect on water is particularly beneficial for bifacial PV modules because the water's surface reflects sunlight onto the rear side of the panels. This reflection can substantially increase the energy yield of bifacial panels compared to monofacial panels, which only capture light on one side. In FSPV systems, this can lead to an increase in energy output by up to 20-30%, depending on the reflectivity of the water surface and the height at which the panels are mounted above the water.

To maximize the benefits of the albedo effect, the orientation and tilt of the bifacial panels should be optimized to capture the maximum amount of reflected light. Additionally, maintaining a clean water surface by managing algae growth or other surface contaminants can enhance reflectivity, thus improving the overall efficiency of the FSPV system.

Beyond enhancing solar energy capture, the albedo effect can also contribute to passive cooling of the panels. The presence of water helps to regulate the temperature of the PV modules, potentially reducing the heat-induced losses that typically affect solar panels. This synergistic effect of cooling and additional light capture from reflections makes the albedo effect a valuable component of FSPV system performance.

2.7 Solar Components

The LG450S2W-U6, manufactured by LG Electronics, is a monofacial solar module known for its high performance and reliability. It uses high-efficiency monocrystalline cells, which allow it to convert sunlight into electricity more efficiently than many other types of solar cells. This makes it a preferred choice for solar project developers, homeowners, and businesses aiming to efficiently utilize solar energy. Its reliability and effectiveness have established a strong reputation in the industry, making it a sought-after option for various solar energy projects and applications. Figure 5 illustrates the I-V curve of an LG monofacial solar module.

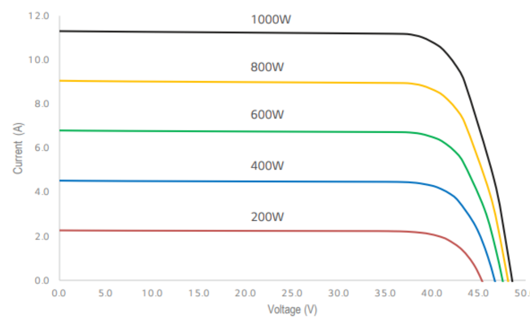


Figure 5 LG450S2W-U6 I-V Curves

The LG340N1T-V5, also from LG Electronics, is a bifacial solar module designed to generate electricity from both the front and rear sides by capturing reflected and diffuse sunlight. This innovative design significantly boosts energy output and overall efficiency, making it an attractive option for solar energy installations. With LG's reputable presence in the solar industry, the LG340N1T-V5 bifacial module provides a reliable and advanced solution, delivering higher energy yields and optimized solar power generation across a variety of environmental conditions. Figure 6 displays the I-V curve of an LG bifacial solar module.

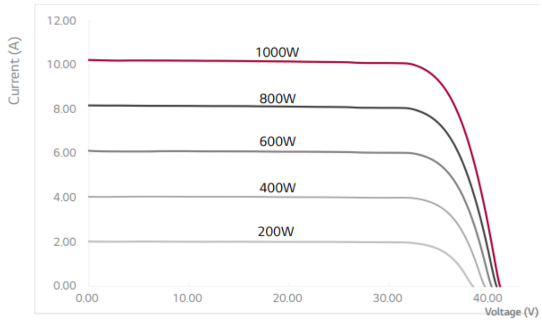


Figure 6 LG340N1T-V5 I-V Curves

For this study, the Schneider Electric Conext CL20000E inverter was utilized for the monofacial module, and the Schneider Electric Conext CL33 inverter was used for the bifacial module. Schneider Electric is a global leader in energy management and automation, known for producing robust and efficient inverters that convert DC electricity generated by solar panels into AC electricity for residential, commercial, and industrial applications. Their inverters incorporate advanced Maximum Power Point Tracking (MPPT) technology to optimize energy production and enhance system performance, ensuring reliability and efficiency in various conditions. Schneider Electric offers a diverse range of string inverters designed for different solar system sizes and applications, facilitating the widespread adoption of renewable energy. Their commitment to sustainability and innovative energy solutions strengthens their reputation as a key player in the global transition to clean energy. Tables 3 and 4 outlines the comprehensive specifications of the Schneider Electric Conext CL20000E and Schneider Electric Conext CL33 inverters used in this research.

Table 3 Conext CL20000E Specifications

Maximum AC Power	20000 W
Maximum Input Voltage	1000 Vdc
Maximum Input Current	30 A
Maximum Inverter Efficiency	98.3 %
Maximum Power AC Output	27600 VA
Night Power Consumption	<3 W

Table 4 Conext CL20000E Specifications

Maximum AC Power	33000 W
Maximum Input Voltage	1100 Vdc
Maximum Input Current	30 A
Maximum Inverter Efficiency	98.3 %
Maximum Power AC Output	36300 VA
Night Power Consumption	<2 W

The experimental setup in this study focuses exclusively on monofacial and bifacial floating solar modules, specifically using the LG450S2W-U6 for the monofacial configuration and the LG340N1T-V5 for the bifacial configuration. This approach aims to assess the performance and efficiency of these two types of floating solar modules, without the inclusion of more complex configurations such as dual-axis trackers or seasonal tilt systems.

The modules will be mounted at two angles: 30° and 60°. The 30° angle is designed to enhance solar exposure while maintaining system stability, commonly used in scenarios where moderate optimization is desired. The 60° angle aims to further maximize sunlight capture, particularly advantageous for bifacial modules which gain additional energy from reflected light on the rear side.

A total of 100 modules will be deployed, evenly divided between the monofacial and bifacial setups. All modules will utilize the SolarEdge SE27.6K-EU-APAC/AUS inverter, selected for its high efficiency and advanced MPPT algorithms that enhance overall energy output.

Detailed specifications of the LG450S2W-U6 and LG340N1T-V5 modules, will be presented in Table 5. This setup provides a clear comparison of the performance impacts of different tilt angles on monofacial and bifacial floating solar PV systems, delivering key insights into their operational efficiency in floating solar applications.

Table 5 Modules Specifications

Specifications	Monofacial	Bifacial
Manafacturers	LG	LG
Model	LG450S2W-U6	LG340N1T-V5
Cell Properties	Monocrystalline/P-type	Monocrystalline/N-type
Number of Cells	144	60
Module Power [W]	450	340
Module Efficiency [%]	20.2	19.8
Rated Voltage (Vmpp) [V]	40.91	32.3
Rated Current (Impp) [A]	11.01	9.89
Open Circuit Voltage (Voc) [V]	50.27	40.8
Short Circuit Current (Isc) [A]	11.43	10.38

2.7 Work Flowchart

For this research, the first step involved selecting the site, after which various meteorological data were collected to inform the system design. The design was carried out using PV*Sol and PVSyst, software tools that are widely used for simulating solar PV systems. Initially, solar panels were positioned in an open area, followed by the installation of inverters and wiring. Two distinct setups were created using monofacial and bifacial solar modules, each tested at two tilt angles: 30° and 60°.

The model designs were input into the simulation software, with specific parameters set for accurate performance modeling. Following the simulations, the energy generated by the monofacial and bifacial modules at the different angles was analyzed. A comparative study was conducted to evaluate the energy generation between the monofacial and bifacial setups, and between the two tilt angles, 30° and 60°. Additionally, a deviation analysis was performed to examine variations in performance.

Figure 7 illustrates the steps involved in the project, from site selection and data collection to design, simulation, and comparative analysis.

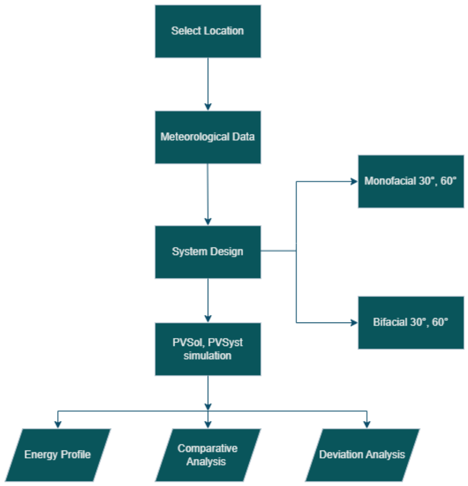


Figure 7 Research Flowchart

3.0 RESULTS AND DISCUSSION

For this research, there are 2 types of modules utilized: Monofacial module and Bifacial Module. The angles that has been used in this study are 30° and 60 °. The reason that this angle is used because of bifacial module are not optimized when the angle is 0°. PVsyst is used to collect meteorological data integrated with Meteonorm 8.1. The meteorological data, location details, and module specifications have been analysed and compared in PV*Sol.

The consumption settings that have been used for both of the modules are 2 households, first is two person households with 2 children and 2 person households with one child. Figure 8 below show the annual consumption.

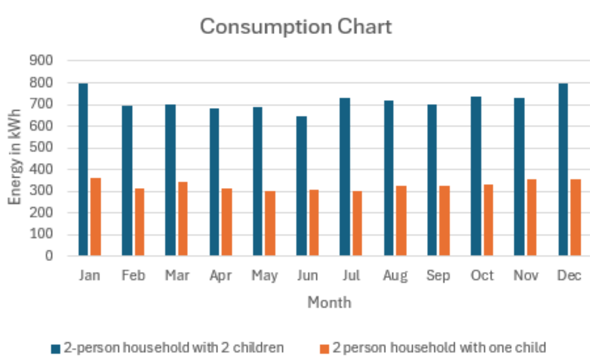


Figure 8 Consumption Chart

3.1 Monofacial Module

Photovoltaic panels with a single active side are known as monofacial solar modules. They are made up of layers that include an electrical connection, a back sheet, a semiconductor material (usually silicon), and a front glass cover. They cost less for solar power systems even though they are marginally less effective than bifacial panels. These panels, which are frequently mounted on rooftops, in power plants, and in solar farms, function best when they are facing direct sunlight. Despite not using reflected light, research is still being done to increase their efficiency, which makes them a good option for a variety of solar energy applications.

Table 6, table 7 figure 9 and 10 below provides the monthly energy generation for 30° and 60° angle respectively.

Table 6 Monofacial Module 30° Angle

Month	Usable PV Energy (kWh)
January	1492,9
February	1203,5
March	1271,5
April	1208,8
May	1212,9
June	1207,7
July	1237,5
August	1267,1
September	1238,8
October	1305,1
November	1287,1
December	1379

Table 7 Monofacial Module 60° Angle

Month	Usable PV Energy (kWh)
January	1491,5
February	1200,7
March	1269,5
April	1212,3
May	1220
June	1207,3
July	1245,9
August	1271
September	1241,1
October	1286,5
November	1324,2
December	1380,4

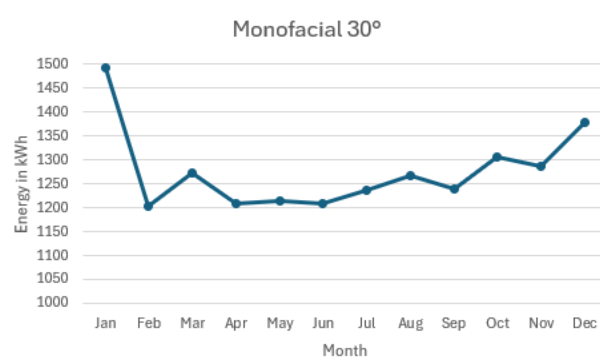


Figure 9 Energy in Monofacial 30°

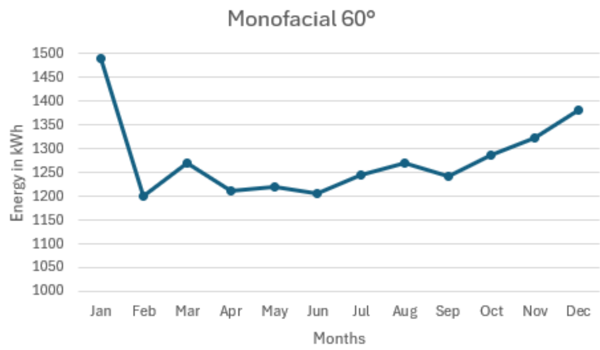


Figure 10 Energy in Monofacial 60°

The monofacial PV modules' data at 30° and 60° tilt angles demonstrate essentially constant energy production with very little variation over the course of the year. While the 60° angle performs better in the late autumn and winter months, especially in November and December, the 30° angle generates slightly more useable energy in most months, peaking in January with 1492.9 kWh. The small energy output difference between the two angles indicates that both function similarly here. While the 30° angle offers more evenly distributed energy output all year round, the 60° angle has a slight advantage in capturing sunlight during lower sun angles in the winter. Overall, the results indicate that while modifying the tilt angle may maximize energy yield for sites with seasonal variations, a 30° angle is still more efficient for the majority of the year.

3.2 Bifacial Module

Photovoltaic panels with two active sides are known as bifacial solar modules. They are made up of layers that include an electrical connection, a back sheet, a semiconductor material (usually silicon), and a front and back glass cover. While they are slightly more expensive than monofacial panels, they can significantly increase energy output, especially in environments with reflective surfaces like snow or water. These panels, which are frequently mounted on rooftops, in power plants, and in solar farms, function best when they are facing direct sunlight and can also utilize reflected light. Due to their higher efficiency, bifacial modules are becoming increasingly popular for various solar energy applications.

Table 8, table 9, figure 11, and figure 12 below provide the monthly energy generation for 30° and 60° angles respectively.

Table 8 Bifacial Module 30° Angle

Month	Usable PV Energy (kWh)
January	1454,2
February	1199,8
March	1266,1
April	1203,4
May	1209,4
June	1194,1
July	1240,3
August	1264,4
September	1235,2
October	1282,8
November	1315,1
December	1356,4

Table 9 Bifacial Module 60° Angle

Month	Usable PV Energy (kWh)
January	1454,1
February	1199,2
March	1266
April	1206,3
May	1212,6
June	1193,9
July	1243,3
August	1265,3
September	1238,4
October	1282,8
November	1314,1
December	1357

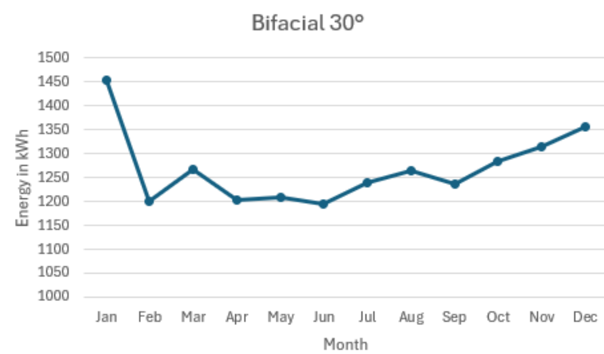


Figure 11 Energy in Bifacial 30°

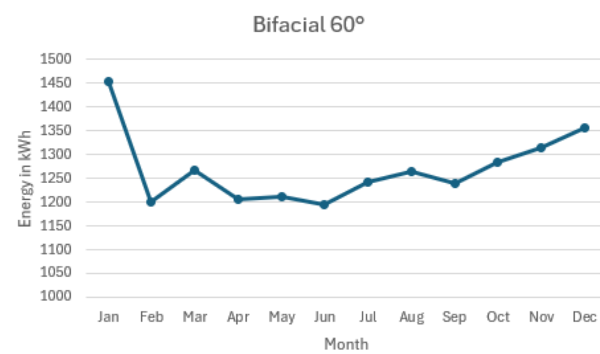


Figure 12 Energy in Bifacial 60°

With only slight variations between the two tilt angles, the data from the bifacial PV modules at both 30° and 60° tilt angles demonstrates a similar trend to the monofacial modules, with relatively consistent energy production throughout the year. While the 60° angle displays a similar pattern with a slightly higher energy output in December (1357 kWh) and a similar low in June (1193.9 kWh), the 30° angle shows the highest energy generation in December (1356.4 kWh) and the lowest in June (1194.1 kWh). In this location, both angles perform nearly equally well because the differences between them are small—typically less than 5 kWh per month. Nonetheless, the 60° angle tends to perform marginally better in late autumn and winter, while the 30° angle performs slightly better in other seasons of the year, much like the monofacial data. This implies that both angles are useful for bifacial modules, with seasonal solar angles only slightly affecting energy output. The data supports the hypothesis that modifying the tilt angle seasonally could increase efficiency slightly, especially in the winter months, but overall, both angles perform about equally well all year long.

3.3 Energy Yield Comparison

The simulation results showed that monofacial modules slightly outperformed bifacial modules in total annual energy output at both tilt angles. At 30°, monofacial modules produced 15,011.9 kWh annually compared to 14,917.9 kWh for bifacial modules. Similarly, at 60°, the monofacial setup generated 15,125.2 kWh, while bifacial produced 14,927.2 kWh.

This outcome is contrary to global findings where bifacial modules often demonstrate higher energy yield due to rear-side irradiance [21][30]. However, in this study, the water surface albedo at Lake Singkarak (~0.2–0.3) might not be high enough to fully leverage the bifacial potential, thus reducing their performance advantage.

Moreover, panel height, mounting distance from water, and local diffuse radiation patterns may have contributed to the marginal energy difference. Prior studies in high-albedo regions (e.g., deserts or snow) report bifacial gains of up to 10–30% [25][26], which were not replicated in this equatorial water-based setting.

3.4 Deviation Analysis

This analysis compared the monthly energy output of the two module types and determine how much more or less energy is produced by the bifacial modules compared to the monofacial modules in order to perform a deviation analysis between the monofacial and bifacial modules at both tilt angles (30° and 60°). This can be useful in assessing how the two technologies differ in terms of performance. Tables 10 and 11 shows the analysis for 30° and 60° respectively. The deviation percentage between the bifacial and monofacial modules for each month can be calculated using the following formula:

Deviation (%)=((Bifacial Energy Output−Monofacial Energy)/(Monofacial Energy Output)) ×100

Table 10 30° Angle Deviation Analysis

Month	Monofacial (kWh)	Bifacial (kWh)	Deviation
January	1492,9	1454,2	-2.59%
February	1203,5	1199,8	-0.31%
March	1271,5	1266,1	-0.42%
April	1208,8	1203,4	-0.45%
May	1212,9	1209,4	-0.29%
June	1207,7	1194,1	-1.12%
July	1237,5	1240,3	+0.23%
August	1267,1	1264,4	-0.21%
September	1238,8	1235,2	-0.29%
October	1305,1	1282,8	-1.71%
November	1287,1	1315,1	+2.18%
December	1379	1356,4	-1.64%

Table 11 60° Angle Deviation Analysis

Month	Monofacial (kWh)	Bifacial (kWh)	Deviation
January	1491,5	1454,1	-2.51%
February	1200,7	1199,2	-0.12%
March	1269,5	1266	-0.28%
April	1212,3	1206,3	-0.49%
May	1220	1212,6	-0.61%
June	1207,3	1193,9	-1.11%
July	1245,9	1243,3	-0.21%
August	1271	1265,3	-0.45%
September	1241,1	1238,4	-0.22%
October	1286,5	1282,8	-0.29%
November	1324,2	1314,1	-0.76%
December	1380,4	1357	-1.69%

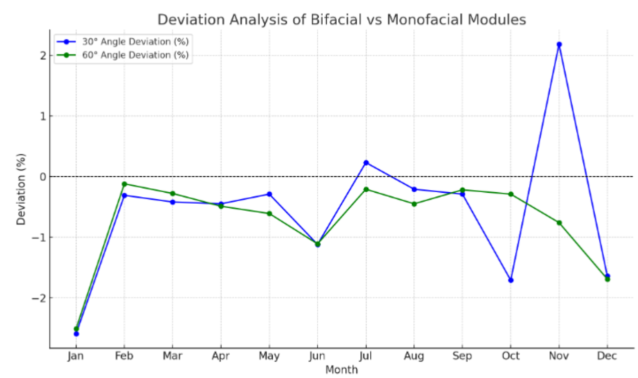


Figure 13 Deviation Analysis of Bifacial vs Monofacial

Figure 13 illustrates that, on average, bifacial modules produce slightly less energy than monofacial modules throughout the year when comparing their energy output at both 30° and 60° angles. The deviations vary between -2.6% and +2.18%, with the biggest negative deviations for both angles happening in January and December. This suggests that monofacial modules function better in the winter. Nevertheless, there are some situations where bifacial modules slightly outperform monofacial ones, especially in July and November at a 30° angle. In general, there is not much of a performance difference; most months, bifacial modules only exhibit slightly reduced energy output. Efficiency patterns remained consistent across months, with monofacial modules showing better stability and slightly higher output in most cases. Deviation analysis indicated that bifacial modules underperformed by 0.2%–2.6% in most months, though a few months (e.g., November) showed positive deviation (up to +2.18%), particularly at a 30° tilt. The energy consistency of monofacial modules supports their suitability for stable year-round yield in equatorial floating installations, especially where rear reflectivity is limited.

3.5 Economic Analysis Levelized Cost of Electricity (LCOE)

Economic analysis based on Levelized Cost of Electricity (LCOE) reveals that monofacial systems had a slightly lower LCOE:

- Monofacial: USD 0.0230–0.0231/kWh
- Bifacial: USD 0.0235/kWh (both tilt angles)

Despite the small cost difference, the monofacial system's lower capital cost and marginally higher yield led to better overall cost-effectiveness. This aligns with [18] and [29], which emphasize that bifacial PV's economic viability strongly depends on environmental conditions and system configuration.

It's also worth noting that although the capital cost of bifacial modules is slightly higher (~2.7% more), the marginal increase in yield was insufficient to justify this cost in a standard tropical lake environment. In contrast, [22] showed that in arid or high-albedo areas, bifacial modules yielded higher NPV and faster payback periods due to more effective rear-side energy harvesting.

The LCOE is calculated using the formula:

$$LCOE=\sum C_t/\sum E_t$$

Where total costs include capital expenditures and the present value of O&M costs over the system's lifespan. Table 12 and table 13 shows the monthly LCOE at 30° and 60° respectively. While table 14 shows the LCOE analysis summary

Assumptions:

- Discount Rate: 5% (to account for the time value of money).

System Size:

- Assumed to be 1 kW for simplification; results can be scaled accordingly.

Monofacial PV System:

- Capital Cost: $113.
- Annual O&M Cost: Assuming an average of $15 per kW per year
- Total O&M Cost over 25 Years (undiscounted): $15 * 25 = $375.
- Present Value of O&M Costs: Using a discount rate of 5%, the present value factor for a 25-year annuity is approximately 15.62. Therefore, PV of O&M costs = $15 x 15.62 ≈ $234.30.
- Total Cost: $113 (capital) + $234.30 (O&M) = $347.30.
- Total Energy Production: Assuming an average of 15,011.9 kWh over 25 years = 15,011.9 kWh.
- LCOE: $347.30 / 15,011.9 kWh ≈ $0.0231 per kWh.

Bifacial PV System:

- Capital Cost: $116.
- Annual O&M Cost: Assuming an average of $15 per kW per year.
- Total O&M Cost over 25 Years (undiscounted): $15 * 25 = $375.
- Present Value of O&M Costs: $15 * 15.62 ≈ $234.30.
- Total Cost: $116 (capital) + $234.30 (O&M) = $350.30.
- Total Energy Production: Assuming an average of 14,917.9 kWh over 25 years = 14,917.9 kWh.
- LCOE: $350.30 / 14,917.9 kWh ≈ $0.0235 per kWh.

Table 12 Monthly LCOE at 30° tilt

Month	LCOE Monofacial (USD/kWh)	LCOE Bifacial (USD/kWh)
January	0.00366	0.00427
February	0.00454	0.00517
March	0.00429	0.00490
April	0.00452	0.00516
May	0.00450	0.00513
June	0.00452	0.00520
July	0.00441	0.00500
August	0.00431	0.00491
September	0.00441	0.00502
October	0.00418	0.00484
November	0.00424	0.00472
December	0.00396	0.00457

Table 13 Monthly LCOE at 60° tilt

Month	LCOE Monofacial (USD/kWh)	LCOE Bifacial (USD/kWh)
January	0.00366	0.00427
February	0.00455	0.00517
March	0.00430	0.00490
April	0.00450	0.00514
May	0.00447	0.00512
June	0.00452	0.00520
July	0.00438	0.00499
August	0.00430	0.00490
September	0.00440	0.00501
October	0.00424	0.00484
November	0.00412	0.00472
December	0.00395	0.00457

Table 14 LCOE Analysis Summary

System Configuration	Capital Cost ($/kW)	Average Annual Energy (kWh)	LCOE ($/kWh)
Monofacial Module at 30°	113	15,011.9	0.0231
Monofacial Module at 60°	113	15,125.2	0.0230
Bifacial Module at 30°	116	14,917.9	0.0235
Bifacial Module at 60°	116	14,927.2	0.0235

Because of their comparable energy production and lower capital costs, monofacial PV systems have a slightly lower LCOE than bifacial systems, according to the analysis. In areas with typical reflectivity, bifacial modules may not always be worth the higher initial costs, even though they have the potential to produce higher energy yields in certain situations (such as high albedo environments).

3.6 Economic Performance and LCOE Analysis

Economic analysis based on Levelized Cost of Electricity (LCOE) reveals that monofacial systems had a slightly lower LCOE:

- Monofacial: USD 0.0230–0.0231/kWh
- Bifacial: USD 0.0235/kWh (both tilt angles)

Despite the small cost difference, the monofacial system's lower capital cost and marginally higher yield led to better overall cost-effectiveness.

It's also worth noting that although the capital cost of bifacial modules is slightly higher (~2.7% more), the marginal increase in yield was insufficient to justify this cost in a standard tropical lake environment.

3.7 Tilt Angle Impact

Across both technologies, the 60° tilt showed slightly higher annual energy yield than 30°, especially during the rainy season and winter months. Steeper tilt angles enhance performance in high-diffuse or cloud-prone environments.

However, the gain from 60° over 30° was minor (~0.5%–1%), indicating that 30° remains more efficient for year-round generation and system stability, particularly where wind load and mechanical stress on floating platforms are of concern.

4.0 CONCLUSION

This study presents a comparative analysis of monofacial and bifacial floating solar PV (FSPV) systems under equatorial conditions using PVSol and PVSyst simulation tools. The systems were evaluated at two tilt angles (30° and 60°) to examine performance differences in energy output, efficiency, and economic feasibility.

The simulation results reveal that monofacial modules consistently produced slightly higher annual energy output than bifacial modules across both tilt configurations. This performance advantage is attributed to the relatively low albedo of the water surface at Lake Singkarak, which limited the rear-side irradiance gain potential of bifacial modules. While bifacial modules theoretically offer higher yields in reflective environments, their performance in this tropical water-based setting remained marginally below that of monofacial systems.

From an efficiency standpoint, monofacial modules demonstrated more stable and predictable performance throughout the year. The deviation analysis confirmed that bifacial modules experienced slight underperformance in most months, with only a few showing minor positive gains.

The economic analysis reinforces the technical findings. Monofacial systems achieved a lower Levelized Cost of Electricity (LCOE), averaging USD 0.0230/kWh, compared to USD 0.0235/kWh for bifacial modules. The lower capital cost and consistent energy generation of monofacial setups make them more cost-effective for equatorial floating PV applications, particularly in regions without highly reflective surfaces.

In conclusion, monofacial floating PV modules are recommended for deployment in equatorial climates such as West Sumatra, where ambient conditions and water albedo do not strongly favor bifacial gain. While bifacial modules may become more competitive in high-albedo environments or with optimized elevation and tracking systems, their application in typical equatorial lakes may not yet be financially justified without further cost reductions or system enhancements.

Acknowledgement

This authors would like to thank Lembaga Penelitian dan Pengabdian Masyarakat Universitas Negeri Padang for funding this work with a contract number: 1757/UN.35.15/LT/2024

Conflict of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

References

[1] S. Vunnam, M. VanithaSri, and R. Alla, 2023. "An outline of solar photovoltaic systems impact on environment," *Bulletin of Electrical Engineering and Informatics,* 12(5): 2635–2642. DOI: 10.11591/eei.v12i5.5584.

[2] G. Kakoulaki *et al.* 2023. "Benefits of pairing floating solar photovoltaics with hydropower reservoirs in Europe," *Renewable and Sustainable Energy Reviews.* 171: 112989. DOI: 10.1016/j.rser.2022.112989.

[3] G. Raina, S. Mathur, and S. Sinha, 2022. "Behavior of bifacial and monofacial photovoltaic modules under partial shading scenarios," *International Journal of Energy Research.* 46(9): 12837–12853. DOI: 10.1002/er.8057.

[4] H. Park, S. Chang, S. Park, and W. K. Kim, 2019, "Outdoor Performance Test of Bifacial n-Type Silicon Photovoltaic Modules," *Sustainability*, 11(22): 6234. DOI: 10.3390/su11226234.

[5] D. F. Silalahi, A. Blakers, M. Stocks, B. Lu, C. Cheng, and L. Hayes, 2021, "Indonesia's Vast Solar Energy Potential," *Energies*, 14(17): 5424. DOI: 10.3390/en14175424.

[6] J. Johnson and S. Manikandan, 2021. "Rear Side Solar Radiation Model of Bifacial Photovoltaic Module for Equatorial zone," *IOP Conference Series: Materials Science and Engineering*. 1130(1): 012018. DOI: 10.1088/1757-899X/1130/1/012018.

[7] A. Desai, I. Mukhopadhyay, and A. Ray, 2022 "Feasibility Assessment of Bifacial Rooftop Photovoltaic Systems in the State of Gujarat in India," *Frontiers in Energy Research.* 10. DOI: 10.3389/fenrg.2022.869890.

[8] Y. Muñoz, M. De La Rosa, L. C. Acevedo, and W. Velandia, 2023. "Technical and Financial Assessment of Photovoltaic Solar Systems with Bifacial Technology Comparing Four Scenarios with Different Albedos with Respect to the Base Scenario with Monofacial Technology, in a Tropical Location in Colombia, *International Journal of Energy Economics and Policy,* 13(4): 389–393. DOI: 10.32479/ijeep.14194.

[9] Z. Serat, S. A. Z. Fatemi, and S. Shirzad, 2023. "Design and Economic Analysis of On-Grid Solar Rooftop PV System Using *Archives of Advanced Engineering Science,* 1(1): 63–76 DOI: 10.47852/bonviewAAES32021177.

[10] A. B. Pulungan, L. Son, S. Syafii, S. Huda, and U. Ubaidillah, 2023. "Low Speed Orientation Control Using Variable Mass System: Application In Solar Panel, *Journal of Sustainable Development of Energy, Water and Environment Systems* 11(2): 1–17. DOI: 10.13044/j.sdewes.d11.0456.

[11] H. Hao *et al.* 2023, "Energy Yield Prediction of Bifacial Perovskite/Silicon Tandem Photovoltaic Modules," *Solar RRL*

7(15) DOI: 10.1002/solr.202300218.

[12] R. O. Yakubu, L. D. Mensah, D. A. Quansah, and M. S. Adaramola, 2022, “Improving solar photovoltaic installation energy yield using bifacial modules and tracking systems: An analytical approach,” *Advances in Mechanical Engineering.*, 14(12): 168781322211397. DOI: 10.1177/16878132221139714.

[13] N. Mohamed, S. Sulaiman, and S. Rahim, 2022, “Design of ground-mounted grid-connected photovoltaic system with bifacial modules using PVsyst software,” *Journal of Physics: Conference Series.* 2312(1): 012058. DOI: 10.1088/1742-6596/2312/1/012058.

[14] E.-M. Grommes, F. Schemann, F. Klag, S. Nows, and U. Blieske, 2023, “Simulation of the irradiance and yield calculation of bifacial PV systems in the USA and Germany by combining ray tracing and view factor model,” *EPJ Photovoltaics*, 14: 11. DOI: 10.1051/epjpv/2023003.

[15] C. F. Abe, J. Batista Dias, G. Notton, G.-A. Faggianelli, G. Pigelet, and D. Ouvrard, 2023. “Estimation of the Effective Irradiance and Bifacial Gain for PV Arrays Using the Maximum Power Current,” *IEEE Journal of Photovoltaics*. 13(3): 432–441. DOI: 10.1109/JPHOTOV.2023.3242117.

[16] E.-M. Grommes and U. Blieske, 2022, “BifacialSimu: Holistic Simulation of large-scale Bifacial Photovoltaic Systems,” *Journal of Open Source Software*, 7(78): 4443. DOI: 10.21105/joss.04443.

[17] E. S. Ghunaim, 2022, “Improving the Performance of Bifacial Modules by Adding Reflection Material,” in *2022 11th International Conference on Power Science and Engineering (ICPSE)*, IEEE, 10–14. DOI: 10.1109/ICPSE56329.2022.9935349.

[18] I. Farhat *et al.*, 2023, “Performance analysis of monofacial and bifacial over-canal solar photovoltaic (PV) system and assessment of water and land conservation potential *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects.,* 45(3): 6981–6993, Aug. DOI: 10.1080/15567036.2023.2217774.

[19] G. A. Matarneh, M. A. Al-Rawajfeh, and M. R. Gomaa, 2022, “Comparison review between monofacial and bifacial solar modules,” *Technology audit and production reserves,* 61(68): 24–29. DOI: 10.15587/2706-5448.2022.268955.

[20] K. Jose, S. Sheik Mohammed, and O. Mohammed Mansoor, 2023, “Performance Study of Solar PV System with Bifacial PV Modules,” 659–670. DOI: 10.1007/978-981-19-4971-5_48.

[21] S. D. Naik and S. V Kulkarni, 2022, “Design and Analysis of Underwater Bifacial Solar Photovoltaic Cell,” in *2022 IEEE 3rd Global Conference for Advancement in Technology (GCAT)*, IEEE, Oct. 1–5. DOI: 10.1109/GCAT55367.2022.9971927.