

Comparative Study of Design and Simulation Monofacial and Bifacial Panel on the PV Rooftop of Ibrahim Tower at Roemani Muhammadiyah Hospital, Semarang

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ABSTRACT

As a multi-story healthcare facility, the Ibrahim Tower of Roemani Muhammadiyah Hospital in Semarang faces increasing electricity demand, resulting in high operational loads and dependence on PLN and fossil-fuel generators, leading to increased long-term costs and carbon emissions. The utilization of Photovoltaic (PV) systems presents a strategic alternative to enhance energy efficiency and support emission reduction initiatives. In the context of photovoltaic technology development, monofacial and bifacial modules offer opportunities for more optimal solar energy utilization, particularly bifacial modules that can absorb radiation on both sides of the panel. This study aims to determine the optimal number of solar modules and total installed capacity on the east–west pitched roof while comparing the energy potential of monofacial and bifacial PV modules to achieve a technically efficient rooftop PV design. The study was conducted through roof dimension measurements and modeling using AutoCAD, panel configuration planning that includes row spacing to minimize shading, and system performance

simulation using Pvsyst software. Data collection methods comprised direct field observations and a literature review of previous studies. Simulation results show that the bifacial PV system yields an annual energy output of 107,199 kWh/year, an increase of 2,358 kWh/year (approximately 2.25%) compared to the monofacial system's 104,841 kWh/year. Furthermore, the bifacial system achieved a higher Performance Ratio (PR) of 85.93% compared to the monofacial system's 84.04%. This demonstrates that bifacial technology provides superior performance and operational efficiency for the specific installation conditions.

Keywords: Photovoltaic System, Monofacial PV, Bifacial PV, Pvsyst, AutoCAD.

INTRODUCTION

Photovoltaic (PV) systems, or Solar Power Plants (SPPs), convert sunlight into electricity. Solar energy is environmentally friendly, and as a country with abundant solar potential, Indonesia has a significant opportunity to develop PV systems to reduce reliance on fossil fuels and lower greenhouse gas emissions [1]. According to

IESR (2019), Central Java is among the top ten regions with a renewable energy potential of 19,450 MW. Currently, PV system implementation represents only 8% of the total renewable energy capacity [2]. However, it is continually promoted through government policies, including tax incentives, renewable energy programs, and facilitated financing[3].

Roemani Muhammadiyah Hospital is currently constructing the Ibrahim Tower with a total area of 25,577 m², which increases electricity consumption. Solar modules consist of monofacial and bifacial types. Monofacial modules convert sunlight from the front surface into electricity. Bifacial modules have a transparent rear layer, allowing both sides to capture sunlight, with the front side receiving direct radiation and the rear side capturing reflected light, thereby generating higher energy output [4].

Several studies indicate that bifacial modules can increase energy output by up to 20%, depending on environmental factors such as tilt angle, shading, and surface albedo [4]. However, panel orientation and placement, including tilt angle and shading, significantly affect their performance. Tilted bifacial modules have been found to generate 7.85% more energy, and increasing surface albedo can boost energy output by up to 16.2% [5]. Albedo indicates that optimal installation enhances performance compared to flat-mounted panels. A distinct feature of bifacial modules is their ability to absorb radiation on both sides, both direct and reflected [6], making them more tolerant to shading [7].

The construction of the Ibrahim Tower has increased the transformer capacity from 1,000 kVA to 3,500 kVA and the generator capacity from 500–600 kVA to 2,000 kVA. Full reliance on PLN electricity and fossil-fuel generators raises operational costs and carbon emissions. As a 24-hour institution, the hospital requires reliable, efficient, and environmentally friendly energy. Considering the significant increase in electricity demand following the

construction of Ibrahim Tower, the hospital requires a reliable and efficient renewable energy source. Rooftop PV installation is therefore aligned with national renewable energy policies and emission-reduction targets. While bifacial modules offer higher potential output, their performance strongly depends on system orientation, tilt angle, and rooftop albedo. Hence, a comparative study is required to determine the most suitable module type for the Ibrahim Tower.

MATERIALS & METHODS

The research subject refers to the entity or object that serves as the focus of observation, analysis, and data collection in a study. In this research, the subject is not human or a physical population, but rather a photovoltaic (PV) system model consisting of two types of module configurations: bifacial and monofacial modules.

Technical Subject (Simulative)

The technical subject in this study is the design model of bifacial and monofacial PV systems with equivalent capacities and design parameters, which include: Type of solar modules: bifacial and monofacial with crystalline silicon (monocrystalline) technology. System parameters: installed capacity, tilt angle, panel orientation, string configuration, and inverter type. Environmental data: solar radiation intensity and surface reflectance (albedo) values used as simulation inputs. Simulation reference location: an area with tropical climate characteristics and medium to high radiation levels.

2. Theoretical Subject (Literature Study)

The theoretical subject in this study consists of theories and scientific sources relevant to the design and performance of photovoltaic systems, including: Basic theories of solar energy conversion into electricity. Operating principles and characteristics of bifacial and monofacial solar modules. Influence of environmental parameters (radiation and albedo) on solar module efficiency. Methods for simulating PV

system performance using software such as PVsyst.

This study uses tools and devices that support the design process, performance simulation, and analysis of bifacial and monofacial PV systems. The proper use of these tools is essential to ensure that simulation results accurately represent technical and environmental conditions.

1. PV Simulation Software (PVsyst)

Used to simulate the performance of PV systems for both bifacial and monofacial modules. This software can calculate energy output, system efficiency, and the effects of environmental factors such as temperature, albedo, and panel orientation. The simulation results from this software serve as the primary basis for comparing the performance of the two module types.

2. Design and Visualization Software (AutoCAD)

Used to design the physical layout of the PV system on the roof area to be simulated. The design includes panel positions, row spacing, tilt angles, and orientation to ensure the system is planned according to real-world conditions.

3. Weather and Solar Radiation Data (Meteonorm / BMKG)

Serves as the main input for system simulations. The data includes global horizontal irradiance (GHI), direct normal irradiance (DNI), air temperature, and

humidity. Accurate data sources are required so that the simulation realistically reflects the solar energy potential at the study location.

4. Computing Devices (Laptop or Computer)

Used to run all design and simulation processes. The devices are equipped with adequate specifications for graphical processing and numerical calculations required by PV simulation software.

Data Analysis

1. Processing Simulation Results

Simulation data from each system (bifacial and monofacial) are extracted in the form of tables and graphs containing key performance parameters, such as:

- Total annual energy (kWh)
- Performance Ratio (PR)
- Specific Yield (kWh/kWp)

2. Results Interpretation and Validation

- Simulation results are compared with previous studies to assess their validity.
- If significant discrepancies occur between simulation data and theoretical expectations, interpretations are made regarding possible contributing factors (e.g., differences in albedo models, panel configurations, or software limitations).

RESULT

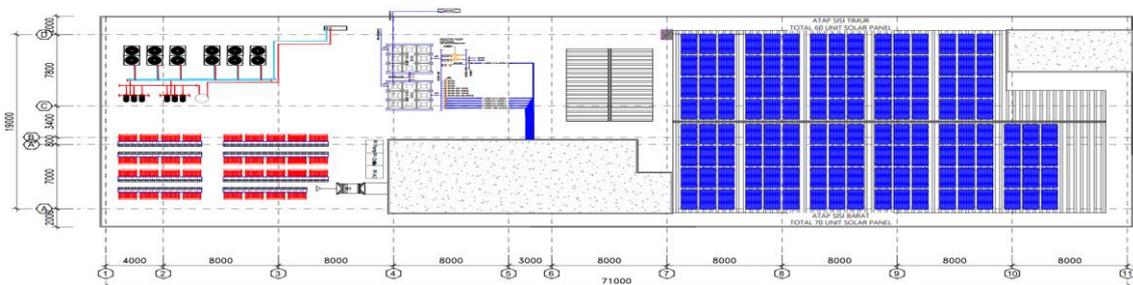


Figure 1. Location of the PV System Installation on the Roof of Ibrahim Tower

Figure 1 illustrates the layout design of the PV system on the roof of Ibrahim Tower. The roof is divided into two sections: a flat concrete deck on the left side and a corrugated metal gable roof on the right

side. The concrete deck is reserved for mechanical equipment such as pumps and chillers, making it unsuitable for PV installation. This aligns with the study by Yin, Li & Han [8], which states that PV roof

design and maintenance should consider building materials, structural characteristics, and construction processes, and that placing modules in utility areas can add load and hinder maintenance access.

The right side of the building features a gable roof with two surfaces: the east side with an area of 267 m² and the west side with 313 m², both designated for solar panel

installation. Research by Alkan & Ates [9] indicates that an east-west orientation allows for higher power installation per unit area and a more balanced energy load distribution, making it suitable for regions near the equator.

DISCUSSION

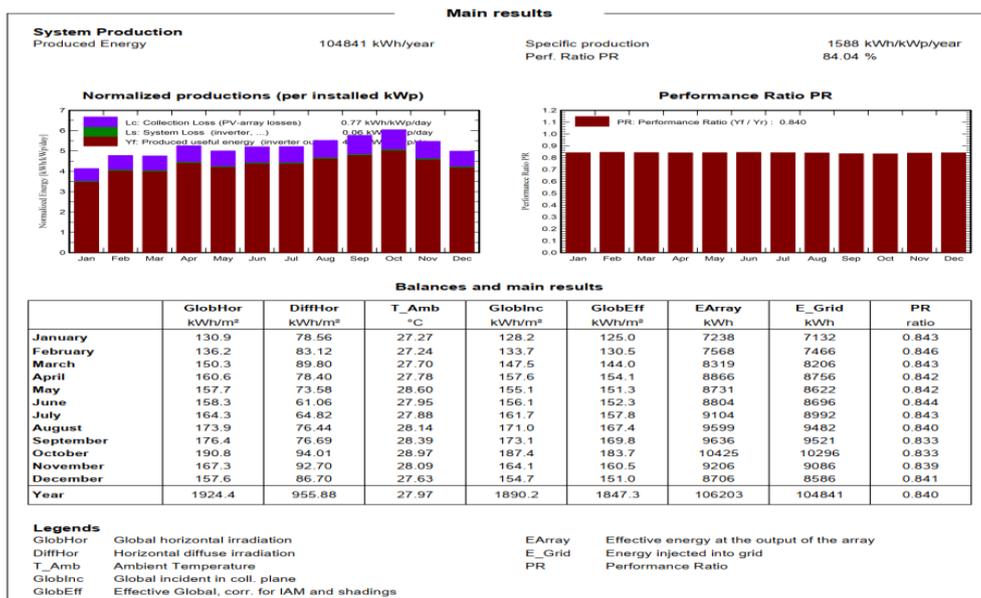


Figure 2. Energy Output of the Monofacial PV System

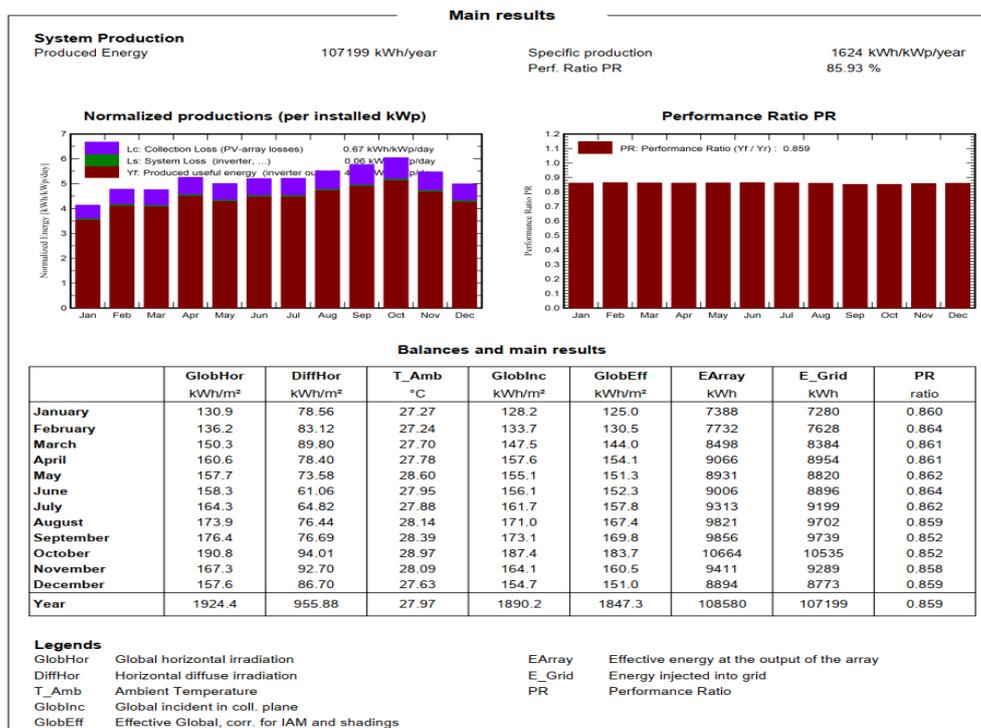


Figure 3. Energy Output of the Bifacial PV System

Figures 2 and 3 present the main simulation results of the monofacial and bifacial PV systems, including annual energy production, specific production values, Performance Ratio (PR), normalized energy production graphs, and monthly energy balance data. The results indicate a clear performance difference between the two types of solar modules, even though the system configuration, array capacity, and environmental conditions are identical.

A. Comparison of System Energy Production

The monofacial PV system generates an annual energy output of 104,841 kWh/year, while the bifacial PV system produces a higher output of 107,199 kWh/year. Thus, bifacial modules demonstrate an energy increase of 2,358 kWh/year, or approximately 2.25% higher than monofacial modules. This difference reflects the positive contribution of rear-side reflection (rear-side gain) in bifacial modules, which adds electricity generation even though the nominal panel power in both systems is the same at 500 Wp. Furthermore, the specific production of the monofacial module is 1,588 kWh/kWp/year, whereas the bifacial module increases to 1,624 kWh/kWp/year. This indicates that bifacial modules can better utilize solar radiation at the same installed capacity.

B. Comparison of Performance Ratio (PR)

The Performance Ratio (PR) of the monofacial system is 84.04%, while the bifacial system increases to 85.93%. The 1.89% PR improvement demonstrates that the bifacial system has higher operational efficiency and maintains more stable performance under varying weather conditions. The monthly PR graphs for both systems show a stable pattern throughout the year; however, bifacial modules consistently exhibit slightly higher PR compared to monofacial modules, particularly during months with high radiation, such as July–October. This

reinforces evidence that bifacial modules are more adaptive to both direct and diffuse radiation conditions.

C. Comparison of Normalized Energy Production

The Normalized Production graphs (per installed kWp) display three components:

- Yf: useful energy produced by the system
- Lc: collection losses at the array level
- Ls: inverter losses

For monofacial modules, the average collection losses are 0.77 kWh/kWp/day, whereas bifacial modules have lower losses of 0.67 kWh/kWp/day. This reduction in losses indicates that bifacial modules operate more efficiently, mainly due to lower heat generation and better response to diffuse radiation. System losses (inverter losses) are similar for both systems, approximately 0.06 kWh/kWp/day, indicating that the inverter is not a differentiating factor in the performance of the two systems.

D. Comparison of Monthly Energy Balances (Balances and Main Results)

In the monthly energy balance tables, the Global Incident (GlobInc) and Effective Global (GlobEff) values for both systems are nearly identical since the modules receive the same solar radiation intensity. However, differences are observed in EArray and E_Grid values, with bifacial modules showing higher values in almost all months.

For example:

- October:
 - Monofacial: 10.425 kWh
 - Bifacial : 10.664 kWh
- August:
 - Monofacial: 9.599 kWh
 - Bifacial : 9.821 kWh
- March:
 - Monofacial: 8.319 kWh
 - Bifacial : 8.498 kWh

These differences indicate that bifacial modules gain additional energy from reflected environmental radiation,

particularly during midday when the sun is high and diffuse light increases. Monthly PR values (PR ratio) show a similar trend, with bifacial modules consistently achieving slightly higher PR throughout the year, reflecting more stable energy conversion performance.

E. Overall Analysis

Overall, bifacial modules deliver superior performance compared to monofacial modules under the same conditions. The increase in energy production, higher PR, and lower collection losses demonstrate that bifacial technology is more effective in utilizing both direct and reflected radiation, even though the simulation assumed an

albedo of only 0.20. This indicates that bifacial modules are highly suitable for locations with sufficiently reflective surfaces, such as concrete or bright materials.

This enhanced performance is consistent throughout all months, showing that bifacial modules are more adaptive to variations in solar radiation intensity over the year. Therefore, the implementation of bifacial modules in buildings like Ibrahim Tower offers clear technical advantages over monofacial modules.

Comparison of Loss Diagrams for Monofacial and Bifacial PV Systems

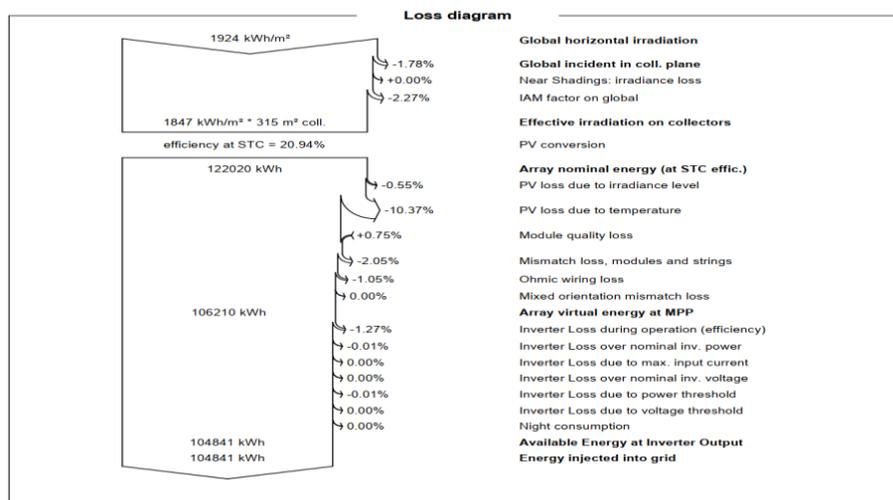


Figure 4. Loss Diagram of the Monofacial PV System

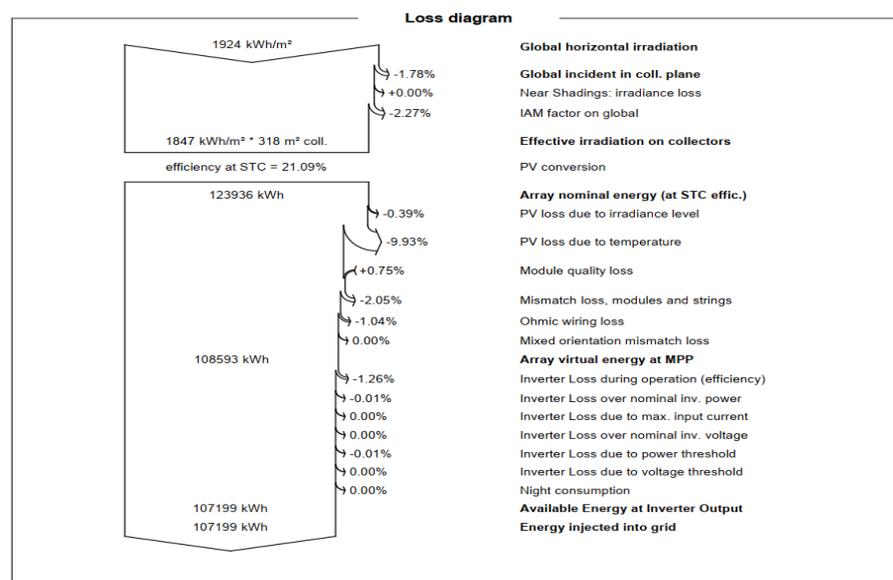


Figure 5. Loss Diagram of the Bifacial PV System

Figures 4 and 5 illustrate the loss diagrams of the monofacial and bifacial PV systems. These diagrams depict the energy conversion flow from solar radiation received by the modules to the final energy delivered to the electrical grid. By comparing the two diagrams, differences in efficiency and sources of energy losses that affect the performance of each system can be observed.

A. Global and Effective Radiation

At the top of the diagram, both systems receive the same global horizontal irradiance (GlobHor) of 1,924 kWh/m², indicating identical solar exposure conditions. After transposition to the panel tilt angle, the irradiance incident on the panel plane (GlobInc) is 1,847 kWh/m² for both systems. This identical value confirms that performance differences do not stem from the geometric aspect of light reception, as the modules are installed with the same orientation and tilt.

B. Energy Conversion Efficiency and Collector Area

After transposition, the effective irradiation is obtained, representing the radiation corrected for angle of incidence (IAM) and shading effects.

- Monofacial: Module area 315 m²
- Bifacial: Module area 318 m²

Although the area difference is only 3 m², bifacial modules have a slightly higher STC efficiency of 21.09% compared to 20.94% for monofacial modules. This efficiency difference indicates the bifacial module's ability to absorb more diffuse and reflected radiation from the underlying surface.

C. Nominal Array Energy and Module-Level Losses

- PV Loss Due to Irradiance Level
 - Monofacial: -0.55%
 - Bifacial: -0.39%
- Bifacial modules experience lower losses, indicating more optimal operation even when irradiance is not at maximum.

- PV Loss Due to Temperature
 - Monofacial: -10.37%
 - Bifacial: -9.33%

Temperature-induced losses are the largest energy loss factor for both systems. However, bifacial modules have lower losses due to their double-glass structure, which allows better cooling and thus lower operating temperatures compared to monofacial modules.

- Module Quality Loss

Module Quality Loss: Both systems have a value of +0.75%, indicating identical module component quality and manufacturing precision, which do not affect performance differences.

- Mismatch Loss (Modules & Strings)

- Monofacial: -2.05%
- Bifacial: -2.05%

Identical mismatch losses demonstrate uniform module quality and string design consistency.

- Ohmic Wiring Loss

- Monofacial: -1.05%
- Bifacial: -1.04%

Wiring losses are minimal and nearly identical, showing that cable design and spacing between modules and inverter are well-optimized.

D. Inverter Losses

- Total inverter losses for both systems are almost the same:

- Monofacial: -1.27%
- Bifacial: -1.26%

- Inverter losses consist of several components, such as:

- Inverter operational efficiency
- Power loss when the inverter operates off the maximum power point
- Voltage loss
- Current loss

Inverter losses include factors such as operational efficiency, power losses when operating off the maximum power point, voltage losses, and current losses. All these components are very small (<0.1%) for both systems and do not significantly contribute to performance differences, as both systems

use the same inverter under identical load conditions.

E. Energy at MPP, Inverter Output, and Energy Injected to Grid

• Virtual Energy at MPP:

- Monofacial: 106.210 kWh
- Bifacial: 108.593 kWh

Bifacial modules have 2,383 kWh higher energy at MPP, consistent with the increased maximum power output.

• Energi Output Inverter / Injected to Grid

- Monofacial: 104.841 kWh
- Bifacial: 107.199 kWh

The final difference of +2,358 kWh/year demonstrates the bifacial system's advantage in delivering additional energy to the grid.

F. General Analysis of Loss Diagram Comparison

Overall, the most notable differences between the monofacial and bifacial diagrams are:

- Temperature losses → lower for bifacial
- Irradiance level losses → lower for bifacial
- Module conversion efficiency → higher for bifacial
- Energy at MPP and energy to grid → higher for bifacial
- No differences in shading, wiring loss, mismatch, or inverter loss

This confirms that the superior performance of the bifacial system arises solely from the bifacial module characteristics, which allow:

- Additional radiation capture from the rear side
- Operation at lower temperatures
- Higher conversion efficiency

With identical system parameters, bifacial modules clearly provide additional benefits at the study location.

Comparison of Input/Output Graphs and Power Distribution of Monofacial and Bifacial PV Systems

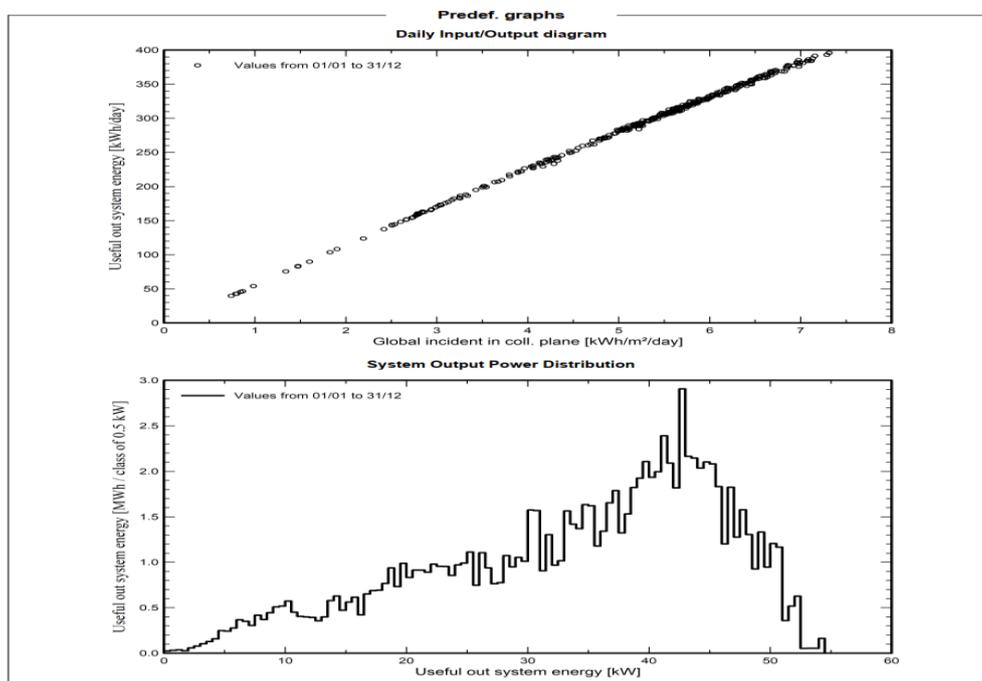


Figure 6. Input/Output Graph of the Monofacial PV System

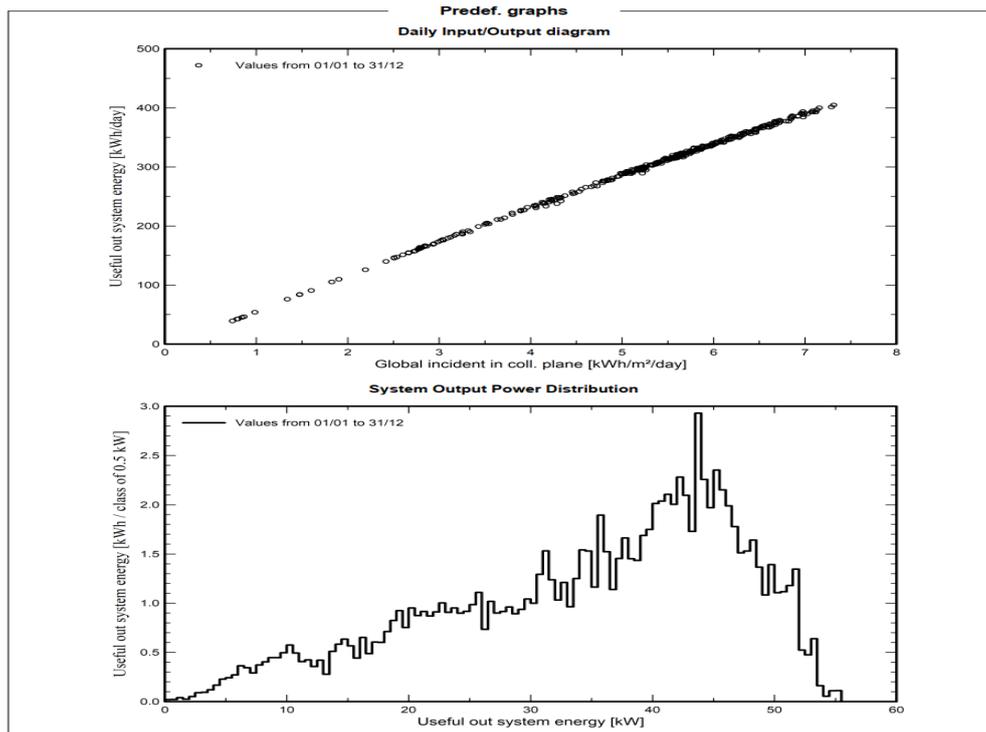


Figure 7. Input/Output Graph of the Bifacial PV System

Figures 6 and 7 present two key graphs from the PV system simulations: the Daily Input/Output Diagram and the System Output Power Distribution. These graphs illustrate the relationship between solar radiation received by the modules and the electricity generated, as well as the distribution of system output power levels throughout an entire year. Both graphs are used to evaluate performance stability and the modules' response to daily radiation variations.

A. Daily Input/Output Diagram

The Daily Input/Output graph illustrates the relationship between Global Incident in the Collector Plane ($\text{kWh}/\text{m}^2/\text{day}$) and Useful Output Energy (kWh/day). In both systems monofacial and bifacial the graphs exhibit a strong linear pattern, indicating that the systems respond to solar radiation very consistently.

However, several key differences are observed:

- **Range of Daily Energy Output:**
 - Monofacial PV: maximum daily output of approximately 380 kWh/day .

- Bifacial PV: maximum daily output of approximately 450 kWh/day

The increase of about 70 kWh/day in bifacial modules demonstrates their ability to generate more energy, especially on days with high radiation intensity. This is a direct effect of rear-side gain and the higher efficiency of bifacial modules.

- **Data Point Density:**

The scatter of data points for bifacial modules appears slightly denser and more uniform along the regression line compared to monofacial modules. This indicates better performance stability for the bifacial system, particularly under variable lighting conditions.

- **Response to High Radiation:**

- At 7–8 $\text{kWh}/\text{m}^2/\text{day}$ radiation:
 - Monofacial: approximately 350–380 kWh/day
 - Bifacial: approximately 400–450 kWh/day

Improved performance under high radiation suggests that bifacial modules are more effective at utilizing diffuse and reflected radiation.

B. System Output Power Distribution

This graph shows the distribution of inverter output power levels over a year, ranging from 0–60 kW.

- **System Peak Power:**

- Monofacial: peaks around 40–45 kW
- Bifacial: peaks higher at around 45–50 kW

This indicates that bifacial modules more frequently operate near the inverter's maximum capacity, thereby increasing the total annual energy production.

- **Low Power Frequency:**

The monofacial module graph shows a slightly higher frequency of low power occurrences (0–20 kW) compared to bifacial modules. This suggests that monofacial modules operate more often under low to moderate radiation, while bifacial modules produce higher power under the same conditions.

- **Dominant Power Distribution:**

- Monofacial: dominant range at 30–40 kW.
- Bifacial: dominant range shifts to 35–45 kW, with a noticeable increase in the 45–50 kW range

This aligns with the higher annual energy output reported in the main system results.

- **Inverter Capacity Utilization:**

Bifacial modules approach the inverter capacity limit more frequently than monofacial modules, indicating that the additional rear-side energy effectively increases system output without changing the inverter configuration.

C. Overall Analysis

In general, both systems show a linear pattern and good power distribution. However, bifacial modules exhibit clear advantages:

- Higher daily energy output, particularly on days with intense radiation.
- Power distribution shifted to higher levels, indicating more optimal inverter utilization.
- Better performance stability, shown by denser and more consistent output point distribution.

- Higher peak power achievement, reaching nearly 50 kW for bifacial modules compared to 40–45 kW for monofacial modules.

Therefore, bifacial modules not only produce higher annual energy but also demonstrate more stable and efficient operational performance throughout the year.

CONCLUSION

The 66 kWp rooftop PV system on Ibrahim Tower consists of 130 modules 60 on the east side and 72 on the west—arranged to minimize shading and maximize solar exposure. Both monofacial and bifacial systems share identical configurations, including tilt and orientation settings. Simulation results show that the bifacial system outperforms the monofacial one, producing 107,199 kWh/year compared to 104,841 kWh/year, a 2.25% increase due to rear-side irradiation gains. The bifacial system also achieves a higher Performance Ratio (85.93% vs. 84.04%), indicating better efficiency and more stable performance under varying weather conditions.

Declaration by Authors

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