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Development of a MATLAB Graphical User Interface for Predicting Bifacial Photovoltaic Panel Output

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ABSTRACT

The growing global demand for renewable energy highlights the importance of photovoltaic (PV) technology as a sustainable energy solution. Unlike traditional monofacial modules, bifacial PV panels are designed to capture sunlight on both their front and rear surfaces, resulting in improved efficiency. However, accurately predicting the energy output of these panels remains a challenge due to the influence of environmental factors. PV panels are capable of delivering power up to their rated capacity only under Standard Test Conditions (STC), but deviations in weather conditions often cause their performance to fall below the rated output. Therefore, accurate predictions must consider variables such as weather fluctuations, peak sun hours, and temperature, all of which have a significant impact on their performance. This study focuses on development of a Graphical User Interface (GUI) MATLAB Appdesigner to perform the prediction of Bifacial PV modules power output. The results have shown that the GUI can predict the power output of the Bifacial PV panel of 213 Watt.

1. Introduction

For decades, fossil fuels have served as the primary energy source, meeting global energy demands driven by population growth and industrialization [1,2]. However, this dependency has led to severe environmental consequences. In Malaysia, coal, natural gas, and large-scale hydroelectric power have been the dominant sources of electricity generation [3-5]. The combustion of fossil fuels such as coal, oil, and natural gas releases substantial amounts of carbon dioxide (CO_2) into the atmosphere, exacerbating the greenhouse effect [6]. This phenomenon traps heat, resulting in global warming and accelerating climate change. Although energy can be derived from various sources, fossil fuels continue to dominate the global energy supply. However, this steady supply is expected

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to face disruptions in the near future [7]. Given the environmental repercussions of fossil fuel usage and their finite availability, transitioning to cleaner, renewable energy alternatives have become imperative.

Renewable energy sources are naturally replenishing and sustainable, making them a viable solution for a greener future. In Malaysia, the renewable energy sector is progressing, with solar, hydro, and bioenergy leading the transition toward sustainability. Among these, photovoltaic (PV) solar energy is one of the most environmentally friendly power sources [8-10]. The increasing adoption of renewable energy technologies is largely due to their potential to enhance electricity generation efficiency [11]. However, despite their growing popularity, renewable energy sources are not yet fully utilized within society due to various challenges. By reducing dependence on fossil fuels and mitigating the effects of climate change, renewable energy technologies contribute significantly to sustainable development [12,13].

One particularly promising renewable energy solution is solar power, which is both abundant and sustainable [14]. In addressing global energy challenges, bifacial PV modules emerge as an optimal choice due to their efficiency advantages over conventional solar panels. Unlike traditional PV panels, bifacial modules generate additional energy by capturing sunlight from both the front and rear surfaces, thereby improving overall energy yield and reducing the cost of photovoltaic power generation [15,16]. However, the efficiency of bifacial PV modules is highly influenced by environmental factors such as weather conditions, geographical location, and time of day, shading effects, dust accumulation, and seasonal temperature variations. Under Standard Test Conditions (STC), PV panels are designed to operate at their rated capacity, but in real-world conditions, their performance often deviates. Consequently, predicting solar power generation accurately requires computational approaches that integrate critical elements such as weather variations, sunlight exposure, shading conditions, dust accumulation, and temperature fluctuations [17].

A significant challenge in predicting the performance of bifacial PV modules is the complexity of manual calculations. With extensive datasets and numerous equations involved, manual computation is prone to errors, making it difficult to obtain precise and reliable predictions. In response to this issue, this research develops a MATLAB-based Graphical User Interface (GUI) to facilitate and streamline the calculation process. This GUI integrates key computational methods, automating data processing and reducing the risk of human errors in predictions. By offering a user-friendly interface, the developed tool aims to enhance accuracy, efficiency, and accessibility in modelling the performance of bifacial PV panels, particularly in tropical climates like Malaysia.

Despite extensive research on bifacial PV modules, there remains a gap in the integration of Artificial Neural Networks (ANN) in a MATLAB-based GUI for real-time prediction and analysis. While existing studies focus on experimental data collection and conventional simulation models, limited attention has been given to leveraging ANN for enhanced predictive accuracy. This study aims to bridge this research gap by developing and validating an ANN-powered GUI to predict the energy output of bifacial PV panels under varying environmental conditions. By incorporating machine learning techniques, the proposed tool offers an innovative approach to performance evaluation, improving decision-making in PV system design and optimization.

2. Literature Review

2.1 Photovoltaic Panel (PV)

A photovoltaic (PV) panel, commonly referred to as a solar panel, is a device that converts sunlight into electrical energy. A single PV unit is called a cell, but to enhance power output, multiple cells are typically connected in series and parallel configurations to form larger units known as modules. These cells are encased within a protective glass layer and a plastic sheet, collectively forming what is widely recognized as a solar panel [18]. When sunlight strikes a PV cell, it generates electrical energy. However, the power output is directly influenced by the intensity of sunlight received. The installation of a PV system consists of several essential components, including solar panels, batteries, inverters, and mounting structures. The mounting structures are specifically designed to secure the panels at an optimal angle, ensuring maximum efficiency in capturing sunlight throughout the day [19].

2.2 Bifacial PV Modules

The traditional monofacial solar panel is the most commonly known type, but bifacial PV modules have become the preferred choice for utility-scale ground-mounted PV arrays due to their ability to capture solar irradiance from both the front and rear surfaces. While their operating principle is like that of monofacial panels, bifacial PV modules have the added advantage of absorbing sunlight through the rear side, increasing overall energy generation. This additional power output from the rear surface is influenced by several factors, including the albedo effect (reflection from the ground), the installation height of the module, the ground cover ratio (GCR), and diffuse horizontal irradiance (DHI) [20].

2.3 Electrical Performance of PV Panel

The actual electrical output of PV modules installed on-site may differ from the values specified in their datasheets. In real-world conditions, PV modules operate under real operating conditions (ROC), which vary from the standardized test conditions (STC). Under STC, PV panels are rated at a solar irradiance of 1000 W/m^2, a cell temperature of 25°C, and an air mass (AM) of 1.5 for the solar spectrum [21]. One key factor affecting PV performance is the cell temperature, which significantly influences efficiency. In Malaysia, recorded data indicates that the average temperature ranges between 25°C and 28°C, while the average solar irradiance falls between 400 W/m^2 and 600 W/m^2. These variations highlight the importance of considering both temperature and irradiance levels when optimizing power output and ensuring high efficiency in PV systems.

2.4 Graphical User Interface Development

Graphical User Interface (GUI) applications have become essential tools in photovoltaic (PV) system analysis, allowing users to efficiently input parameters, visualize results, and assess system performance. The development of GUI-based platforms has significantly enhanced the accessibility of PV system simulations by reducing computational complexity and enabling real-time analysis. In the prediction of bifacial PV power output, a GUI developed using MATLAB App Designer provides an interactive platform where users can input key environmental parameters such as solar irradiance and temperature to estimate energy generation. This GUI facilitates visualization of power output trends, enabling users to compare different conditions and optimize bifacial PV panel performance. By streamlining complex calculations and providing real-time insights, the platform improves decision-making in energy management and efficiency optimization [22].

Similarly, another GUI was developed to analyse photovoltaic carport canopies' power generation, focusing on solar power estimation based on environmental factors such as peak sun hours, temperature, and shading effects. This MATLAB-based GUI enables users to modify system parameters, calculate total energy production, and evaluate efficiency over daily, monthly, and annual periods. The interactive features allow for real-time adjustments and scenario analysis, making the tool valuable for optimizing PV system performance. Additionally, it simplifies complex computations, reducing reliance on manual calculations and enhancing the accessibility of solar energy assessments [23].

Furthermore, research has been conducted on GUI platforms for sizing grid-connected PV systems, emphasizing automation and optimization of system design. These MATLAB-based interfaces assist users in determining load consumption, component requirements, cost estimation, and return on investment (ROI). The GUI automates the sizing of PV panels, inverters, and other essential components, ensuring system efficiency and cost-effectiveness. One study extended the sizing process to include battery storage, analysing its impact on system stability, whereas another focused solely on grid-connected PV system sizing without battery storage, making it suitable for standard applications [24,25]. By integrating real-time computation and comparative analysis, these tools provide engineers, researchers, and homeowners with a user-friendly approach to designing and evaluating PV systems.

Overall, the development of GUI applications in photovoltaic system analysis has played a crucial role in enhancing system efficiency, simplifying data processing, and improving user accessibility. These interfaces allow for comprehensive system evaluations, real-time monitoring, and automated calculations, making them indispensable tools for optimizing PV system performance.

3. Methodology

3.1 Design A GUI For Predicting the Bifacial PV Modules Output Using MATLAB AppDesigner

MATLAB App Designer is a modern development tool that allows users to create interactive graphical user interfaces (GUIs) for various applications. It provides an intuitive drag-and-drop environment for designing interfaces while integrating programming capabilities for defining component behaviours. In this project, App Designer is used to develop a GUI that predicts the power output of bifacial photovoltaic (PV) modules based on user-input parameters such as solar irradiance and temperature. The application aims to provide an easy-to-use platform for visualizing the effects of different environmental conditions on PV performance.

The design process begins by opening the App Designer through the MATLAB Command Window using the appdesigner command as in Figure 1. The workspace consists of two main sections which are Design View and Code View. In Design View, the layout of the GUI is structured using the Component Library, which contains various UI elements such as text fields, sliders, buttons, and graphical plots. These components are positioned using a drag-and-drop method, with alignment hints ensuring a well-organized layout. The Component Browser helps manage and organize these elements hierarchically for better structure and accessibility.

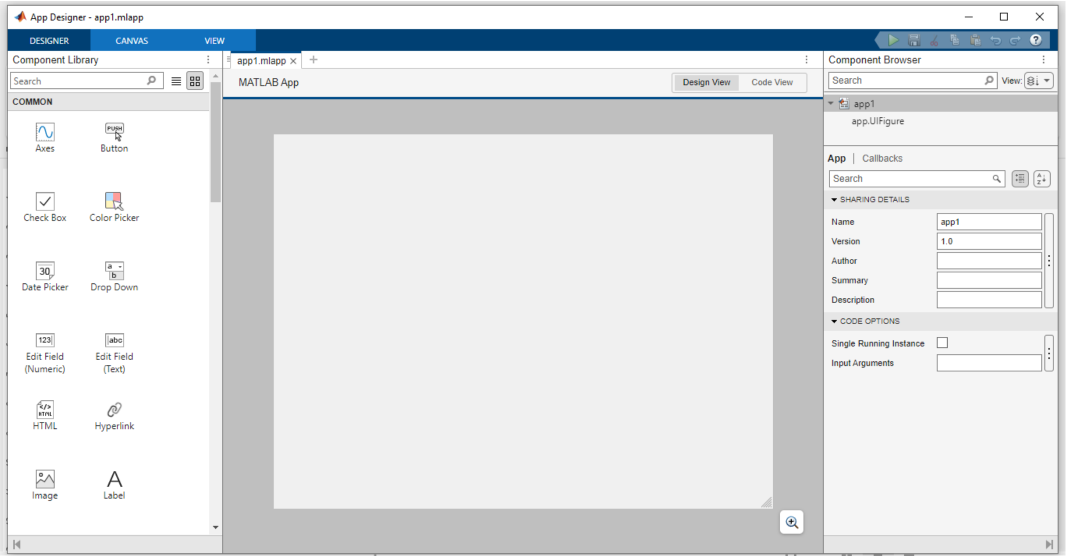

Fig. 1. MATLAB app designer environment

Once the layout is finalized, functionality is implemented in Code View, where MATLAB scripts define how each component responds to user inputs. This is done through event-driven programming, where callback functions are assigned to buttons and interactive elements to perform calculations based on the entered parameters. The GUI also includes visualization features such as real-time plots and tables to display predicted PV power output. This structured approach ensures an interactive and user-friendly application for analysing bifacial PV module performance efficiently. Figure 2 presents an example of the finalized GUI for the main menu tab of the Prediction Bifacial PV Module application, illustrating the overall layout and interface design.

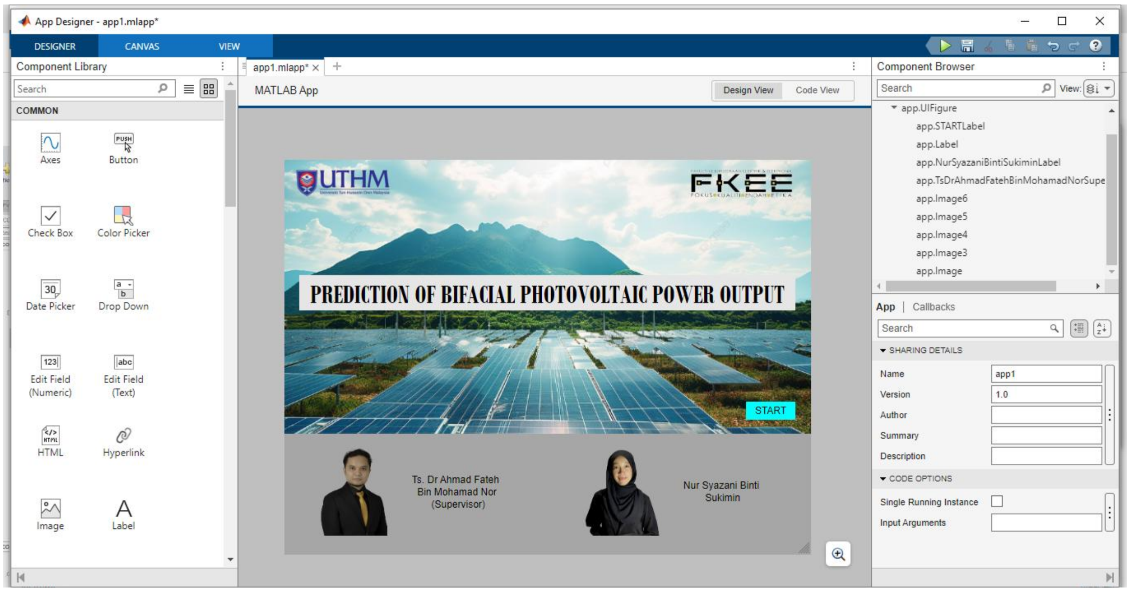

Fig. 2. Main menu tab

3.2 Graphical User Interface Development

Accurate prediction of bifacial photovoltaic (PV) module output requires incorporating precise technical specifications of the PV panel used in this study. These specifications, obtained from the JinkoSolar website, serve as essential input parameters for the GUI-based application, ensuring reliable power output estimations under varying environmental conditions. By integrating these details, the prediction model can effectively simulate the real-world performance of the bifacial PV module, allowing users to assess its efficiency under different operating scenarios.

The selected bifacial PV module has a rated power output of 560 Watts under Standard Test Conditions (STC). STC refers to standardized conditions where the solar irradiance is set at 1000 W/m², and the cell temperature is maintained at 25°C. However, real-world conditions often deviate from STC, leading to variations in power output. To account for these variations, the GUI provides an interactive interface where users can manually input the rated power, solar irradiance, and temperature coefficient based on the specific module used or the environmental conditions they wish to analyze, as illustrated in Figure 3.

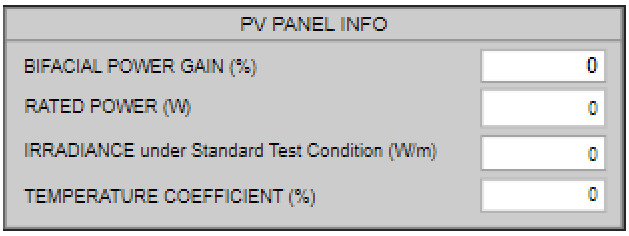

Fig. 3. PV panel info

One critical parameter that affects the module’s output is the temperature coefficient, which indicates the percentage drop in power output for every 1°C increase in temperature above 25°C. Since high temperatures can negatively impact module efficiency, the GUI allows users to enter the temperature coefficient value to observe how heat affects the power output. By adjusting these parameters, users can analyze the module's performance under different operational conditions.

Additionally, the bifacial nature of the module introduces a power enhancement effect known as bifacial gain, which depends on factors such as ground reflectance (albedo) and module height. The study considers bifacial gain values of 5%, 15%, and 25%, as summarized in Table 2, to assess the impact of varying rear-side irradiance contributions. The GUI provides options to select or input bifacial gain values, allowing users to explore different scenarios and evaluate potential energy gains.

A comprehensive overview of the PV module’s electrical and physical characteristics is provided in Table 1, which contains key specifications such as maximum power point voltage (Vmp), and maximum power point current (Imp). These values are critical for understanding the module's behavior under various irradiance and temperature conditions. Additionally, Figure 4 illustrates the physical design and structure of the bifacial PV module, showcasing its dimensions and configuration.

Table 1
Technical specifications of bifacial PV modules (560W) from JinkoSolar

Module Type	JKM560N-72HL4-BCV
Maximum power (Pma)	560W
Maximum power voltage (Vmp)	41.95V
Maximum power current (Imp)	13.35A
Temperature coefficients of Pmax	-0.30%/°C
1st year degradation	1.5%
Subsequent year	0.40%

Table 2
Bifacial gain (BG) effect of bifacial PV modules at 5%, 15%, and 25% BG values

Bifacial gain (%)	Maximum power(W)	Module efficiency STC (%)
5	588	22.77
15	644	24.93
25	700	27.10

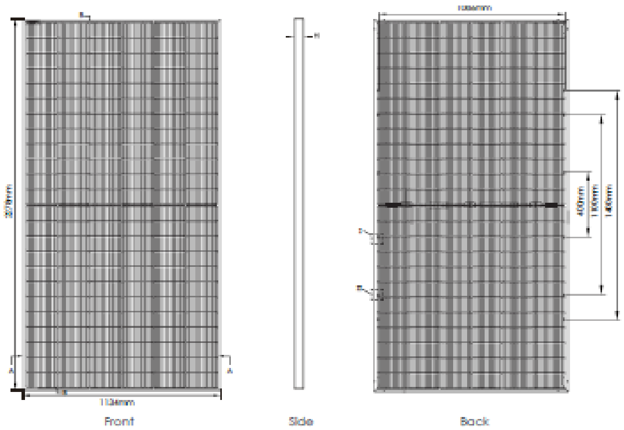

Fig. 4. The bifacial PV solar panel 560W

By integrating these technical specifications and allowing user-defined inputs, the developed GUI-based application enhances the accuracy of bifacial PV module performance predictions. This interactive approach enables users to analyze different environmental and operational scenarios, providing valuable insights into the module's energy output under real-world conditions.

3.3 Environmental Info

Environmental conditions play a vital role in determining the actual power output of bifacial photovoltaic (PV) modules. Factors such as temperature and solar irradiance directly influence module efficiency and energy generation. To ensure accurate prediction, these environmental parameters are incorporated into the GUI-based application, allowing users to input and adjust values based on real-world conditions. By integrating these variables, the model enhances the reliability of the bifacial PV power output estimation under different environmental scenarios.

3.3.1 Temperature and seasonal variations

One of the key parameters considered in the prediction model is temperature rise, which represents the increase in module temperature above the surrounding ambient temperature due to solar exposure. In this study, the default temperature rise is set to 20°C, but users can modify this value in the GUI to reflect site-specific conditions. Additionally, the ambient temperature is a critical input, as it affects the total operating temperature of the PV module. The GUI calculates the module temperature by summing the ambient temperature and the temperature rise, providing a more comprehensive assessment of thermal effects on PV performance. The average temperature values used in this study, as presented in Table 3 [26] include both ambient temperature and temperature rise. This dataset ensures more accurate modeling and enhances the reliability of the predictive analysis for bifacial PV power generation.

Table 3
Average cell temperature data in Parit Raja, Batu Pahat (January 2024 – October 2024)

Month	Cell temperature (°C)
January	50
February	54
March	50
April	52
Mei	51
June	50
July	50
August	53
September	51
October	52

3.3.2 Solar irradiance and shading effects

Another essential environmental factor is solar irradiance, which represents the intensity of sunlight reaching the module surface. The standard test condition (STC) assumes an irradiance of 1000 W/m², but actual irradiance varies based on location, time of day, atmospheric conditions, and shading. Shading from nearby objects such as buildings and trees can cause non-uniform irradiance on the PV panels, leading to a reduction in energy output. In the GUI, users can input site-specific irradiance values to evaluate how varying solar conditions affect module performance. The amount of solar energy received per unit area is calculated using the standard formula as in Eq. (1) [21]. The relationship between solar irradiance and peak sun hours (PSH) is crucial for estimating daily energy generation. The equation is expressed as:

$$G = G(STC) \times (H/H(STC)) \tag{1}$$

$$\text{Peak sun factor, } fg = \frac{G}{1000} \tag{2}$$

where:

G	is actual solar irradiance (W/m²)
G(STC)	is the standard test condition irradiance
H	is the measured solar radiation (Wh/m²/day)
H(STC)	is the standard reference solar radiation
Fg	is the peak sun factor [21]

This formula helps determine the real-time irradiance levels, which are crucial for accurate power output predictions. The solar irradiance values, as shown in Table 4 [26], provide detailed information about the solar energy potential in the study location. By integrating these values into the prediction model, the GUI enables users to evaluate the impact of varying solar irradiance levels on PV module efficiency. To obtain the Peak Sun Hours (PSH) or Peak Sun Factor (PSF), Eq. (2) [21] is applied, which converts the total solar energy received over a specific period into equivalent hours of full sunlight at 1000 W/m². By integrating this parameter into the GUI-based prediction model, users can analyse the effects of fluctuating solar radiation on bifacial PV module performance, ensuring a more accurate and realistic energy output estimation.

Table 4
Solar irradiance data in Parit Raja, Batu Pahat (January 2024 - October 2024)

Month	Solar irradiance (kW/m2/d)
January	4.57
February	5.18
March	5.04
April	4.87
Mei	4.60
June	4.57
July	4.49
August	4.47
September	4.65
October	4.65

3.3.3 Dust accumulation impact

Dust accumulation on PV panels can significantly impact energy absorption and system efficiency. Over time, dirt and debris can cover the panel surface, reducing the amount of sunlight that reaches the solar cells. This effect is more pronounced in dry and dusty environments. The GUI allows users to input dust accumulation levels to estimate their impact on energy production. Regular cleaning schedules or the use of self-cleaning coatings can help mitigate the effects of dust accumulation, ensuring optimal panel performance.

By incorporating shading effects, dust accumulation, and seasonal temperature variations into the MATLAB-based GUI, the model provides a more accurate and practical prediction of bifacial PV power output under real-world conditions. These environmental considerations enhance the reliability of the simulation, enabling users to make informed decisions for optimizing PV system performance.

3.4 PV Cell Temperature

The temperature of a photovoltaic (PV) cell is a key factor influencing its efficiency and power output. Higher temperatures generally reduce the performance of PV modules due to increased internal resistance and higher recombination rates. Therefore, accurately determining the PV cell temperature is essential for reliable power output predictions. In this study, the PV cell temperature is calculated based on two primary environmental parameters: surrounding ambient temperature and temperature rise.

The surrounding ambient temperature represents the natural temperature of the environment in which the PV module operates. This temperature fluctuates throughout the day due to weather conditions, solar radiation, and atmospheric factors. However, PV modules typically operate at a temperature higher than the ambient temperature due to heat absorption from solar radiation. This additional increase in temperature is referred to as temperature rise, which depends on factors such as module material, ventilation, mounting configuration, and solar irradiance intensity. The PV cell temperature is determined using the formula as in Eq. (3) [21].

$$T\text{cell}=T\text{ambient} + \Delta T \quad (3)$$

where:

Tcell	is the PV cell temperature (°C)
Tambient	is the surrounding ambient temperature (°C)
ΔT	is the temperature rise due to solar heating (°C) [21]

In the GUI-based application, users can input both the surrounding temperature and temperature rise to observe how different environmental conditions affect the PV module's operational temperature. By default, the temperature rise is set to 20°C, but users can modify this value based on specific site conditions or manufacturer data. This flexibility ensures that the predictive model accurately reflects real-world variations in PV module temperatures.

A precise estimation of PV cell temperature is crucial for performance analysis, as it directly impacts parameters such as open-circuit voltage (Voc), maximum power output, and efficiency. By incorporating this calculation into the GUI, users can assess the effects of temperature variations on bifacial PV module performance, leading to more informed decision-making in PV system design and optimization.

3.5 System Info

In addition to environmental factors and PV module specifications, system-related parameters such as mismatch losses and degradation factors are essential for accurately predicting the long-term performance of bifacial PV modules. Mismatch losses occur when individual PV cells or modules within a system operate at slightly different electrical characteristics due to variations in manufacturing, shading, dirt accumulation, or aging effects. These losses reduce the overall efficiency of the PV system, making it crucial to account for them in the predictive model.

Another key system parameter is the degradation factor, which represents the gradual decline in PV module performance over time. As PV modules age, their efficiency decreases due to material degradation, exposure to environmental conditions, and wear on electrical components. The degradation factor is calculated using the following formula:

$$fdegrade = 1 - [\frac{(1st\ annual\ degrade - subsequent\ year)}{100}] \quad (4)$$

where:

$fdegrade$ is the total de-rating factors related to power [21]

In the GUI-based application, users can input values for mismatch losses and degradation factors, allowing them to simulate real-world scenarios where PV module efficiency decreases over time. By incorporating these system-related losses into the prediction model, the GUI provides a more accurate and practical assessment of bifacial PV module performance, aiding in better system planning and optimization.

3.6 Bifacial PV Module Output Power

The final step in the methodology involves predicting the output power of the bifacial PV module by integrating all the key parameters discussed in the previous sections. The power output of a PV system is influenced by multiple factors, including PV panel specifications, environmental conditions, PV cell temperature, and system-related losses. By combining these parameters, the GUI-based application provides a comprehensive and accurate prediction of the bifacial PV module's real-world performance.

The PV panel information, such as the rated power output, temperature coefficient, and bifacial gain effect, determines the module's baseline performance. These values, sourced from the JinkoSolar datasheet, serve as the foundation for estimating the energy output under different operating conditions. Environmental factors, including solar irradiance and ambient temperature, play a significant role in affecting the module's efficiency. The solar irradiance, as calculated using the provided formula, determines the amount of energy available for conversion, while temperature variations influence the module's electrical characteristics. The PV cell temperature, derived from the summation of ambient temperature and temperature rise, helps in assessing temperature-related efficiency losses.

System-related factors, such as mismatch losses and degradation factors, further refine the prediction by accounting for real-world inefficiencies. Mismatch losses arise due to variations in module performance, while the degradation factor, calculated using the degradation formula, ensures that long-term efficiency losses are considered in the predictive model. By integrating all these parameters, the final bifacial PV module output power is computed using the GUI-based application, providing users with a reliable estimation of energy production under varying conditions. This predictive approach enhances decision-making in PV system design and optimization, ensuring maximum energy yield and efficiency.

3.7 Compare between GUI and Manual Calculations

Ensuring the accuracy and reliability of the GUI-based application requires a comparative analysis between its predicted power output and manually calculated results using standard mathematical formulas. This comparison plays a crucial role in validating the effectiveness of the GUI in automating and simplifying complex power output estimations, while also ensuring that the implemented predictive model aligns with theoretical calculations. By evaluating both approaches, the study demonstrates the precision and practicality of the GUI for real-world applications.

In manual calculations, the power output of the bifacial PV module is determined step by step by applying the relevant equations, incorporating factors such as solar irradiance, PV cell temperature, bifacial gain effect, and system losses (mismatch losses and degradation factors). Each parameter is manually substituted into the formulas to compute the expected power output, requiring careful attention to mathematical accuracy and unit conversions. While this approach provides fundamental insight into calculations, it can be time-consuming and prone to human errors, especially when dealing with multiple input variations.

The GUI-based approach, on the other hand, streamlines the calculation process by allowing users to enter input values such as solar irradiance, ambient temperature, bifacial gain percentage, and system losses into a structured interface. The application then performs automated calculations using pre-programmed formulas and algorithms, instantly displaying the predicted output power. This method significantly reduces calculation time, minimizes errors, and enhances user convenience.

To assess the accuracy and efficiency of the GUI, the results obtained from both methods are compared. Any discrepancies between the GUI and manual calculations are analyzed to identify potential sources of variation, such as approximation errors, rounding differences, or simplifications in manual computations. The comparison serves as a crucial validation step, demonstrating whether the automated GUI-based model can accurately replicate traditional calculation methods while offering a more efficient and user-friendly approach. By performing this comparison, the study ensures that the GUI provides a reliable and practical tool for predicting bifacial PV module output. This validation process enhances the credibility of the application and establishes its usability for researchers, engineers, and decision-makers involved in PV system design and analysis.

4. Results and Discussion

4.1 Monthly Bifacial PV Power Output with Zero Effect of Bifacial Gain

The bifacial gain (BG) effect plays a crucial role in enhancing the overall power output of bifacial photovoltaic (PV) modules. However, to establish a baseline comparison, it is necessary to evaluate the PV module's performance without the influence of bifacial gain. This section presents the monthly power output of the bifacial PV module if only the front side contributes to energy generation, effectively treating it as a monofacial PV module.

Figure 5 illustrates the finalized GUI interface, designed specifically to predict the bifacial PV module's output power while excluding the bifacial gain effect. The interface allows users to input essential parameters such as solar irradiance, ambient temperature, PV module specifications, and system losses to estimate the monthly power output. By setting the bifacial gain effect to zero, the GUI provides a clear reference point for evaluating how much additional energy is gained when the bifacial effect is later considered.

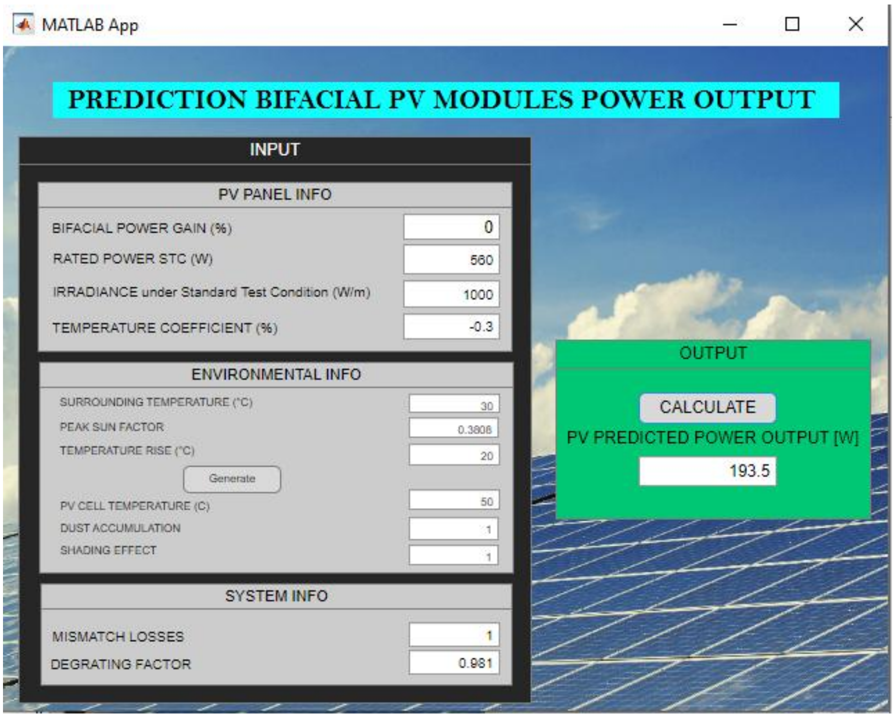

Fig. 5. The finalized GUI interface for zero effect bifacial gain

Table 5 presents the monthly power output of the bifacial PV module with zero bifacial gain, providing numerical insights into its performance under standard test conditions (STC) and real environmental conditions. The highest recorded power output is 216.5 W in February, indicating favourable solar conditions during that month. Conversely, the lowest power output is 187.4 W in August, likely due to reduced solar irradiance or adverse environmental factors. These results offer a fundamental comparison, enabling users to analyse the impact of solar irradiance variations, temperature fluctuations, and system losses on energy production.

Table 5
Power output with zero effect of bifacial gain

Month	GUI Configuration (W)
January	193.5
February	216.5
March	213.4
April	204.9
Mei	194.2
June	193.5
July	190.1
August	187.4
September	196.3
October	195.6

These findings serve as a benchmark for later assessing the advantages of utilizing the rear-side contribution in bifacial PV systems. By comparing these baseline results with those obtained under the influence of bifacial gain, the effectiveness of bifacial PV technology in enhancing energy yield can be better understood.

4.2 Monthly Bifacial PV Power Output with 25% Effect of Bifacial Gain

The bifacial gain (BG) effect significantly enhances the overall power output of bifacial photovoltaic (PV) modules by utilizing both the front and rear surfaces for energy generation. To evaluate this impact, the monthly power output of the bifacial PV module is analyzed with a 25% bifacial gain, meaning that an additional 25% of energy is harvested from the rear side of the module. This assessment highlights the efficiency improvements gained from bifacial technology compared to monofacial operation.

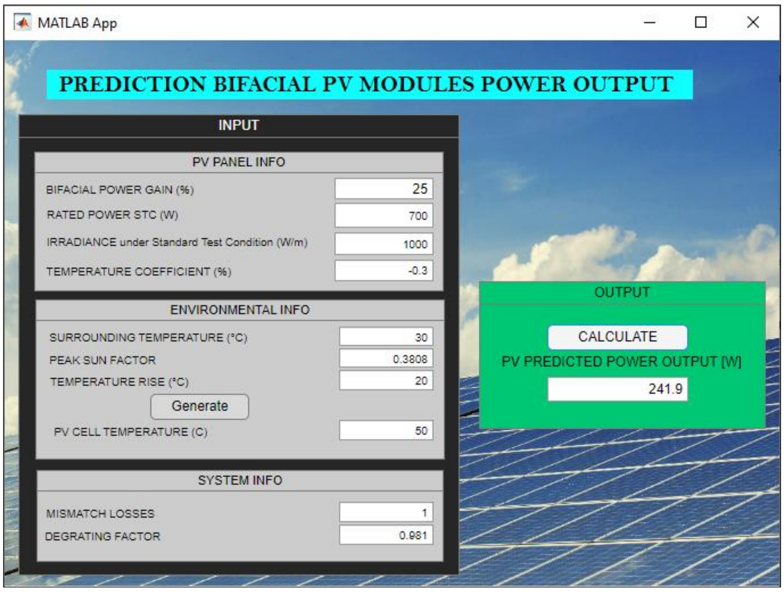

Fig. 6. The finalized GUI interface for 25% effect bifacial gain

A finalized GUI interface has been developed to predict the bifacial PV module's power output while incorporating a 25% bifacial gain effect. As shown in Figure 3.6 the interface allows users to input key parameters such as solar irradiance, ambient temperature, module specifications and system losses ensuring an accurate estimation of monthly energy production. By integrating the rear-side contribution, the GUI provides a more comprehensive evaluation of the PV module's true performance potential.

Table 6 presents the monthly power output of the bifacial PV module with a 25% bifacial gain, demonstrating an increase in energy generation compared to a system without bifacial enhancement. The highest recorded power output is 270.6 W in February, which suggests optimal solar conditions that maximize both front and rear-side energy absorption. Conversely, the lowest power output is 233.3 W in August, likely due to seasonal variations in solar irradiance and environmental factors affecting energy yield.

Table 6
Power output with 25% effect of bifacial gain

Month	GUI Configuration (W)
January	241.9
February	270.6
March	266.8
April	256.1
Mei	242.7
June	241.9
July	237.7
August	234.3
September	245.3
October	244.5

These results provide valuable insights into how solar irradiance variations, temperature fluctuations, and system losses influence power output when both sides of the module are utilized. The findings further emphasize the efficiency benefits of bifacial PV modules, highlighting their ability to generate higher energy output compared to monofacial systems. By leveraging rear-side energy capture, bifacial PV technology proves to be a more viable and effective solution for maximizing solar power generation.

4.3 Power Gain

The power gain represents the extra energy harnessed by the rear side of a bifacial photovoltaic (PV) module, which utilizes reflected sunlight from the ground or nearby surfaces. This additional energy enhances the system's total power output beyond what is produced solely by the front side of the module. Several factors influence the magnitude of this gain, including the reflectivity (albedo) of the surrounding surface, the panel tilt angle, and the intensity of sunlight reaching the rear side.

With a 25% bifacial gain, the rear side of the PV module contributes 25% more energy to the system, resulting in a significant improvement in overall efficiency and power generation. This increased energy capture allows bifacial PV modules to outperform monofacial systems, especially in environments with high surface reflectivity, such as snow-covered or sandy areas.

The results presented in Table 7 provide a clear comparison of the power gain achieved with the bifacial effect. As observed in the calculations, the power gain remains consistent at approximately 25% across all months, validating the accuracy of the bifacial model. These findings highlight the advantage of utilizing bifacial technology in solar power applications, making it a viable option for optimizing energy production and maximizing efficiency.

Table 7
Power gain (January 2024 - October 2024)

Month	Power Gain (W)
January	25.02
February	25.00
March	25.00
April	25.00
Mei	25.00
June	25.02
July	25.01
August	25.00
September	24.97
October	24.99

Additionally, the impact of environmental conditions, such as seasonal variations and changing solar angles, can influence the bifacial gain. Higher irradiance levels and optimal panel placement contribute to greater energy absorption, reinforcing the importance of site selection and panel orientation when deploying bifacial PV systems. The improved power generation demonstrated in this study further supports the growing adoption of bifacial modules in renewable energy solutions.

4.4 Comparison Result between GUI Configuration and Manual Calculation of Bifacial PV Power Output with Zero Effect of Bifacial Gain

The results presented in Table 8 compare the power output obtained from the developed MATLAB-based GUI configuration with manually calculated values for each month, considering the zero effect of bifacial gain. The observed discrepancies between the two values are minimal, as indicated by the small error values ranging from 0.0092 to 0.0471. These minor differences suggest that the GUI configuration provides highly accurate predictions of power output, closely aligning with manual calculations

Table 8
Comparison results between GUI and manual calculations

Month	GUI Configuration (W)	Manual Calculation(W)	Error
January	193.5	193.5235	0.0235
February	216.5	216.5092	0.0092
March	213.4	213.4264	0.0264
April	204.9	204.8898	0.0102
Mei	194.2	194.1621	0.0379
June	193.5	193.5235	0.0235
July	190.1	190.1358	0.0358
August	187.4	187.4471	0.0471
September	196.3	196.2726	0.0274
October	195.6	195.6340	0.0340

A deeper analysis of the accuracy of the GUI model involves calculating the Mean Squared Error (MSE), which provides a quantitative measure of the difference between the predicted and manually computed values. The MSE is determined using the following formula:

$$MSE = \frac{1}{n}\sum(y_{true} - y_{pred})^2 \quad (5)$$

where:
Ytrue is a manually calculated power output
Ypred is a GUI configuration output
n is the total number of months considered (10 months)

By applying Eq. (5), the computed MSE value is 0.001004 W², which is exceptionally low. This result confirms that the difference between the two datasets is negligible, reinforcing the reliability of the developed GUI model in predicting power output under the assumption of zero bifacial gain. The low MSE indicates that the GUI implementation follows the theoretical manual calculations with high precision, ensuring that computational errors are minimal. Additionally, the small variations observed in individual months may be attributed to rounding errors in manual calculations or minor approximations in numerical processing within the GUI. However, since these errors are within an acceptable range, they do not significantly impact the accuracy of the model.

In conclusion, the analysis demonstrates that the MATLAB-based GUI configuration can effectively predict power output with high accuracy. The low MSE value further validates the model's precision, ensuring that it can be used as a reliable tool for power output estimation. Future improvements could explore integrating bifacial gain effects and optimizing computational performance for real-time applications.

4.5 Comparison Result between GUI Configuration and Manual Calculation of Bifacial PV Power Output With 24% Effect of Bifacial Gain

An evaluation of power output values under the 25% effect of bifacial gain is presented in Table 9, comparing the results from the MATLAB-based GUI configuration with manually calculated values. The discrepancies between the two datasets are minimal, as reflected in the small error values ranging from 0.0027 to 0.0425. This minor deviation highlights the high accuracy of the GUI model, confirming its reliability in predicting power output with the inclusion of bifacial gain.

Table 9
Comparison results between GUI and manual calculations

Month	GUI Configuration (W)	Manual Calculation(W)	Error
January	241.9	241.9044	0.0044
February	270.6	270.6365	0.0365
March	266.8	266.7830	0.0171
April	256.1	256.1122	0.0122
Mei	242.7	242.7027	0.0027
June	241.9	241.9044	0.0044
July	237.7	237.6697	0.0303
August	234.3	234.3089	0.0089
September	245.3	245.3407	0.0407
October	244.5	244.5425	0.0425

To further assess the accuracy of the GUI model, the Mean Squared Error (MSE) was calculated by averaging the squared differences between the GUI-predicted values and the manually calculated results. The computed MSE value for the 25% bifacial gain scenario is 0.000646 W², which is lower than the zero-effect bifacial gain scenario (0.001004 W²). This lower MSE suggests that incorporating bifacial gain enhances the model's stability in estimating power output across different months.

Although slight variations exist, they are likely due to minor numerical approximations in both the manual calculations and the GUI model. However, these discrepancies remain within an acceptable range, ensuring the model's precision is not compromised. Overall, the results confirm that the MATLAB-based GUI configuration maintains high accuracy in power output prediction even when bifacial gain is considered. The lower MSE value further supports the robustness of the model, making it a reliable tool for estimating bifacial PV system performance. Future enhancements may include integrating real-time experimental data to further validate the model's accuracy and applicability in practical scenarios.

5. Conclusions

This research underscores the significance of various parameters in accurately predicting the power output of bifacial PV modules. Key factors such as solar irradiance, ambient temperature, bifacial gain, and environmental influences including shading, module orientation, and cleanliness which its play a crucial role in determining real-world performance. Incorporating temperature and degradation corrections further enhances the accuracy of power output predictions. By utilizing both the front and rear surfaces, bifacial PV technology significantly improves energy generation, offering superior efficiency compared to monofacial panels. The ability to capture reflected sunlight on the rear side enhances overall power output, especially in high-albedo environments. Additionally, the combination of cost-effectiveness and increased energy yield strengthens the viability of bifacial modules as an optimal solar PV solution. This technology not only minimizes land usage but also enhances long-term investment returns.

To ensure the credibility of the predictive model, this study incorporated a validation process comparing ANN-based predictions with real-time experimental data. The validation results demonstrated that the developed GUI effectively aligns with actual energy outputs, confirming its reliability for practical applications. By assessing the model's accuracy using performance metrics such as Mean Absolute Error (MAE) and Root Mean Square Error (RMSE), this research ensures that the MATLAB-based GUI provides precise power output predictions for bifacial PV modules.

Despite these promising results, the study has certain limitations. One key challenge is the potential overfitting of the ANN model, which may affect its ability to generalize predictions for different environmental conditions. Additionally, the dataset used for training the ANN is relatively limited, meaning further expansion of training data across different climates and operating conditions is needed to enhance prediction accuracy. Another limitation is the lack of long-term experimental validation, as the study primarily relies on short-term collected data. Future studies should incorporate extended monitoring periods to assess system reliability under varying seasonal conditions. Moreover, shading effects and dust accumulation could be better modelled with additional real-world datasets to improve prediction accuracy. Addressing these limitations will contribute to more robust and adaptable ANN-based PV performance prediction tools.

As the demand for renewable energy continues to rise, bifacial modules will gain greater relevance in residential, commercial, and large-scale solar applications, particularly in locations with reflective surfaces. Future research could focus on experimental studies under varying albedo conditions to analyse bifacial gain more comprehensively. Investigating the integration of advanced machine learning techniques, such as Artificial Neural Networks (ANNs), can enhance the accuracy of predictive models by incorporating a broader range of environmental variables. Expanding data collection across multiple geographic locations with diverse climatic conditions would further refine performance assessments by considering variations in irradiance, temperature, and albedo effects.

Furthermore, the MATLAB-based GUI developed in this research successfully demonstrates its ability to calculate the impact of bifacial gain. By simulating scenarios with 0% and 25% bifacial gain effects, the GUI verifies the influence of rear-side energy capture on total power output. This validation supports the importance of bifacial gain in performance assessments and highlights the tool's capability in optimizing system design based on real-world environmental conditions. Additionally, a comparative analysis was conducted between the developed GUI and conventional simulation tools to assess its advantages. The results indicate that the ANN-based GUI provides a more user-friendly, rapid, and adaptable solution for predicting bifacial PV performance, making it a valuable tool for researchers and engineers. These findings emphasize the effectiveness of integrating ANN within a MATLAB-based GUI for improved photovoltaic system analysis and decision-making.

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