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Comparative Study on the Predicted Energy Generated from GCPV System Between PVsyst Simulation and Mathematical Models

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ABSTRACT

PVsyst is a simulation software that is widely used by researchers and industry professionals for PV system design, performance simulation, technical analysis, and economic assessment. However, a study to verify the accuracy and reliability of PVsyst is necessary to ensure the simulation results align with industry standard with minor inconsistencies in the prediction of energy production. This paper presents a comparison of the design, simulation, and performance analysis of a grid-connected solar system in Johor Bahru. Three methods were applied in this study, which are two Mathematical Models (MM)s and PVsyst commercial software. A comparison of PVsyst simulation with existing mathematical models was conducted to identify discrepancies in the prediction of energy production between the methods. The comparison involved assessing the annual and monthly energy generation predicted by MMs and PVsyst. Results shows that the percentage difference between PVsyst and MM 1, as well as PVsyst and MM 2, are respectively 14.63% and 5.803%. This study also highlighted several technical understandings of designing PV systems by using the three methods which can help in understanding the differences in the predicted energy generation.

Keywords:
PVsyst; preliminary design tool; grid-connected; photovoltaic; renewable energy

1. Introduction

Malaysia has made significant development, particularly in the areas of poverty reduction and expanding access to electricity, both of which have had a significant impact on rural development. In the development of electricity supply in Malaysia, the main goal is to ensure a safe, reliable, and cost-effective energy supply, to increase the competitiveness and resilience of the country's economy [1]. Technology advancements, population growth, economic development, and changing lifestyles have all contributed to an increase in electricity usage in recent years. Electricity demand has risen in the

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residential, commercial, and industrial sectors, posing new challenges for energy providers. Previous publications have presented an analysis of the factors contributing to the increase in electricity usage and the implications for energy infrastructure and sustainability [2,3].

In Malaysia, the percentage of renewable energy (RE) in electricity generation has increased significantly, with a target of reaching 20% penetration by 2025 [4]. Photovoltaic (PV) system has arisen as a feasible and sustainable option for generating electricity in Malaysia due to its location near equator [5]. PV technology can also be installed either on land or it can be fixed to the roofs or exterior walls of buildings while supplying electricity to the buildings. The potential for utilizing PV systems in Malaysia is substantial, contributing to efforts aimed at reducing carbon emissions and to addressing climate change, which are crucial parts of the transition to a more sustainable and renewable energy in the future. It is also proven that solar score the highest overall priority matrix among other RE resources in Malaysia from previous study [6].

PVsyst is PV design software intended for architects, engineers, and researchers, serving as an exceptional educational tool. It provides a rich contextual help menu that depicts the techniques and models utilized, and a user-friendly approach with a project development guide. It can simulate the performance for the grid-connected PV system (GCPV) rooftop system, integrated with large scale plans system, standalone system with batteries, and solar power pumping system. The simulation of the PV system is to determine the production of electricity throughout the year, evaluation of loses of production and can be used for economic analysis [7,8].

Based on the literature review, there are several studies presented PV systems simulations by using the PVsyst platform. A journal presented the design and simulation of a solar plant in Algeria. The energy storage-based PV system was evaluated in the technical and economic aspects of the simulated PV system to supply domestic electricity demands [9]. Another published journal evaluated the performance and economic analysis of a GCPV project in Afghanistan, aiming to cover 30% of future electricity demands in 2032 [10]. A study was published on the feasibility and viability of installing 1MW GCPV at multiple cities in northern Morocco using PVsyst using two system configurations [11]. Another study on design optimization for PV water pump systems assisted by PVsyst was published, with an analysis of the system performance via different parameters [12]. A proposal for developing a solar plant at Cairo International Airport was published, where various tilt angle values and azimuth were analysed to get the best optimization of GCPV energy value using PVsyst software [13]. Another study presents the design, simulation, technical analysis, economic potential, and annual performance of a GCPV system of 100MW capacity at Umm Al-Qura University [14].

Even though PVsyst is widely used in simulating PV systems, it is important to conduct a study to validate and verify the PVsyst accuracy and reliability. The comparison of the PVsyst simulation with existing mathematical models are necessary to ensure the simulation results is align with industry standard and expectations. This comparison helps to reveal any errors or inconsistencies in the prediction of energy production, which is part of quality assurance process, where significance difference between PVsyst and trusted model may be an issue to be addressed.

2. Methodology

Figure 1 presents the research framework and the methodology. The framework illustrates the tasks executed to achieve the defined objectives.

The first objective is to design, simulation, and performance analysis of the GCPV system using PVsyst, and it was achieved by study and understanding the GCPV system's design. This followed by gaining the knowledge of series and parallel connection photovoltaic panels to set the array and subarray connection in PVsyst software.

Meanwhile, the second objective is to simulate the performance of GCPV with mathematical modelling. The objective was achieved by understanding the equation used by previous researchers to calculate the energy produced by PV system. Previous research studies have employed various equations and models to predict the energy generated from a PV system.

The third objective is to compare the simulated performance from PVsyst with mathematical models. It was accomplished by finding the energy produced by three different methods and comparing the results annually and monthly. Comparing the annual energy generated from PVsyst with results from mathematical modelling involves evaluating the accuracy, reliability, and limitations of both approaches. PVsyst simulations often consider a wide array of real-world conditions, leading to potentially more accurate annual energy predictions. Mathematical models' accuracy depends on the rigor of model development and validation.

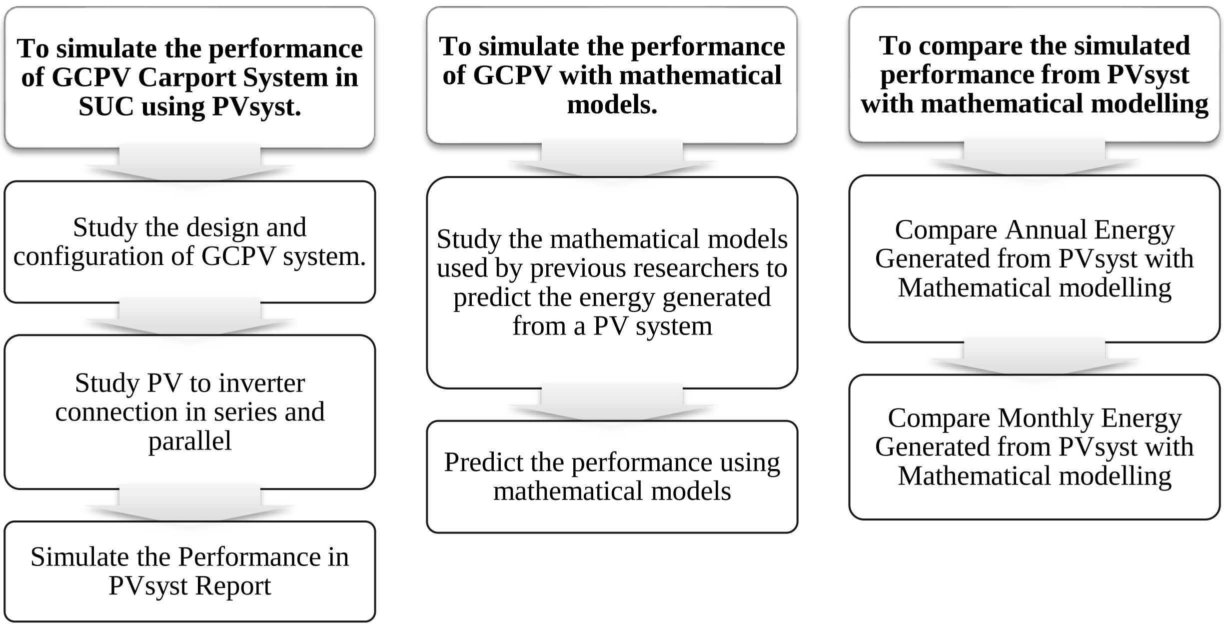

Fig. 1. Framework of the project

2.1 Simulation Method for Grid-Connected Photovoltaic System in PVsyst Software

This section explains the flowchart of the simulation method using PVsyst [7,15]. PVsyst starts by importing meteorological data to simulate the performance of GCPV systems. This data includes information about solar radiation, temperature, wind speed, and other environmental factors that impact the system's energy generation. Selecting the exact location of this study is very important to excess accurate meteorological database.

Then, the PV panel tilt value and azimuth are set. Adjusting the tilt angle and azimuth of solar panels is crucial for predicting their energy production based on the local sun position and weather conditions. Solar panels' tilt angle refers to their angle relative to the horizontal plane.

Then, the process continues with defining the PV and inverter models. A list of models is embedded in the software for user convenience. Users also may add other models that is not available in the software. Afterwards, the configuration of PV panels and inverters is defined by defining how PV array is connected in series and parallel connections. The software also assists users by stating whether the inverter is undersized or oversized [16].

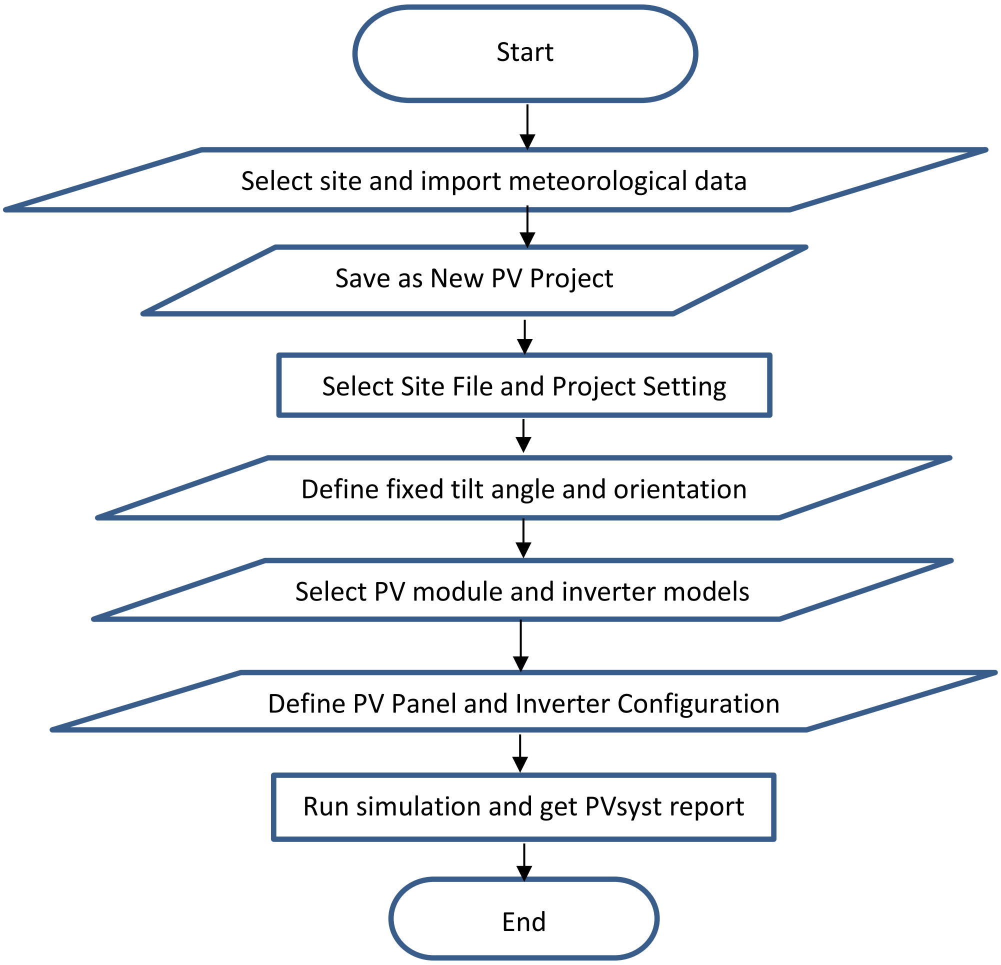

Fig. 2. Simulation flowchart using PVsyst

2.2 Mathematical Modelling 1 (MM1)

Typically, a PV panel uses energy from sun irradiation and converts it into direct current (DC). The DC flows through an inverter and supplies to load in alternating current (AC). The energy produced in a specific period by a PV array can be calculated as Eq. (1), where E_{pv} is the calculated energy output from the photovoltaic system, A_{pv} is the area of the photovoltaic panels, E_{sun} represents the solar irradiance or sunlight energy that falls on the panels in (W/m²), η_{pv} is the photovoltaic panels efficiency, η_{inv} is the efficiency of the inverter, η_{wire} is the efficiency of the wiring and other components in the system [17-20].

$$E_{pv} = A_{pv} \times E_{sun} \times \eta_{pv} \times \eta_{inv} \times \eta_{wire} \tag{1}$$

2.3 Mathematical Modelling 2 (MM2)

Another standards formulation to predict energy generation from PV system is shown in Eq. (2), where *PSH* is peak sun hour (h), N_{pv} is number of PV panels, P_{mp_stc} is the maximum power point in standard test condition (STC) in (W), f_{temp} is temperature de-rating factor calculated by Eq. (4), f_{mm} is temperature module mismatch, η_{wire} is cable efficiency, f_{dirt} is dirt de-rating factor, and η_{inv} is inverter efficiency. PSH can be calculated by Eq. (3), where *G(t)* is the hourly solar irradiation on the PV surface [21,22].

$$E_{PV} = PSH \times N_{pv} \times P_{mp\_stc} \times f_{temp} \times f_{mm} \times f_{dirt} \times \eta_{inv} \times \eta_{wire} \quad (2)$$

$$PSH = \frac{G(t)}{1kW/_{m^2}} \quad (3)$$

$$f_{temp\_pmp}(t) = 1 + \left({}^{\gamma_{pmp}}/_{100}\right) * (T_{cell}(t) - T_{stc}) \quad (4)$$

2.4 Percentage Difference

This subsection discusses the calculation for percentage difference by using Eq. (5). The percentage of change is used to quantify the difference in the value from mathematical models with the PVsyst simulation value. This calculation is suitable to study whether the value increase or decrease compared to the original or referred value [23].

$$Percentage\ Difference\ (\%) = \left(\frac{Mathematical\ Model - PVSyst}{(Mathematical\ Model + PVSyst)/2}\right) \times 100 \quad (5)$$

3. Results

3.1 Comparison of Annual Energy Generated from PVsyst Simulation and Mathematical Models

This section explains the comparison result obtained from PVsyst software, MM 1, and MM 2. Afterwards, the results were compared and analysed. The purpose of this section is likely to compare the outcomes of these three different methods for a specific application, possibly in the field of solar energy or photovoltaic systems.

3.1.1 Result 1: Annual energy generated from PVsyst simulation

The proposed system is made up of 396 units of PV panel with model LONGi LR4-72HPH 450, and the inverter model is Huawei’s SUN2000-100KTL-M1 Smart String Inverter. The configuration of the system is illustrated in Figure 3. The proposed configuration is divided into 3 arrays. The first array with 200 PV panel units is connected to 10-MPPT in 1 unit of inverter. The second inverter is connected to the second array with 16 units of PV panel connected to 1 MPPT and 180 units PV panel connected to 9 MPPT. It shows the system tilt angle, which is 15° and the azimuth angle is 135°. These values were determined based on the selected location. The total number of PV modules are 396 units with a nominal power of 178kWp with a total of 2 inverters with nominal power of 100 kWac each are used.

General parameters

Grid-Connected System	**No 3D scene defined, no shadings**	
PV Field Orientation		
Orientation	**Sheds configuration**	**Models used**
Fixed plane	No 3D scene defined	Transposition: Perez
Tilt/Azimuth: 15 / 135 °		Diffuse: Perez, Meteonorm
		Circumsolar: separate
Horizon	**Near Shadings**	**User's needs**
Free Horizon	No Shadings	Unlimited load (grid)

PV Array Characteristics

PV module		**Inverter**	
Manufacturer	Generic	Manufacturer	Generic
Model	LR4-72 HPH 450 M G2	Model	SUN2000-100KTL-M1-400Vac
(Original PVsyst database)		(Original PVsyst database)	
Unit Nom. Power	450 Wp	Unit Nom. Power	100 kWac
Number of PV modules	396 units	Number of inverters	2 units
Nominal (STC)	178 kWp	Total power	200 kWac
Array #1 - PV Array			
Number of PV modules	200 units	Number of inverters	10 * MPPT 10% 1 unit
Nominal (STC)	90.0 kWp	Total power	100 kWac
Modules	10 Strings x 20 In series		
At operating cond. (50°C)		Operating voltage	200-1000 V
Pmpp	82.5 kWp	Max. power (=>33°C)	110 kWac
U mpp	745 V	Pnom ratio (DC:AC)	0.90
I mpp	111 A	No power sharing between MPPTs	
Array #2 - Sub-array #2			
Number of PV modules	16 units	Number of inverters	1 * MPPT 10% 0.1 unit
Nominal (STC)	7.20 kWp	Total power	10.0 kWac
Modules	1 String x 16 In series		
At operating cond. (50°C)		Operating voltage	200-1000 V
Pmpp	6.60 kWp	Max. power (=>33°C)	110 kWac
U mpp	596 V	Pnom ratio (DC:AC)	0.72
I mpp	11 A		
Array #3 - Sub-array #3			
Number of PV modules	180 units	Number of inverters	9 * MPPT 10% 0.9 unit
Nominal (STC)	81.0 kWp	Total power	90.0 kWac
Modules	9 Strings x 20 In series		
At operating cond. (50°C)		Operating voltage	200-1000 V
Pmpp	74.3 kWp	Max. power (=>33°C)	110 kWac
U mpp	745 V	Pnom ratio (DC:AC)	0.90
I mpp	100 A	No power sharing between MPPTs	
Total PV power		**Total inverter power**	
Nominal (STC)	178 kWp	Total power	200 kWac
Total	396 modules	Number of inverters	2 units
Module area	861 m²	Pnom ratio	0.89
Cell area	782 m²	No power sharing	

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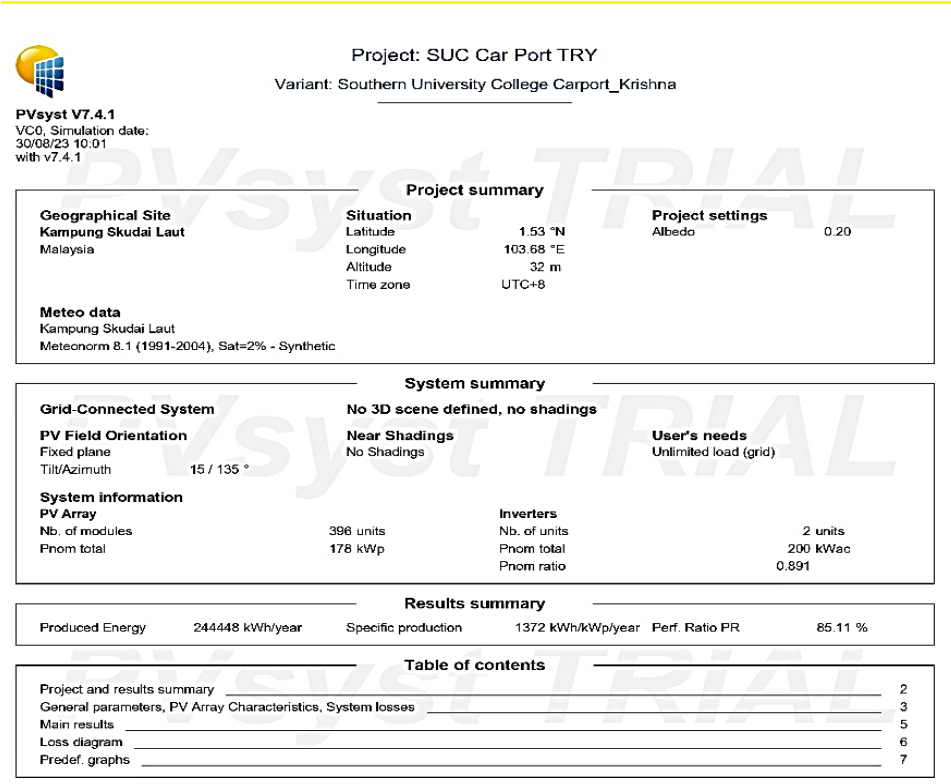
Fig. 3. Configuration in PVsyst simulation

Figure 4 presents the summary of the PVsyst simulation. The system produces 244448 kWh per year and the performance ratio will be 85.111 percent.



Project: SUC Car Port TRY
Variant: Southern University College Carport_Krishna

PVsyst V7.4.1
VC0, Simulation date:
30/08/23 10:01
with v7.4.1

Project summary

Geographical Site		**Situation**		**Project settings**	
Kampung Skudai Laut		Latitude	1.53 °N	Albedo	0.20
Malaysia		Longitude	103.68 °E		
		Altitude	32 m		
		Time zone	UTC+8		

Meteo data
Kampung Skudai Laut
Meteonorm 8.1 (1991-2004), Sat=2% - Synthetic

System summary

Grid-Connected System		**No 3D scene defined, no shadings**		
PV Field Orientation		**Near Shadings**	**User's needs**	
Fixed plane		No Shadings	Unlimited load (grid)	
Tilt/Azimuth	15 / 135 °			

System information

PV Array		**Inverters**	
Nb. of modules	396 units	Nb. of units	2 units
Pnom total	178 kWp	Pnom total	200 kWac
		Pnom ratio	0.891

Results summary

Produced Energy	244448 kWh/year	Specific production	1372 kWh/kWp/year	Perf. Ratio PR	85.11 %

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Fig. 4. Summary of project, system, and result from PVsyst simulation

Figure 5 presents the Sankey diagram, a graphical representation to visualize energy flows and losses in a PV system. It helps to understand how energy input is distributed throughout the system, accounting for various losses at each stage. In the context of a PV system, a Sankey diagram can provide insight into how solar irradiation is converted into usable electricity and the losses that occur during this process.

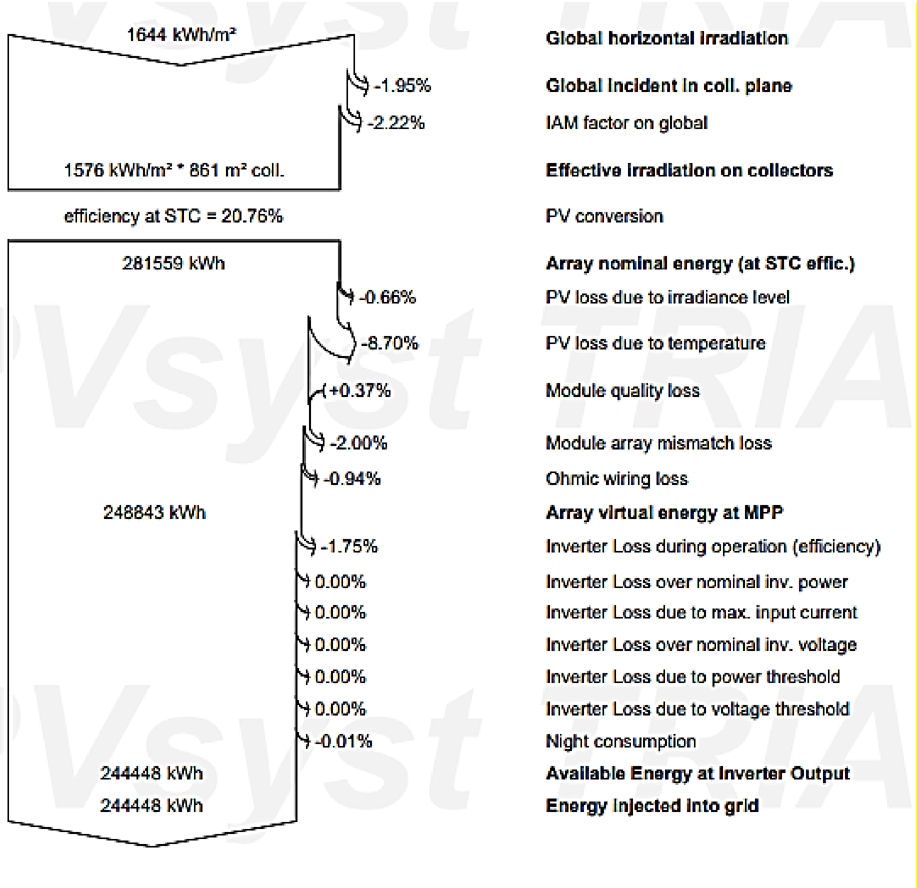

Fig. 5. Sankey loss diagram over the year from PVsyst simulation

After the loss due to the global incident on the collector plane and the IAM factor on global, the total energy production was around 281559 kWh. The array can generate 248843 kWh of virtual energy at MPP despite differences in irradiance levels, high temperatures, low modules quality losses, defects caused by light, mismatch losses with modules and strings, and ohmic wiring losses in cables. The result presents that 244448 kWh of energy is available at the inverter output after considering various losses due to inverter loss throughout operation period and night use. Accordingly, the total energy pumped into the GCPV system is 244448 kWh.

3.1.2 Result 2: Annual energy generated from MM 1

The energy produced by the proposed system is calculated using MM 1 in Eq. (1) and the result is explained in this section. This mathematical modelling considers the PV panel area in the calculation. Table 1 shows the parameter and its value used in the formulation.

Table 1
Parameters and annual energy produced by MM 1

Parameters	Value
A_{pv}	860.734512 m^2
E_{sun}	1643.9 kWh/m^2
η_{pv}	20.7 %
η_{inv}	98.6 %
η_{wire}	0.98
E_{pv}	283020.54 kWh/year

3.1.3 Result 3: Annual energy generated from MM 2

The energy produces by the proposed system is calculated using MM 2, and Table 2 simplifies the parameter and the values necessary in the computation process. This mathematical model considers the PSH value and P_{mp_stc} value in the calculation.

Table 2
Parameters and annual energy produced by MM 2

Parameters	Value
PSH	1631.55
N_{pv}	396
P_{mp_stc}	450
f_{temp}	0.994
f_{mm}	0.95
η_{inv}	98.6 %
η_{wire}	0.98
f_{dirt}	0.97
E_{PV}	259058.47 kWh/year

3.1.4 Comparison of results 1, 2 and 3

A direct comparison has been made simply in the form of a table to be able to verify the result. Table 3 shows the result of annual energy produced by PVsyst software, MM 1 and MM 2 in kWh/year.

Each case appears to involve different variables and calculations. It is worth noting that the equations provided are the simplified models for calculating the energy output of photovoltaic systems. Real-world performance can be influenced by various factors such as shading, panel degradation, and weather conditions.

From the result of PVsyst simulation, the output energy per year is 244448 kWh/year, which is lower than the other two methods. By using this value as a benchmark, the percentage difference between mathematical modelling and PVsyst was carried out. The percentage difference between PVsyst and MM 1, as well as PVsyst and MM 2, are respectively 14.63% and 5.803%.

Table 3
Methods used and the output results

Case	Method	Result (kWh/year)	Percentage Difference (%)
Result 1	PVsyst simulation	244448	
Result 2	$E_{pv} = A_{pv} \times E_{sun} \times \eta_{pv} \times \eta_{inv} \times \eta_{wire}$	283020.5355	14.626
Result 3	$E_{PV} = PSH \times N_{pv} \times P_{mp\_stc} \times f_{temp} \times f_{mm} \times f_{dirt} \times \eta_{inv} \times \eta_{wire}$	259058.47	5.803

3.2 Comparison of Monthly Energy Generated from PVsyst Simulation and Mathematical Models

This section explains the comparison of monthly energy generation obtained by the same system in Section 3.1 from PVsyst simulation, MM 1, MM 2. Afterwards, the results were compared and analysed. This section aims to compare the outcomes of these three different methods for a specific application, possibly in the field of solar energy or photovoltaic systems.

3.2.1 Result 4: Monthly energy generated from PVsyst simulation

Figure 6 shows the energy produced by PVsyst on a monthly base. From the bar graph generated by PVsyst, energy produce (kWh) in March the is higher compared to other months. This is because of horizontal global irradiation is higher in month of march. It makes sense that the solar energy production would be higher in months when solar irradiance is higher.

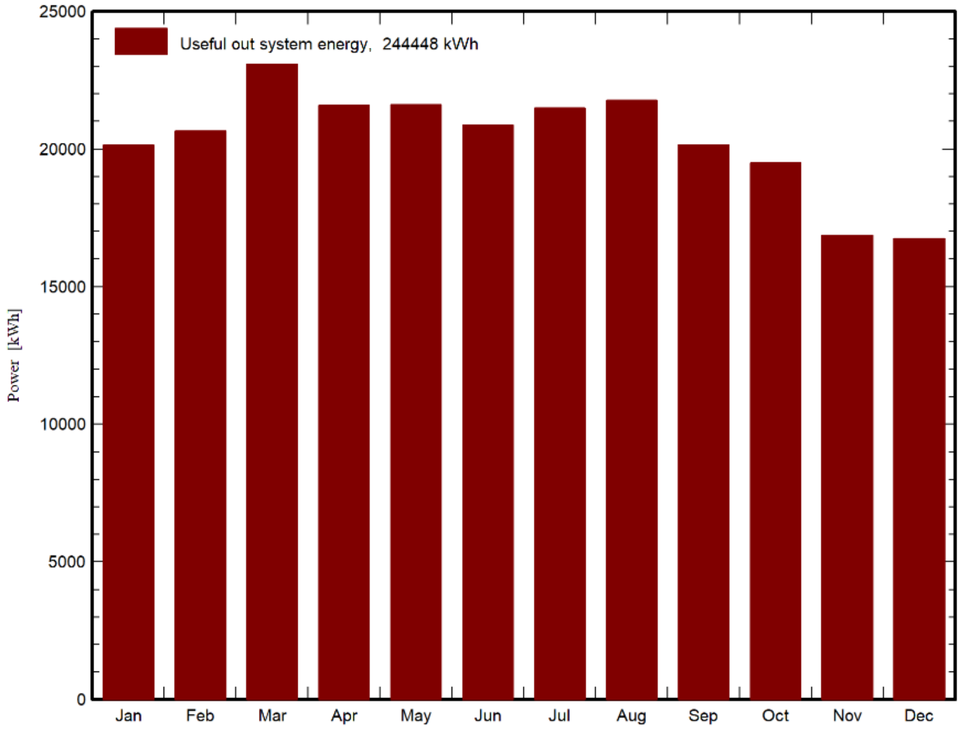

Fig. 6. Monthly energy generated by PVsyst

Figure 7 shows the normalize production the normalized productions, such as system losses (Ls), collection losses, and produced useful energy per installed kWp/day, were. Based on the results, the produced useful energy (inverter output) is 3.75 kWh/kWp/day, while the loss system is 0.07 kWh/kWp/day. Furthermore, the system produces the most and least useful energy in November and December, respectively. And the highest will be in February and March.

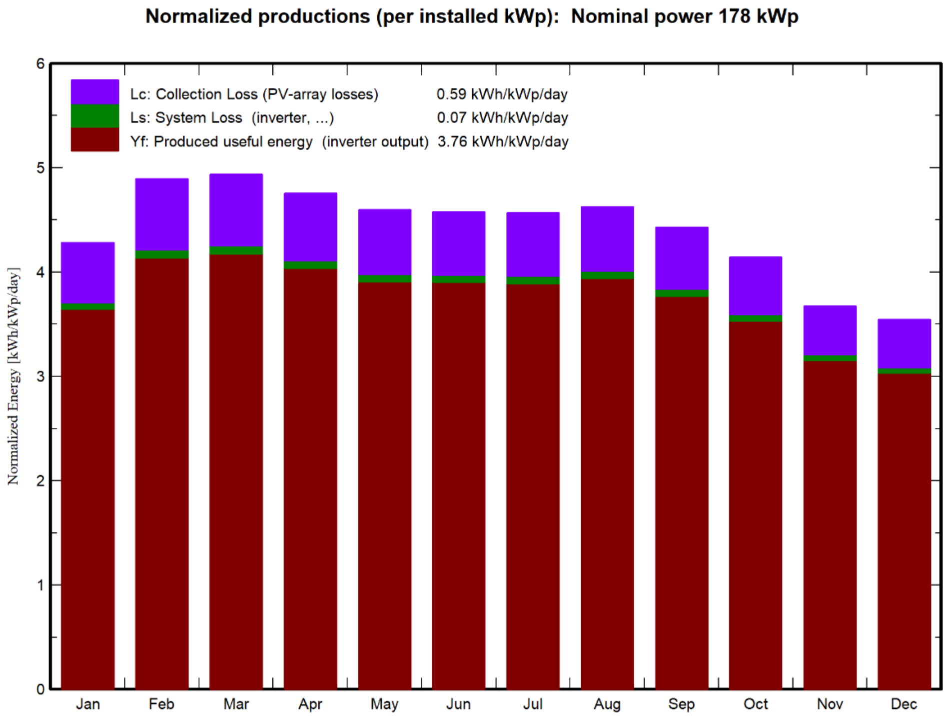

Fig. 7. Normalize production (per installed kWp) generated by PVsyst

3.2.2 Result 5: Monthly energy generated from MM 1

Figure 8 shows line graph of monthly energy production for MM 1. The line graph in Figure 8 immediately stands out as having a striking resemblance to the pattern in Figure 9. Both graphs exhibit similar trends in monthly energy production, suggesting that the two equations yield comparable results. However, the slight variations between the two data merit further exploration.

An essential part in PV system, the inverter converts the DC from PV arrays into AC for typical appliances buildings or fed into the grid. Inverter efficiency refers to how effectively it performs this conversion process, and it is a key factor in determining the overall energy output of the system. Inverter efficiency and efficiency of the wiring and other components can influence the performance.

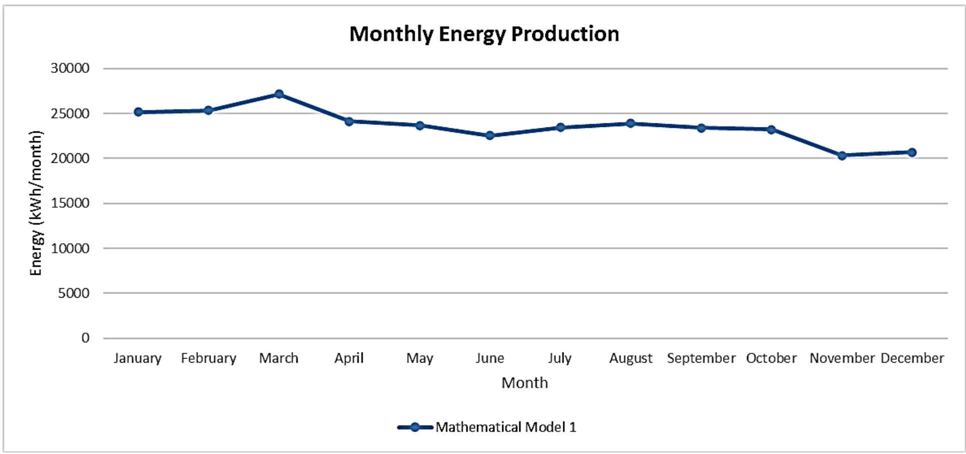

Fig. 8. Monthly energy generated from MM 1

3.2.3 Result 6: Monthly energy generated from MM 2

Figure 9 shows a line graph of monthly energy production for Eq. (2). The figure shows that in March, the energy produced by the GCPV system is higher than in other months, with 26538.16 kWh/month. This can be attributed to several factors. First, seasonal changes such as increased sunlight hours and improved solar irradiance during the spring months contribute to enhanced energy capture by the photovoltaic system. Additionally, the relatively lower ambient temperatures during this period can positively influence the system's efficiency, leading to higher energy yields.

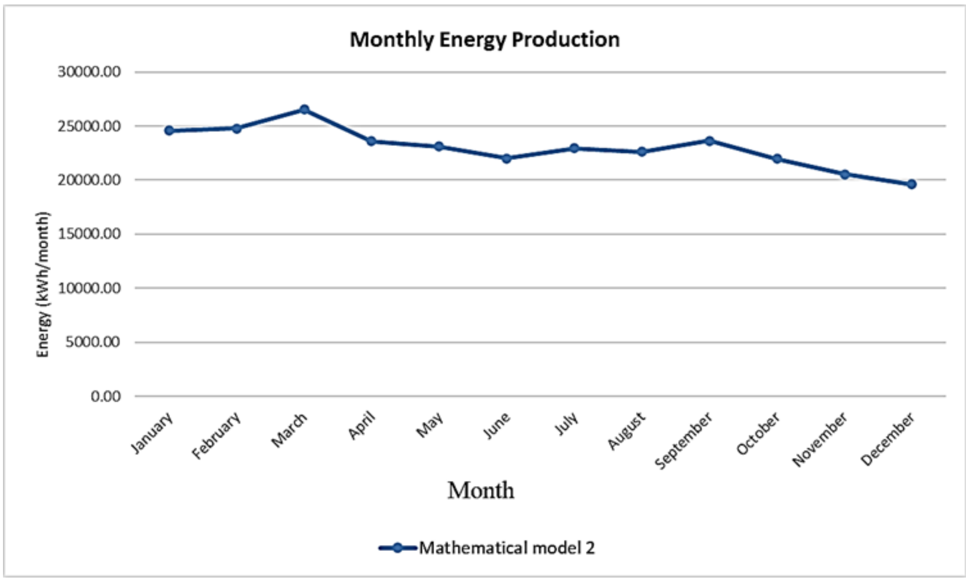

Fig. 9. Monthly energy generated from MM 2

This equation is suitable to model a PV array's performance prediction because it also anticipates possible system losses, such as temperature effects, wiring losses, components mismatch, inverter efficiencies, and losses due to dirt. It is also important to consider factors such as shading and weather conditions, which can play a pivotal role in monthly energy production variations. Months with higher cloud cover or shading, and rainy seasons could lead to decreased energy production due to reduced solar irradiance. These conditions might contribute to the observed energy production fluctuations between months.

3.1.4 Comparison of results 4, 5 and 6

A direct comparison was made simply in the form of a line graph to compare the result as illustrated in Figure 10, showing the monthly energy produced by PVsyst software, mathematical modelling 1 and mathematical modelling 2 in kWh/month. From the graph, it is clearly seen that all three graphs exhibit similar trends in monthly energy production and comparable.

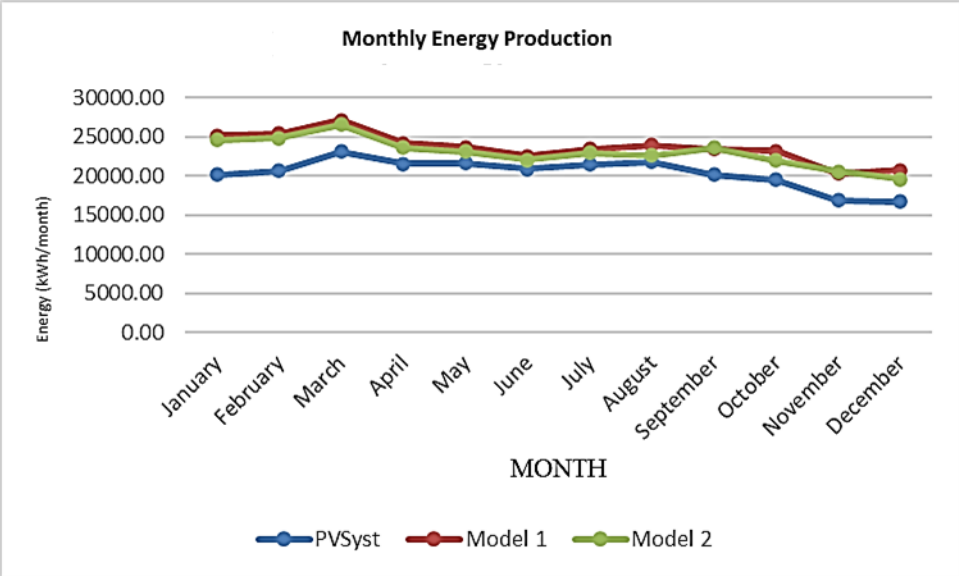

Fig. 10. Comparison of monthly energy generated

Temperature de-rating factors account for the reduction in module efficiency as temperatures rise. Higher temperatures can lead to decreased energy yields due to decreased efficiency levels. Since Eq. (2) considers temperature de-rating factors, unlike Eq. (1), it could explain the subtle differences in monthly energy production observed between the two graphs.

The slight variations between the two graphs also highlight the multifaceted influences of dirt-derating factors and module mismatch on energy production. This analysis underscores the need for meticulous consideration of these factors to accurately predict and optimize the performance of GCPV systems.

Module mismatch refers to the variations in module temperatures within an array, leading to potential differences in energy production. Power tolerance, on the other hand, accounts for the permissible deviation of module performance from the manufacturer's specifications. Particularly when comparing two equations, this factor contributed to Eq. (2), which is contributing to variations in energy production.

4. Conclusions

In summary, we focused on the method that analysed the performance of the GCPV system by using 396 units of LONGi LR4-72HPH 450, and 2 units of inverter model Huawei’s SUN2000-100KTL-M1 Smart String Inverter to produce electricity.

The energy produced annually by PVsyst simulation is 244448 kWh/year, which is used as a benchmark. By Using MM1, the energy produced is 283020.5355 kWh/year. While using MM2, the energy produced is 259058.47 kWh/year. The percentage difference between the mathematical models and PVsyst has been carried out. The percentage difference between PVsyst and MM 1 and MM2 is respectively 14.63% and 5.806%.

A more details comparison in the context of monthly energy production obtained by PVsyst software, MM 1 and MM 2 was illustrated in the form of a line graph, showing that all three graphs exhibit similar trends in monthly energy production and are comparable.

The variations between the three graphs also highlight the multifaceted influences of temperature de-rating factor, dirt derating factor, module mismatch, inverter efficiency, and cable efficiency on energy production. This analysis underscores the need for meticulous consideration of these factors to accurately predict and optimize the performance of GCPV systems.

In nutshell, although the study offered insightful information, there is certainly room for further study. Future research could improve current results by comparison of the simulation and mathematical models with real data. This can be completed by rigorous validation of PVsyst and mathematical models using data collected from an operational PV system, thereby enhancing the confidence of PV system designers, engineers, and researchers in the software's and models' precision against the measured data from the installed PV system. Statistical methods for method analysis can be used for validation.

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