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Towards Sustainable Energy Access: Evaluating Free Online Photovoltaic Design Tools in Support of the SDGs

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Abstract

The transition to clean and affordable energy is a critical step toward achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). This paper presents a comparative analysis of several free online photovoltaic (PV) power design applications, focusing on their usability, technical accuracy, and functionality to support sustainable PV system development. As the demand for solar energy grows globally, especially in underserved regions, accessible and reliable design tools are essential for promoting inclusive energy planning. This study evaluates four widely used tools, PVWatts, PVGIS, OpenSolar, and Global Solar Atlas, based on their simulation capabilities, technical features, financial modeling, and reporting outputs. Using simulation scenarios across diverse geographic locations with different solar irradiance levels, each tool's effectiveness in estimating energy production and project viability is analyzed. To inspect the results, the simulation outputs of the free tools were benchmarked against PVsyst as an industry-standard reference. The results show that while PVWatts tends to produce higher energy estimates suitable for on-grid applications, OpenSolar stands out for its comprehensive feature set and financial assessment based on native tool capabilities. The study highlights the role of open-access design tools in advancing sustainable energy access and contributing to global decarbonization efforts.

Index-words: *Photovoltaic, Solar Design Tools, Energy Access, Sustainable Development, SDG 7.*

I. Introduction

Renewable energy, including photovoltaic (PV) systems, is crucial for several reasons, such as producing little to no greenhouse gas emissions during operation [1], reducing dependence on imported fuels and enhancing national security [2], and creating employment opportunities in manufacturing, installation, and maintenance [3]. It makes the demand for PV installations continue to increase [4]. In 2024, global PV installations range from 600 GW to 660 GW [5].

As the demand for PV systems continues to rise, the need for accurate and efficient design tools becomes more critical. Properly designed PV systems can maximize energy output, ensure system reliability, and optimize cost efficiency, making the initial design phase a crucial step in PV power projects. However, many of the most widely used PV design tools by engineers are not free and require a subscription or one-time payment for access. These professional-grade tools often offer advanced features and higher accuracy, which can be crucial for large-scale or highly specialized PV projects.

Among the most popular paid PV design tools are PVsyst, HelioScope, and HOMER. PVsyst [6] is a comprehensive software tool used for the design and simulation of solar energy systems, offering features for detailed performance studies, preliminary system sizing, and financial modeling. Developed at the University of Geneva, it supports grid-connected, stand-alone, and hybrid PV systems with extensive databases for meteorological data and PV components, making it a preferred choice for engineers and researchers, as done in [7-8].

HelioScope [9] is a comprehensive software tool for designing and optimizing solar photovoltaic (PV) systems, offering advanced modeling capabilities such as system layout, performance simulation, shading analysis, and financial assessment. Some researchers, such as [10-11], prefer to use it because the cloud-based platform and detailed reporting make it an essential tool for solar professionals seeking to maximize system efficiency and profitability.

While PVsyst and HelioScope are primarily geared towards the design and optimization of solar PV systems, HOMER [12] is uniquely designed for microgrid systems, accommodating a broader range of power technologies beyond just solar. HOMER's Sensitivity Analysis feature allows users to assess the impact of various inputs on system outputs, offering a comprehensive tool for evaluating different microgrid configurations. References [13-14] illustrate examples of PV designs utilizing HOMER.

Paid photovoltaic (PV) design tools such as PVsyst, HelioScope, and HOMER are widely adopted due to their advanced technical capabilities; their advantages extend beyond licensing and cost considerations. Previous studies have shown that professional PV software typically implements more detailed performance modeling, including comprehensive loss decomposition, temperature effects, component-level configuration, and advanced system optimization features, which are essential for bankable energy yield assessments and large-scale or hybrid system design [15]. These tools often provide extensive and customizable databases for PV modules, inverters, and balance of system components, as well as sophisticated shading and layout analysis, enabling high-fidelity system representation.

In contrast, free online PV design tools generally rely on simplified or empirical modeling approaches with limited system configuration flexibility and reduced component customization. Although this constrains their applicability for detailed engineering or financial-grade analysis, such tools remain technically adequate for preliminary design, site screening, educational use, and early-stage feasibility assessment, particularly in resource-constrained contexts. This distinction indicates that the primary difference between paid and free PV design tools lies in modeling depth and system complexity rather than basic energy production estimation capability.

In recent years, a variety of free online applications have emerged, offering users the ability to design and simulate PV systems without the need for expensive software. These applications provide a range of features, from simple layout tools to advanced simulation capabilities. For example, PVWatts [16] by the National Renewable Energy Laboratory (NREL) allows users to estimate the energy production and cost savings of grid-connected PV systems based on a few basic inputs. Another popular tool, PVGIS, developed by the European Commission's Joint Research Centre, provides extensive solar irradiance data and performance assessment for PV systems, helping users evaluate potential sites and optimize system configurations [17]. Additionally, OpenSolar [18] offers a comprehensive platform that includes system design, customer proposal generation, and financial modeling, making it accessible to both new users and experienced designers. The Global Solar Atlas, supported by the World Bank Group, offers high-resolution solar resource maps and data, which are essential for assessing the solar potential of different locations worldwide [19]. These tools have significantly lowered the barrier to entry for PV system design, enabling more widespread adoption of solar energy solutions.

The four free online PV design tools, i.e., PVWatts, PVGIS, OpenSolar, and Global Solar Atlas, were selected based on their accessibility, widespread adoption, functional diversity, and relevance to early-stage PV system planning. These tools are fully web-based, publicly accessible without licensing fees, and provide global or near-global geographic coverage, making them particularly suitable for users in resource-constrained or developing regions.

Although other tools developed by the National Renewable Energy Laboratory (NREL), such as the System Advisor Model (SAM), are also freely available, SAM was not included in this study because it is designed as a comprehensive techno-economic platform supporting multiple power generation technologies. PVWatts, which was also developed by NREL, offers a simplified and streamlined approach specifically tailored for rapid PV energy estimation and early-stage assessment. Similarly, tools such as SolarGIS were excluded because they operate under commercial or subscription-based access models. The selected four tools therefore represent a balanced set of widely accessible, web-based PV design applications that capture diverse modeling approaches and user perspectives within the scope of free online tools.

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The key research gap lies in the lack of reference-based benchmarking and irradiance–energy consistency analysis for free, web-based PV design tools across diverse locations and system configurations. In this context, this article aims to fill this gap by conducting a detailed comparative analysis by evaluating these tools based on a set of predefined criteria, and then identifying the most effective applications for different user requirements. The analysis will consider factors such as ease of use, design accuracy, range of features, and user feedback, providing a holistic view of each application's capabilities and limitations. To address concerns regarding output reliability, this study incorporates a reference-based comparison with PVsyst, a widely recognized industry-standard PV simulation software. This comparison is intended to contextualize the results of free tools rather than to establish absolute accuracy.

It should be noted that the financial evaluation in this study is limited to the native capabilities provided by each tool. No external or unified financial model was applied to tools without built-in financial evaluation features. As such, the financial comparison focuses on the availability and scope of financial indicators rather than direct numerical comparability across all tools.

The global shift toward renewable energy is not merely a technical transformation but also a strategic imperative aligned with the United Nations Sustainable Development Goals (SDGs). In particular, SDG 7 (Affordable and Clean Energy) [20] emphasizes universal access to reliable and modern energy services, while SDG 13 (Climate Action) [21] calls for urgent efforts to combat climate change and its impacts. Solar photovoltaics (PV) play a central role in this agenda due to their scalability, declining costs, and potential to serve both urban and remote communities. However, the accessibility of design and simulation tools remains a barrier, particularly in developing regions where resources are limited. Free and open-access PV design tools can bridge this gap, empowering more users (engineers, students, Non-Governmental Organizations/NGOs, and local governments) to plan, evaluate, and deploy solar solutions in support of the SDGs. Thus, this study not only compares the performance of these tools but also underscores their contribution to a more inclusive and sustainable energy transition.

II. Material and Method

This chapter outlines the methodology employed in the comparative analysis of free online PV power design applications. The methodology consists of several steps, including the selection of applications, criteria for evaluation, simulation scenarios, data collection, and analysis procedures, as shown in Fig. 1.

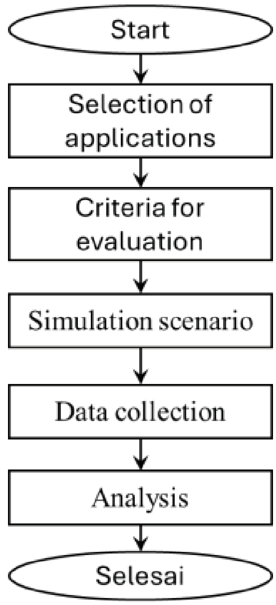


Figure 1. Methodology flowchart.

A. Selection of applications

The first step in our study was to identify a representative sample of free online PV design applications. The following applications were selected:

1. PVWatts (developed by the National Renewable Energy Laboratory), available at https://pvwatts.nrel.gov/

2. PVGIS (developed by the European Commission's Joint Research Centre), available at https://re.jrc.ec.europa.eu/pvg_tools/en/

3. OpenSolar (offered by OpenSolar), available at https://app.opensolar.com/#/home

4. Global Solar Atlas (supported by the World Bank Group), available at https://globalsolaratlas.info/map

B. Criteria for evaluation

To systematically compare these applications, a set of evaluation criteria was defined. These criteria were selected to cover the most relevant aspects of PV system design. They consist of feature availability and simulation results. Feature availability assesses the range and sophistication of features provided by each application, such as system layout tools, shading analysis, component selection, and integration with meteorological databases. The simulation results cover technical, financial, and documentation aspects, demonstrating the accuracy and reliability of the performance simulations.

The financial aspect evaluates the financial modeling capabilities of each application. It includes cost estimation, return on investment (ROI) calculations, payback period analysis, and financial viability assessments. The assessment was conducted based on the native financial modeling capabilities available within each tool. No separate or external financial model was applied to tools lacking built-in financial evaluation features. Consequently, financial comparison focuses on the presence, type, and scope of financial indicators (e.g., payback period, savings estimation) provided by each application rather than on direct numerical comparison across all tools.

Documentation evaluates the quality and comprehensiveness of the reports and documentation generated by each application. It includes the clarity, detail, and accessibility of design reports, simulation results, and financial analysis.

C. Simulation scenario

To ensure a comprehensive evaluation, a set of simulation scenarios was defined to represent various typical PV system installations. Two scenarios were designed to test the applications under different conditions and system configurations: off-grid and on-grid systems. The capacity for each scenario is 20 kWp. These scenarios are to be implemented in three locations. The selected locations were chosen to represent distinct solar resource conditions based on their typical global horizontal irradiance (GHI) characteristics. Hart, Northern Territory, Australia, represents a high solar irradiance region, with average annual GHI typically exceeding approximately 5.5–6.0 kWh/m²/day. Central Kalimantan, Indonesia, represents a moderate solar irradiance region characterized by relatively stable but lower GHI levels, generally ranging between approximately 4.0–4.8 kWh/m²/day due to high cloud cover and tropical climate conditions. Sichuan Province, China, represents a lower and more variable solar irradiance region, where average annual GHI commonly falls below approximately 4.0 kWh/m²/day and exhibits strong seasonal variability influenced by complex terrain and monsoonal weather patterns. These locations were selected to capture a broad spectrum of solar resource conditions, i.e., high, moderate, and low irradiance, allowing the performance and consistency of free PV design tools to be evaluated across contrasting climatic and geographic contexts. Finally, the same system specifications and assumptions were applied in PVsyst to ensure comparability with the free tools.

D. Data collection

Data collection focused on quantitative approaches to provide a comprehensive analysis of each PV design application. The data collection process for quantitative analysis involved the following key data points for each application and scenario. For each application, the availability of technical features is examined, including location input, meteorological databases, PV orientation, PV tilt angles, PV system layout, shading analysis capabilities, and the selection and specification of system components such as PV modules, inverters, and batteries. The availability of financial features is also examined, including PV system cost components (covering equipment, installation, and maintenance expenses), return on investment (ROI), net present value (NPV), internal rate of return (IRR), and payback period.

Simulation result parameters are also examined to evaluate the performance and efficiency of the PV systems designed using each application for each scenario. These parameters include estimated energy production, energy yield per installed capacity, performance ratio, capacity factor, and losses analysis.

At the end of the data collection step, the availability of documentation related to design reports, simulation result reports, and financial analysis reports is examined.

E. Analysis

The analysis was conducted through a series of structured steps. First, a comparative evaluation was performed in which each free online PV design application was assessed against the predefined criteria, including technical features, simulation outputs, financial evaluation capabilities, and documentation quality. The results were systematically tabulated to enable transparent comparison across tools and scenarios.

Next, simulation outputs from the free tools were compared across different geographic locations and system configurations to examine relative differences in estimated energy production. To provide an external reference for validation, the same system specifications and locations were additionally modeled using PVsyst, which is widely recognized as an industry-standard PV simulation software. PVsyst results were used as a benchmark reference to contextualize the outputs of the free tools rather than as an absolute ground truth.

The comparison focused on annual and monthly energy yield estimates under identical input assumptions, including system capacity, tilt, orientation, loss assumptions, and inverter configuration. Differences between the free tools and PVsyst were analyzed in terms of relative deviation to highlight variations arising from modeling approaches, meteorological databases, and system representation. The analysis emphasizes consistency and trend alignment rather than statistical error metrics, given the absence of measured field performance data.

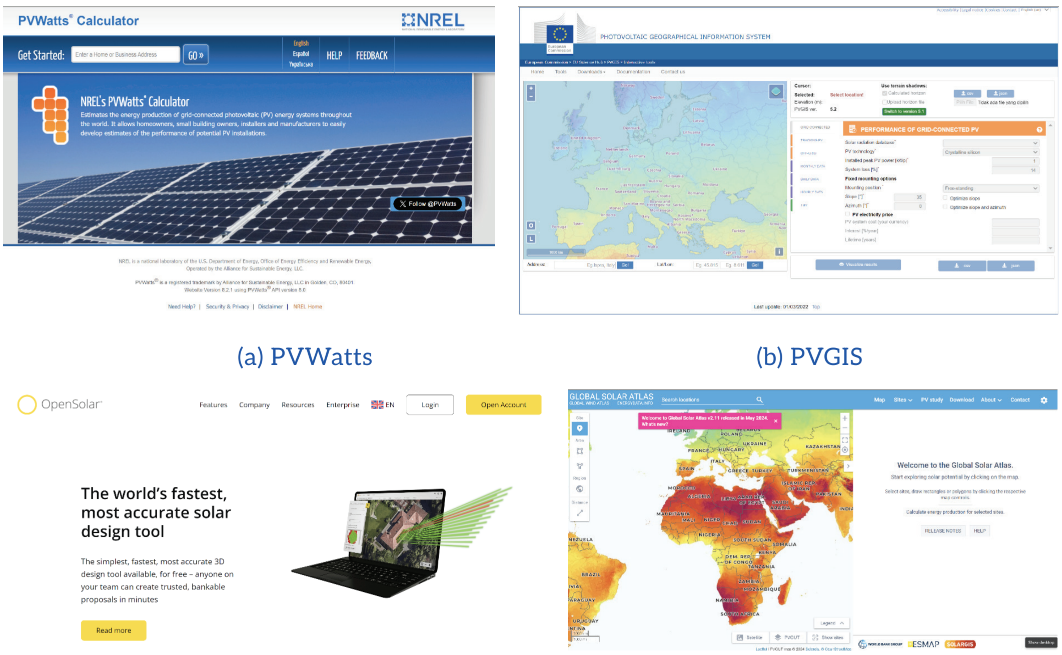
It should be noted that PVsyst itself relies on modeled assumptions and representative meteorological datasets; therefore, discrepancies observed among tools do not directly indicate accuracy or inaccuracy but rather reflect differences in underlying simulation frameworks. Validation against measured operational data is identified as an important direction for future work to further quantify absolute accuracy and uncertainty.

III. Results and Discussion

This chapter presents the findings from our comparative analysis of free online PV power design applications. The results are discussed in terms of the predefined evaluation criteria: technical features, simulation results, financial evaluation, and documentation quality. Each application's performance is highlighted, along with an overall assessment of its strengths and weaknesses.

A. Technical feature comparison

The technical capabilities of each application were evaluated based on their ability to provide comprehensive PV system design features. First, let's look at the appearance of each application. Fig. 2 shows the front-end user interface of four applications.



(a) PVWatts (b) PVGIS

(c) OpenSolar (d) Global Solar Atlas

Figure 2: Front-end user interfaces of the evaluated PV design applications (illustrative screenshots).

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Fig. 2 illustrates the front-end user interfaces of the evaluated PV design applications. Although the core simulation functions differ across platforms, the interface design plays an important role in usability and accessibility, particularly for non-expert users. Tools such as PVWatts and Global Solar Atlas present simplified input layouts focused on essential parameters, whereas OpenSolar offers a more detailed and interactive interface that supports advanced system configuration and visualization. This difference in interface complexity reflects the intended user groups and application scope of each tool.

Next, application features are explored and compiled into a checklist, as summarized in Table 1.

Table 1: Features comparison result

Features	PVWatts	PVGIS	OpenSolar	Global Solar Atlas
Location:				
Geographical information	Yes	Yes	Yes	Yes
Weather data	No	No	No	No
Import data	No	No	No	No
PV module:				
PV database	No	No	Yes	No
PV edit module	No	No	Yes	No
PV parameters import data	No	No	Yes	No
PV orientation	Yes	Yes	Yes	Yes
PV configuration	No	No	Yes	No
PV Tracking	No	Yes	Yes	No
Design visualization	No	No	Yes	No
Load profile:				
Daily consumptions	No	Yes	Yes	No
Hourly distribution	No	Yes	Yes	No
Monthly variation	No	Yes	Yes	No
Controller/Inverter:				
Database	No	No	Yes	No
Customize	No	No	Yes	No
Recommended apparatus	No	No	Yes	No
Faulty design warning	No	No	Yes	No
Battery:				
Database	No	No	Yes	No
Basic parameters setting	No	Yes	Yes	No
Recommended apparatus	No	No	No	No
Faulty design warning	No	No	Yes	No
Technical evaluation:				
Losses Analysis	Yes	Yes	Yes	No
Energy Production Estimation	Yes	Yes	Yes	Yes
Technical report	Yes	Yes	Yes	Yes

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Features	PVWatts	PVGIS	OpenSolar	Global Solar Atlas
Financial evaluation:				
Component Pricing	No	No	Yes	No
NPV/payback analysis	No	No	Yes	No
Financial report	No	No	Yes	No

Yes indicates that the feature is explicitly available within the tool

No indicates that the feature is not supported or not accessible to users

Note: Financial evaluation refers to native financial modeling features available within the tool. No external financial model was applied to tools without built-in financial evaluation capabilities.

B. *Simulation result*

Before presenting the simulation results, Table 2 shows the detailed specifications for each scenario that were previously discussed. Then, each scenario is applied to the PV design applications.

Table 2: Detailed system specification for simulation

Parameters	Scenario					
	1	2	3	4	5	6
Scenario location	Hart, Northern Territory, Australia		Central Kalimantan, Indonesia		Sichuan, China	
PV application	Residential					
Total PV capacity (kWp)	20					
PV Type	Monocrystalline; monofacial					
Single PV capacity (Wp)	500					
Tilt angle (deg)	20		5		25	
Azimuth angle (deg)	0				180	
PV mounting height (m)	5					
Mounting type	Fixed; roof mount					
Total PV system losses	2%, excluding soiling and shading					
Inverter type	Ongrid, 1 phase	Off-grid, 1 phase	Ongrid, 1 phase	Off-grid, 1 phase	Ongrid 1-phase	Off-grid, 1 phase
Inverter capacity (kW)	20					
Inverter efficiency (%)	95					
Load profile	constant					
Load capacity (kW)	5					
Battery voltage (VDC)	-	192	-	192	-	192
Battery capacity (Ah)	-	400	-	400	-	400
Battery depth of discharge (%)	-	80	-	80	-	80

Energy production estimation depends on the weather database stored in the application. Therefore, the information related to solar irradiance was first examined. It depends on the location and varies over time. By inputting the location specified in each scenario, the daily solar irradiance ($kWh/m^2/day$) for each month was obtained, as shown in Fig. 3. Note that solar irradiance is not affected by the on-grid and off-grid schemes. For this evaluation, Scenarios 1, 3, and 5 were used. However, there is no daily solar irradiance information available in the OpenSolar application tool.

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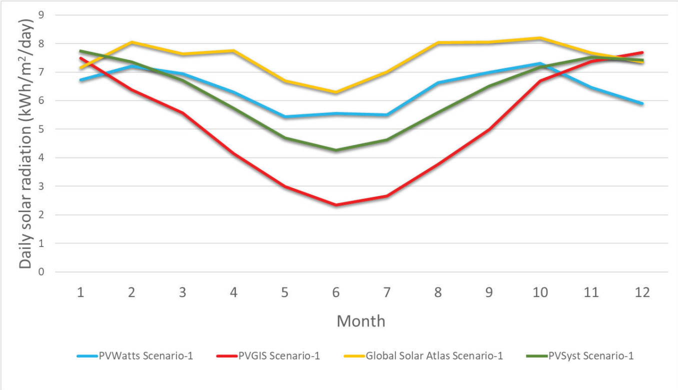
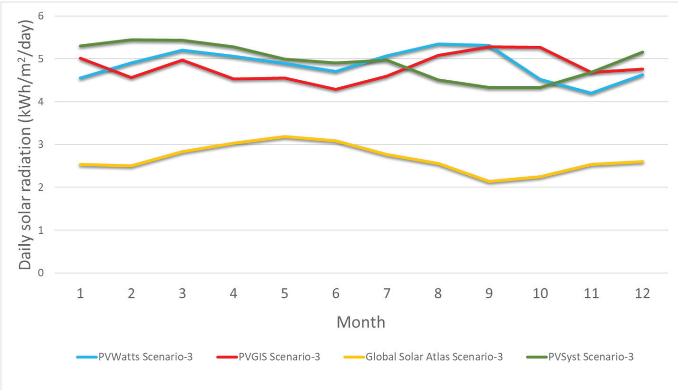
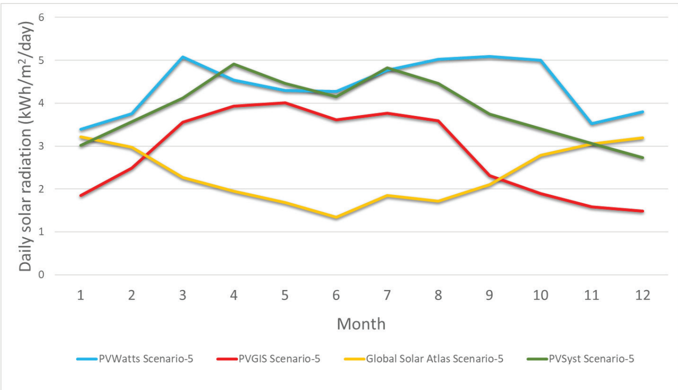


(a) Scenario-1 (Hart, Australia)



(b) Scenario-3 (Central Kalimantan, Indonesia)



(c) Scenario-5 (Sichuan, China)

Figure 3: Monthly average daily solar irradiance (kWh/m²/day) estimated by different PV design tools for Scenario-1 (Hart, Australia), Scenario-3 (Central Kalimantan, Indonesia), and Scenario-5 (Sichuan, China).

Scenario-1 shows relatively high solar irradiance values, with PVWatts reaching around 7 kWh/m²/day during peak months, while PVGIS and Global Solar Atlas provide slightly lower estimates. Scenario-3 indicates moderate solar irradiance, generally around 4 to 5 kWh/m²/day across the year, with minor fluctuations across the months, depending on the tool used. Scenario-5 reflects the lowest solar irradiance, with values hovering between 2 and 4 kWh/m²/day, with noticeable variation between the tools, particularly between PVGIS and Global Solar Atlas.

Each tool provides varying estimates, highlighting the importance of using multiple data sources for comprehensive analysis. The PVWatts tool consistently predicts higher solar irradiance across all scenarios compared to PVGIS and Global Solar Atlas. Additionally, the seasonal variation can be observed, with irradiance typically peaking around the middle of the year and showing a decline during winter months, which is consistent across all scenarios.

To further contextualize these results, PVsyst was used as a reference benchmark for solar irradiance estimation under the same geographic locations. As shown in Fig. 3, the irradiance profiles generated by the free tools generally follow similar seasonal trends to those produced by PVsyst across all scenarios. While differences in absolute irradiance values are observed, particularly in regions with lower or more variable solar resources, the overall temporal patterns remain consistent. This alignment indicates that the free tools capture the dominant seasonal behavior of solar irradiance comparably to an industry-standard model, supporting their suitability for early-stage PV system assessment and site screening.

Figure 3 shows that the PVWatts solar irradiance data is similar to PVsyst for locations in Hart, Australia, and Central Kalimantan. Meanwhile, for the location in Sichuan, China, the solar irradiance data in PVGIS is closest to PVsyst. On the other hand, Global Solar Atlas solar irradiance data has the largest difference to PVsyst in the three locations.

Furthermore, a study by the International Energy Agency (IEA) [22] highlights how technical assumptions, geographic variability, and climate conditions can introduce discrepancies in the financial and energy yield models of PV systems, reinforcing the need for multi-source validation. This finding underscores the limitations in simulation accuracy for regions with variable irradiance levels, as observed in previous simulations.

Next, simulations were performed to estimate the total monthly energy production. Fig. 4 through 9 show the simulation results from four tools

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using the six scenarios described earlier. However, PVWatts and Global Solar Atlas have limitations when it comes to off-grid scenarios, which may be due to limitations in the dataset or tool capabilities.

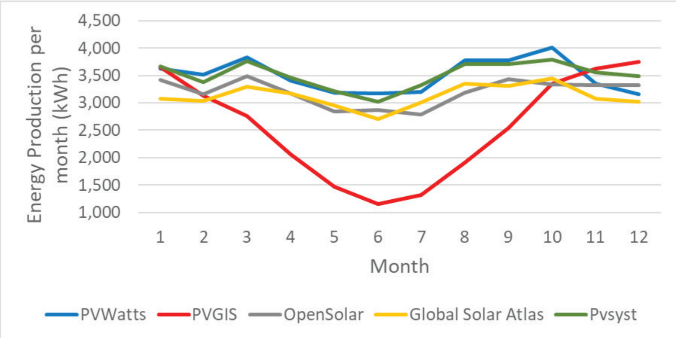

Figure 4: Monthly energy production (kWh) estimated by PVWatts, PVGIS, OpenSolar, and Global Solar Atlas for Scenario-1 (on-grid system, Hart, Australia).

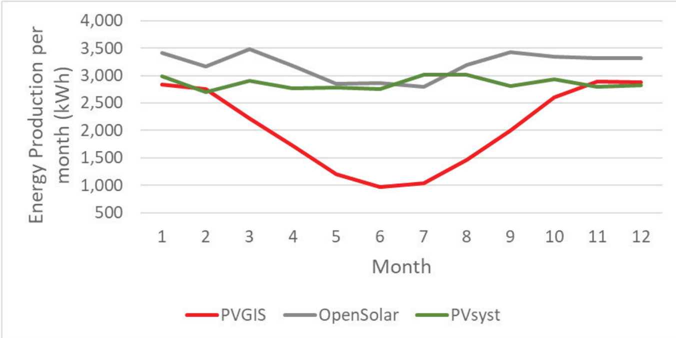

Figure 5: Monthly energy production (kWh) estimated by PVGIS and OpenSolar, for Scenario-2 (off-grid system, Hart, Australia).

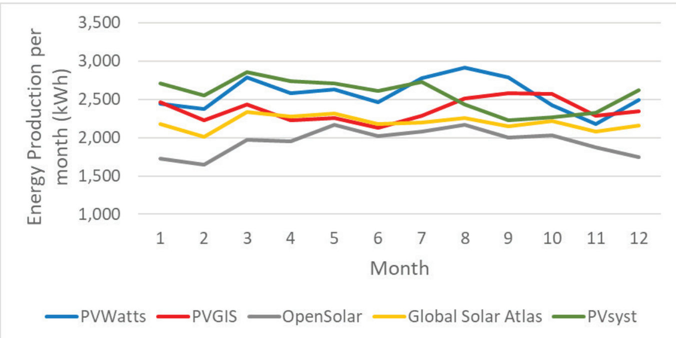

Figure 6: Monthly energy production (kWh) estimated by PVWatts, PVGIS, OpenSolar, and Global Solar Atlas for Scenario-3 (on-grid system, Central Kalimantan, Indonesia).

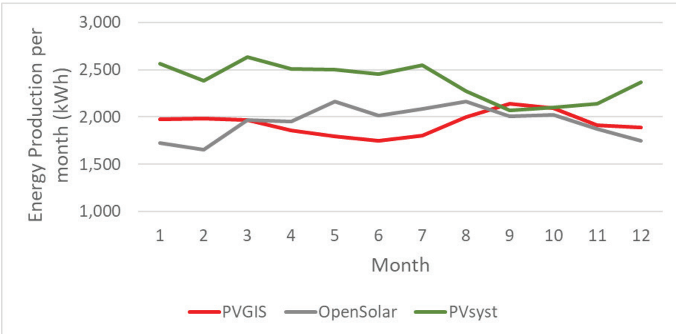

Figure 7: Monthly energy production (kWh) estimated by PVGIS and OpenSolar, for Scenario-4 (off-grid system, Central Kalimantan, Indonesia).

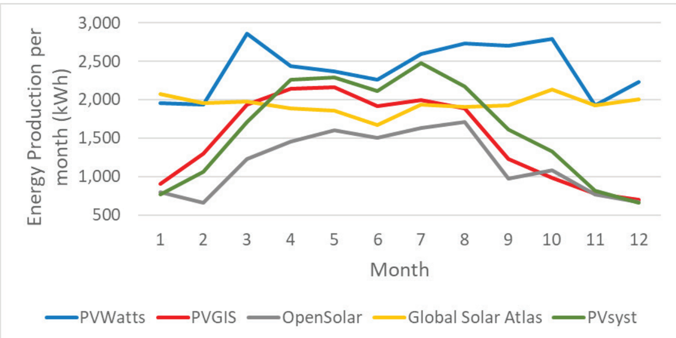

Figure 8: Monthly energy production (kWh) estimated by PVWatts, PVGIS, OpenSolar, and Global Solar Atlas for Scenario-5 (on-grid system, Sichuan, China).

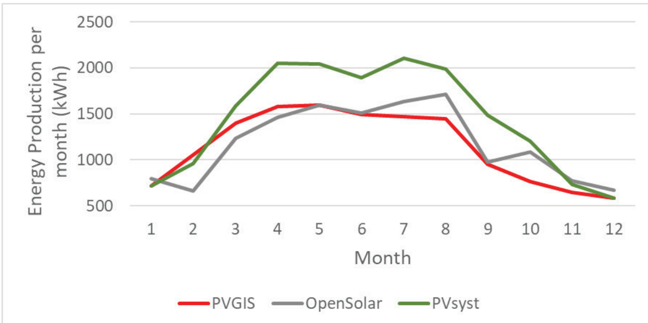

Figure 9: Monthly energy production (kWh) estimated by PVGIS and OpenSolar, for Scenario-6 (off-grid system, Sichuan, China).

For the on-grid system in high solar irradiance conditions (Scenario-1), PVWatts shows the highest total energy production at 42,009 kWh, followed closely by Global Solar Atlas at 37,452 kWh and OpenSolar at 38,346 kWh. PVGIS gives a lower estimate of 30,721 kWh, showing a noticeable difference from the other tools. In a medium solar irradiance location (Scenario-3), the energy production ranges from 30,832 kWh (PVWatts) to 28,307 kWh (PVGIS), showing less variation across tools. The low solar irradiance condition (Scenario-5) shows similar results, where PVWatts provides the highest estimate of 28,807 kWh, while PVGIS and OpenSolar give similar values around 17,958 and 14,108 kWh, respectively.

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For the off-grid (Scenarios 2, 4, and 6), there is significant variation in the results. For Scenario-2 (high irradiance off-grid), OpenSolar provides the highest total energy production (38,346 kWh), while PVGIS estimates 24,585 kWh. Scenario-4 (medium solar irradiance) follows a similar pattern, with OpenSolar giving the highest estimate at 23,376 kWh, while PVGIS estimates 23,164 kWh, showing much smaller differences. Scenario-6 (low solar irradiance) shows significant variation between tools, with OpenSolar estimating 14,108 kWh and PVGIS estimating only 17,958 kWh.

In general, OpenSolar is the most optimistic tool, consistently providing the highest estimates across both on-grid and off-grid scenarios, particularly for high solar irradiance conditions. On the other hand, PVGIS tends to be the most pessimistic tool, giving lower energy production estimates, especially for high solar irradiance scenarios like Scenario-1 and Scenario-2.

The largest variation between tools occurs in Scenario-5, where PVWatts estimates 28,807 kWh, while OpenSolar and PVGIS estimate much lower values, at 14,108 kWh and 17,958 kWh, respectively. This significant spread indicates that the tools likely use different approaches or assumptions when calculating energy production for locations with lower solar irradiance. Factors such as variations in solar irradiance models, assumptions about system losses, or specific treatment of low irradiance conditions could contribute to this disparity in results. Consequently, this scenario highlights the importance of carefully selecting and understanding the assumptions behind the tools used for energy estimation, particularly in regions with low solar irradiance.

The scenario with the smallest variation is Scenario-3. All tools estimate the total energy production to be in the range of 28,307 kWh to 30,832 kWh. This indicates that the tools are more aligned in their calculations for medium irradiance locations, where the environmental conditions might be more predictable or standardized.

PVWatts consistently provides the highest estimates for on-grid scenarios (Scenarios 1, 3, and 5), but not for off-grid scenarios, where OpenSolar dominates in providing higher estimates. Additionally, there are no data for some off-grid scenarios in PVWatts and Global Solar Atlas, indicating that these tools may have limitations or constraints when simulating off-grid solar systems, which could affect their usefulness for users needing off-grid estimates. Moreover, the off-grid scenarios in general tend to have higher variations between tools, particularly in lower irradiance locations, reflecting the complexity and variability in simulating off-grid systems.

To further contextualize the simulation results, PVsyst was employed as a reference benchmark for both on-grid and off-grid scenarios. As illustrated in Figures 4–9, differences in monthly energy production among the evaluated tools are closely associated with variations in solar irradiance estimates discussed earlier in Figure 3. Tools that predict higher irradiance levels generally yield higher monthly energy production, while lower irradiance estimates translate into reduced energy outputs.

To quantify the extent of variation among tools, a comparative summary of monthly energy production differences relative to PVsyst was compiled for each scenario, as shown in Table 3. Overall, the results indicate that the degree of deviation in energy production is strongly influenced by differences in irradiance estimation, although the magnitude of this propagation varies among tools and system configurations.

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Table 3: Quantitative comparison of the free PV design tool design result relative to PVsyst

Aspects	Differences relative to PVsyst			
	PVWatts	PVGIS	OpenSolar	Global Solar Atlas
Scenario-1 (on-grid system, Hart, Australia)				
Solar irradiance	13.01%	21.06%	N/A	24.38%
Energi production	3.68%	29.36%	8.85%	10.96%
Scenario-2 (off-grid system, Hart, Australia)				
Solar irradiance	13.01%	21.06%	N/A	24.38%
Energi production	N/A	29.39%	13.22%	N/A
Scenario-3 (on-grid system, Central Kalimantan, Indonesia)				
Solar irradiance	8.88%	11.41%	N/A	45.96%
Energi production	8.21%	12.56%	23.50%	14.04%
Scenario-4 (off-grid system, Central Kalimantan, Indonesia)				
Solar irradiance	8.88%	11.41%	N/A	45.96%
Energi production	N/A	18.67%	17.54%	N/A
Scenario-5 (on-grid system, Sichuan, China)				
Solar irradiance	17.16%	28.59%	N/A	38.43%
Energi production	75.00%	13.93%	23.70%	64.48%
Scenario-6 (off-grid system, Sichuan, China)				
Solar irradiance	17.16%	28.59%	N/A	38.43%
Energi production	N/A	19.13%	19.67%	N/A

Among the evaluated tools, PVWatts generally exhibits the closest agreement with PVsyst in on-grid scenarios, particularly for Scenario-1 (Hart, Australia) and Scenario-3 (Central Kalimantan), where energy production differences remain below 10%. This suggests that PVWatts provides energy estimates that are relatively aligned with PVsyst when grid-connected systems and moderate irradiance variability are considered.

In contrast, PVGIS and Global Solar Atlas show larger deviations, especially in scenarios characterized by higher climatic variability. Notably, in Scenario-5 (Sichuan, China), PVWatts and Global Solar Atlas display substantial differences in estimated energy production despite moderate irradiance deviations, indicating a stronger sensitivity to local climatic representation and modeling assumptions.

This variation is consistent with recent findings showing that PV energy prediction accuracy is highly dependent on modeling assumptions, irradiance representation, and computational approach. Singh et al. [23] demonstrated that conventional PV prediction models exhibit systematic deviations when compared with intelligent hybrid prediction methods, particularly under varying climatic conditions.

The off-grid scenarios consistently show higher deviations across all tools compared to on-grid configurations. This trend highlights the increased complexity of off-grid system modeling, where battery behavior, load assumptions, and system losses introduce additional sources of uncertainty. In these cases, OpenSolar and PVGIS tend to produce larger energy deviations, reflecting the sensitivity of off-grid simulations to tool-specific assumptions and default settings. These findings reinforce the role of reference-based benchmarking in understanding the applicability and limitations of free PV design tools for early-stage system assessment.

C. *Financial evaluation*

Among the four design tools evaluated, only OpenSolar provides integrated financial analysis capabilities. Users can customize key financial parameters such as electricity tariffs, initial investment costs, pricing schemes (e.g., price per watt or manual pricing), markup percentages, and available incentives. Based on these inputs, OpenSolar generates a Net Financial Impact Report that includes estimated annual electricity bill savings and cumulative savings over the assumed system lifetime, enabling users to approximate the payback period of the proposed PV system.

As an illustrative example, Scenario 3 yields a total system cost of Rp500,000,000 with an estimated annual electricity bill savings of Rp35,466,802. Over the system lifetime as defined within the tool, cumulative savings are projected to reach Rp908,688,649, resulting in an estimated net savings of Rp408,688,649 after deducting the initial investment. The corresponding payback period is approximately 13 years. This projection is based on internal assumptions within the tool, including a 3% annual increase in energy costs and a financial discount rate of 6.75%, which are applied for savings and cash-flow estimation rather than explicit net present value or return-based calculations.

While OpenSolar enables flexible and transparent estimation of utility bill savings as a practical indicator of financial benefit, advanced financial metrics such as return on investment (ROI), net present value (NPV), and internal rate of return (IRR) are not explicitly supported by the evaluated free PV design tools. These metrics typically require more detailed assumptions regarding system lifetime, operational and maintenance costs, component degradation, and financing structures, which are more commonly implemented in paid professional software. Consequently, the absence of ROI, NPV, and IRR calculations represents a key limitation of free online tools when used for financial-grade investment assessment or bankability analysis.

Nevertheless, the availability of basic financial evaluation in OpenSolar, despite being a free platform, offers a significant advantage for stakeholders in developing regions who often lack access to commercial software. This capability enables users such as schools, community organizations, and local governments to conduct early-stage financial feasibility assessments, thereby supporting informed decision-making and improving access to sustainable energy solutions. In this context, OpenSolar contributes to the objectives of SDG 7 by promoting inclusive, affordable, and sustainable energy planning.

D. Design documentation

Documentation is an important aspect of design. Thus, the information provided in the documents generated by the tools is examined. Table 4 depicts the information provided by each tool at the end of the design process. It covers various categories of information, such as site information, solar irradiance, monthly energy production, PV specifications, sun path information, load profile, and financial reports, showcasing the strengths and limitations of each tool.

Table 4: Documentation comparison

Documentation Description	PVWatts	PVGIS	OpenSolar	Global Solar Atlas
Site info	Location name, coordinates	Coordinates	Graphical visualization	Location name, coordinates, map
Solar irradiance	Numerical tables	Graphical visualization	N/A	Graphical visualization
Monthly Energy Production	Numerical tables	Graphical visualization	Graphical visualization	Graphical visualization and numerical tables
PV specification	Numerical tables	Numerical tables	Numerical tables and descriptive textual reports	Numerical tables
Sun path information	N/A	N/A	N/A	Graphical visualization
Load profile	N/A	N/A	Graphical visualization	N/A
Financial report	N/A	N/A	Graphical visualization and descriptive textual reports	N/A

N/A = not available

It seems that OpenSolar emerges as the most comprehensive tool for PV system design, offering a rich combination of data, images, and narratives, including financial reporting and load profiles, making it the best option for users seeking a holistic design experience. However, for users who are more focused on straightforward tabular data, PVWatts and PVGIS might be better suited. Global Solar Atlas is particularly advantageous for projects where sun path information is critical, despite lacking some of the other advanced features provided by OpenSolar. Ultimately, the choice of tool depends on the specific requirements of the project and the designer's preference for data presentation. Furthermore, documentation features, particularly in OpenSolar, play a vital role in enabling transparency and ease of understanding among non-technical stakeholders. In line with recent SDG-oriented PV studies [24], the accessibility of free design tools plays a critical role in enabling broader participation in sustainable energy planning and decision-making processes.

Based on the comparative findings in technical and financial aspects, the following practical implications can be derived for different user groups (see Table 5).

Table 5: Recommended PV Design Tools for Different User Groups

User Group	Primary objective	Recommended Tool(s)	Rationale
Engineers/ Designers	Preliminary PV system design	OpenSolar	Flexible system configuration and basic financial evaluation
Policymakers/ Planners	Regional solar potential assessment	PVGIS, Global Solar Atlas	Reliable geographic and irradiance data
Educational Institutions	Teaching and learning PV concepts	PVWatts, OpenSolar	Ease of use and intuitive output
Community Organizations/ NGOs	Early-stage feasibility assessment	OpenSolar, PVWatts	Accessible tools with basic financial indicators

IV. Conclusion

This study demonstrates that free online PV design tools exhibit varying capabilities and limitations, highlighting the importance of selecting tools that align with specific project objectives and user requirements. While differences in estimated energy production are observed among the evaluated tools, these variations are largely driven by differences in solar irradiance modeling and system assumptions rather than inconsistencies in capturing seasonal trends. As a result, free tools remain suitable for early-stage PV system assessment, provided that their underlying assumptions and intended use cases are well understood.

The incorporation of PVsyst as an industry-standard reference benchmark strengthens the comparative assessment by contextualizing the simulation outputs of free tools. The results indicate that, although absolute energy yield estimates differ, particularly in off-grid configurations and regions with variable irradiance, the overall temporal patterns remain broadly consistent with PVsyst. This finding underscores the influence of irradiance estimation and system complexity on energy production outcomes and highlights the need for cautious interpretation when applying free tools beyond preliminary design and screening stages.

Despite their limitations in advanced financial modeling and investment-grade analysis, free online PV design tools play a critical role in lowering barriers to solar energy adoption, especially in resource-constrained and developing regions. By enabling diverse user groups, including engineers, planners, educators, and community stakeholders, to engage in PV system planning and evaluation, these tools support informed decision-making at early project stages. In this context, free PV design tools contribute meaningfully to the achievement of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), fostering a more inclusive and sustainable global energy transition.

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