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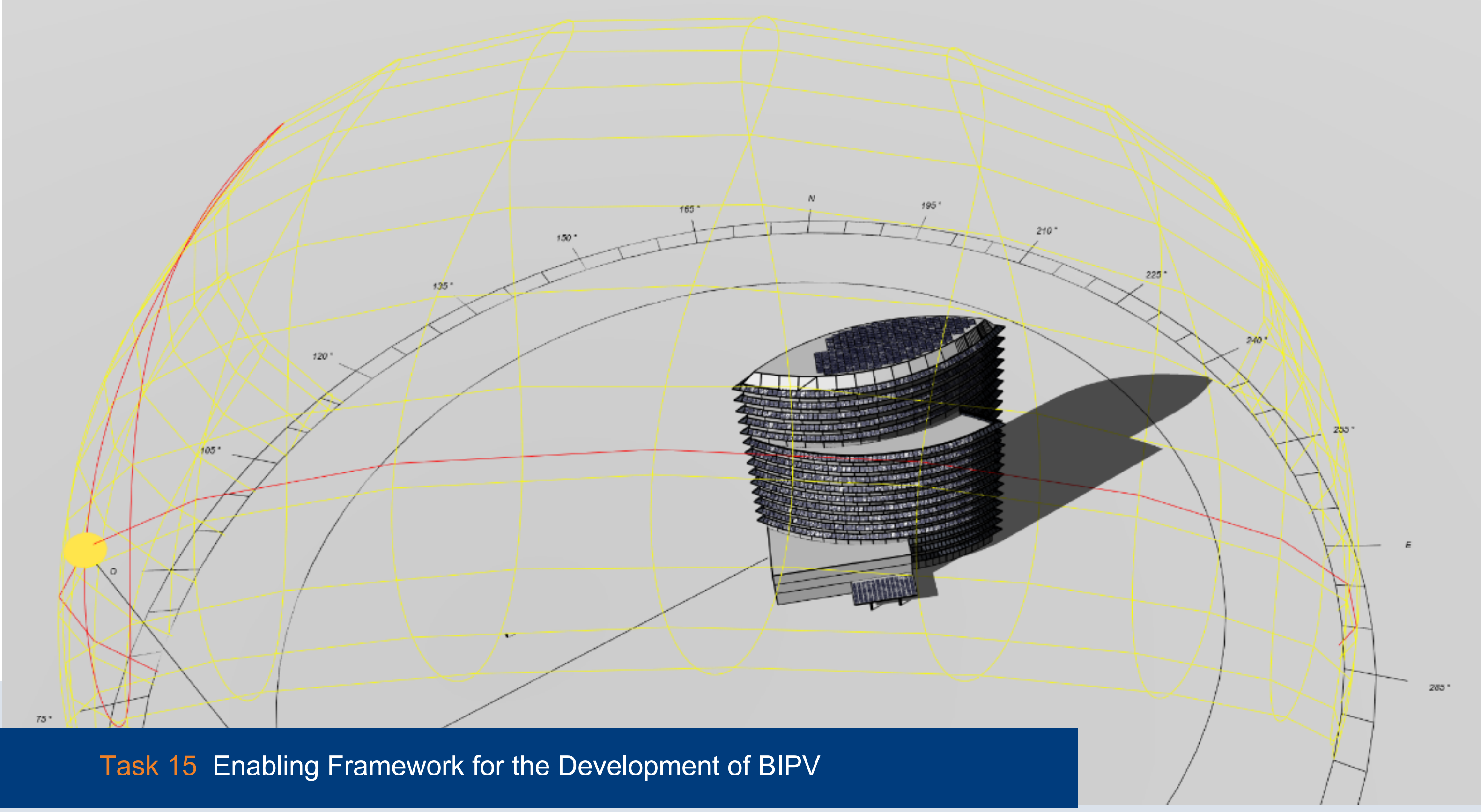

Task 15 Enabling Framework for the Development of BIPV

PVPS

JOURNAL ARTICLE

Energy and Buildings

Digitalising BIPV energy simulation: A cross tool investigation

August 2024

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The 25 IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance, the Solar Energy Industries Association, the Solar Energy Research Institute of Singapore and Enercity SA are also members.

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What is IEA PVPS Task 15?

The objective of Task 15 of the IEA Photovoltaic Power Systems Programme is to create an enabling framework to accelerate the penetration of BIPV products in the global market of renewables, resulting in an equal playing field for BIPV products, BAPV products and regular building envelope components, respecting mandatory issues, aesthetic issues, reliability and financial issues.

Sub-task D Digitalization for BIPV aimed to facilitate the application of BIPV over the whole value chain and to improve its reliability with the potential of digitalization. This sub-task compared the BIPV real performance with the simulated performance; identified operative approaches, methods and workflows relevant under each do-main of BIPV digitalized process, collected requirements for digital product data and defined the main information modelling/management strategies to effectively implement a digital process to improve interoperability along the value chain.

Authors

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COVER PICTURE

Digital simulation of a BIPV case study used in the publication, credits IEA PVPS Task 15

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

IEA PVPS
Task 15
Enabling framework for the acceleration of BIPV

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EXECUTIVE SUMMARY

BIPV design tools represent an inevitable resource for the digital value chain creation that all stakeholders rely on. Moreover, capabilities of tools have a profound impact on quality and reliability of designed BIPV systems. Therefore, assessing and validating their capabilities, as well as proposing areas for improvement may have substantial influence on future BIPV design and implementation speed and quantity. Also, it is crucial to acknowledge that variations exist in assumptions, algorithms, modelling capabilities, input data, and settings among different tools.

This study aims to model complex BIPV systems using eight tools among the most relevant available on the market, investigating their capabilities and limitations, and suggesting potential ways forward and recommendations, rather than focusing on the accuracy of the simulation results of these different tools. Overall, standalone PV tools' limited 3D modelling capabilities and algorithm models restrict their modelling capabilities when encountering complex BIPV façade projects. Additionally, while good at 3D modelling, certain BIM-based tools and plug-ins lack standalone capabilities for detailed electrical simulations, highlighting the necessity to boost their capacity for BIPV system electrical modelling.

Suggestions focus on pointing out the future development directions for BIPV digital simulation. in Energy and Buildings.

The outcome of this study has been published in the Special issue “Photovoltaics in the Built Environment” of Energy and Buildings, edited by Angèle Reinders (Eindhoven University of Technology, the Netherlands) and Francesco Frontini (University of Applied Sciences and Arts of Southern Switzerland)

Keywords: BIPV; Energy performance; Digitalization; Simulation tools; BIM

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Digitalising BIPV energy simulation: A cross tool investigation

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ABSTRACT

The long-term viability of Building Integrated Photovoltaics (BIPV) as a renewable energy technology has garnered increased attention in recent discussions. However, there is currently a noticeable absence of simulation tools specific to BIPV applications that can cover the whole modelling chain. It remains unclear to what extent existing PV and BIM-based simulation tools can effectively address the complexities of BIPV projects. Therefore, this study aims to assess the process of existing simulation tools for BIPV energy simulation, three standalone PV tools (SAM, PV*SOL premium, and PVsyst), two Building Information Modelling (BIM)-based standalone PV tools (BIMsolar and Solarius PV), two plug-ins in BIM-based tools (INSIGHT for Revit, Ladybug Tools for Grasshopper/Rhinoceros 3D), and one Computer-Aided Design and Drafting (CADD) tool plugin (Skelion for Sketchup). Based on one existing building project with three different types of BIPV-installations, this study explored the capability of these eight tools in modelling/importing building geometry, selecting weather data, setting system layout and array, evaluating the solar resource, estimating energy losses, and assessing energy generation. The simulation results are compared with monitored energy yield data and presented with deviation analysis. Suggestions focus on pointing out the future development directions for BIPV digital simulation. This study offers insights and guidance for digitalising the BIPV performance simulation in the complex building design.

1. Introduction

The construction sector accounts for 30 % of global final energy consumption and 26 % of energy-related carbon emissions [1]. As a dependable renewable energy source, solar energy holds significant promise in addressing the growing energy demands of urban areas.

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Building-Integrated Photovoltaics (BIPV) is a versatile renewable energy technology that allows electricity production at the place of consumption. Implementing BIPV systems in building envelopes (i.e., roof and façade) not only boosts the share of renewable energy in the built environment but also reduces the environmental impact [2]. Urban buildings offer large solar power production potentials, minimizing investment for additional power infrastructure and mitigating grid transmission losses [3].

However, due to the variability of the solar resource, the complexity of BIPV, and the relatively high price of BIPV modules, the development of BIPV projects face challenges in terms of economic feasibility [4]. Life-cycle cost analysis (LCCA) is often conducted in the early planning stages of a BIPV project to evaluate its economic viability and assist stakeholders in making informed decisions. The prediction of lifecycle energy generation is the basis of LCCA. Forecasting the lifetime energy generation of a BIPV system typically entails initially simulating the generation in the first year, and then future years are forecasted based on the predicted generation of the first year, while accounting for component degradation rates [5].

Simulating a BIPV system's energy generation involves constructing a comprehensive model that integrates natural, building, and surrounding environment and the BIPV system components. Since BIPV is a component of building envelopes, plug-ins (e.g. Skelion for Sketchup, INSIGHT for Revit, and Ladybug tools for Rhinoceros 3D/Grasshopper) have been developed based on CADD software or BIM modelling interface. 3D models in these tools could be convenient for effectively processing shadow maps for BIPV systems with complex geometry and adjacent environments [6]. However, these tools cannot provide detailed electrical performance simulation for BIPV systems as our study finds.

In the meanwhile, to evaluate and optimize PV system performance, numerous computer simulation tools have been developed, which simulate the physical processes of the PV energy conversion [7]. In PV planning and simulation tools, limited tools are specifically designed for BIPV simulation esp. for buildings with complex designs. Existing standalone PV toolkits, such as System Advisor Model (SAM); RETScreen; Expert Homer Pro; PV*SOL Expert; PVsyst; Helios and Polysun are initially developed for ground-mounted PV systems. Some of these tools contain features suitable for simulating rooftop or Building Attached Photovoltaic (BAPV) system scenarios. Official overviews of these tools do not confirm their suitability for simulating complex BIPV designs. BIMsolar is a standalone tool specifically developed for BIPV and supports simple BAPV and complex BIPV designs. It is important to understand how these standalone tools integrate with architectural thinking [8], and effectiveness to evaluate BIPV designs.

In the case of BIPV, modelling and forecasting are more complex than in traditional PV systems. BIPV systems often comprise modules facing diverse directions and are frequently partially obscured by surrounding obstacles, leading to increased shading effects [9]. Additionally, depending on the installation situation, the ventilation of the BIPV modules is often poorer compared to ground-mounted or roof-top PV power plants, which results in significant temperature fluctuations within the BIPV system [10]. Based on the review of the tools to design and model BIPV systems by IEA PVPS Task 15 [11,12], the current software packages may not be entirely suitable for simulating BIPV systems, and their capability need a comprehensive evaluation.

BIPV design tools represent an inevitable resource for the digital value chain creation that all stakeholders rely on. Moreover, capabilities of tools have a profound impact on quality and reliability of designed BIPV systems. Therefore, assessing and validating their capabilities, as well as proposing areas for improvement may have substantial influence on future BIPV design and implementation speed and quantity. Also, it is crucial to acknowledge that variations exist in assumptions, algorithms, modelling capabilities, input data, and settings among different tools.

Some researchers have conducted systematic studies on the comparison of commercial PV simulation packages. Axaopoulos et al. [13] performed a comprehensive analysis focused on a ground PV power plant, evaluating six tools: TRNSYS, Archelios, Polysun, PVsyst, PV*SOL, and PVGIS. Comparative work on rooftop PV systems was conducted by Milosavljevic et al. [14]. They compared monitored data of a rooftop PV system with estimates from various PV simulation tools, including PVGIS, PVWatts, SolarGIS, RETScreen, BlueSol, PVsyst, HelioScope, PV*SOL, Solarius PV, Solar Pro, PV F-Chart, PolySun, SAM, and HOMER. Buzra et al. [15] validated and compared PV systems installed on the roof of an industrial building with three different simulation packages: SAM, RETScreen and PVsyst. The available studies primarily focus on comparing outcomes related to energy production and solar irradiation, rather than assessing the capabilities and limitations across different simulation tools. Additionally, previous works primarily focused on ground-mounted PV plants or rooftop- PV systems.

To fill in the research gaps mentioned above, this study aims to model complex BIPV systems using different tools among the most relevant available on the market, investigating their capabilities and limitations, and suggesting potential ways forward and recommendations, rather than focusing on the accuracy of the simulation results of these different tools. The decision not to delve into an in-depth investigation of each tool's accuracy stems from inherent limitations in the source of the field data for the BIPV system under study. These limitations render it challenging to obtain a highly precise validation of each simulation step's accuracy. Consequently, the comparative analysis conducted in this research should be interpreted as providing informative insights rather than serving as a decisive judgment on the superiority of any particular tool.

Eight tools (i.e. PVsyst Version 7, SAM, Solarius PV, PV*SOL, BIMsolar, INSIGHT for Revit, Skelion for Sketchup, Ladybug Tools for Grasshopper/Rhino) are selected for simulation. These tools cover both BIM-based plugins and standalone PV design platforms, and are popular platforms as identified by a global survey conducted by the IEA PVPS Task 15 [16]. They are also the most widely used in the market. Therefore, a survey based on these tools offers a reasonably good overview of the typical pros and cons of the state-of-the-art tools currently used for BIPV modelling. The simulation works are conducted based on the BIPV roof, façade and canopy installations on a complex shaped building situated in the city of Zhuhai, China, which is introduced in Section 2. The advantages and limitations in the simulation process are explained in Section 3. Then the simulation results are displayed with deviation metrics in Section 4, where the names of the tools are anonymized to preserve objectivity and prevent any undue bias. Discussion about the tools, and suggestions for future BIPV digitalised simulations are presented at the end.

2. Case Information

The investigated grid-connected BIPV systems are installed on a multi-story office building with a height of 70.35 m located in Zhuhai, China. There are no other tall buildings in the near vicinity that could cast shadows on the case building. The exact geographical coordinates of the installation site are 22°23′19.7″N 113°32′50.9″E. Fig. 1 shows the aerial view of the skyscraper and its BIPV systems.

The project is a demonstration for ultra-low energy buildings in China. The office building has three PV subsystems: a multi-functional BIPV façade, a BIPV roof shading system and a double-layer BIPV canopy. All three subsystems are outfitted with custom sized monocrystalline silicon PV modules. Fig. 1 illustrates the array configuration diagram of the three subsystems. The PV system on the roof consists of 308 PV modules with 245 W nominal power, tilted 5° to the West. These modules are connected to three inverters. The façade system, characterized by a complex geometry, integrates 714 PV modules with 172 W nominal power, installed on a curved façade. The façade system is connected to five inverters. The canopy system consists of 78 PV modules with 192 W nominal power, connected to a 12-kW inverter. Table 1 shows the specifications of the three BIPV subsystems. They are

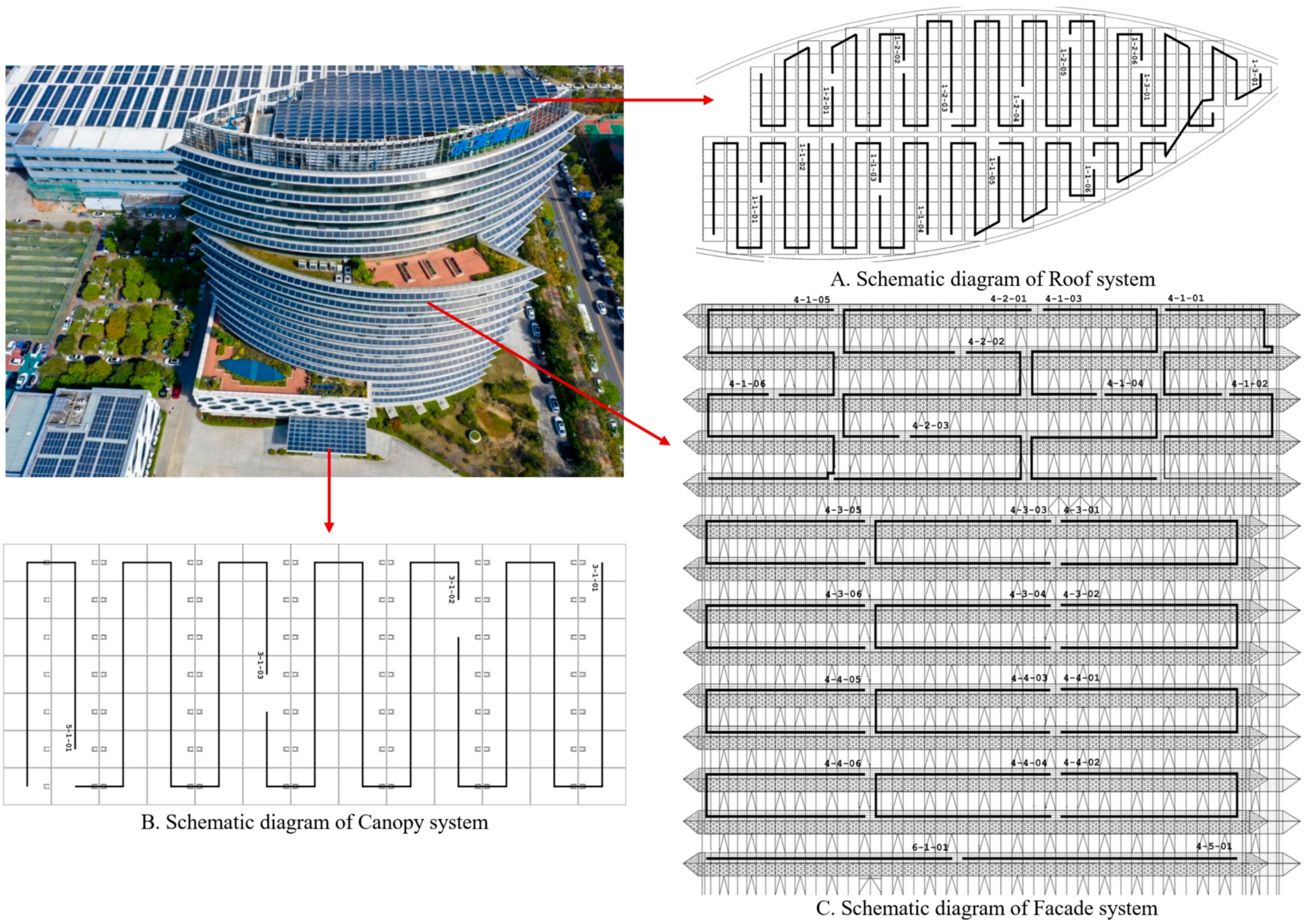


Fig. 1. Schematic diagram of the three BIPV subsystems.

complemented by a monitoring platform to record the energy yields. However not the full installed power is monitored, but a partial system-monitoring is carried out as described in Table 1. The monitored data used in Section 4 spans a 12-month monitoring period from January 2020 to December 2020.

3. Cross-tool comparison of bipv system modelling and simulation processes

To model and analyse the BIPV system performance, this study employs eight tools as explained in the Introduction section. The modelling and simulation process is divided into seven key steps. Appendix 1 contains a table to compare the capabilities of the tools in the simulation process.

3.1. Building geometry modelling

When modelling BIPV systems into the building envelope and simulating their energy performance, the initial step involves creating or using a created three-dimensional (3D) building model. This 3D model enables users to visualize the BIPV integration directly within the building model. For the BIPV system design and simulation process, users rely either on tools with robust 3D modelling capabilities, such as Skelion, Ladybug Tools, and INSIGHT's host platforms used in this study (see Fig. 2), or on importing a 3D model created by design software. For this purpose, a model conversion process is required, involving the export of the 3D model file from the building modelling tool and subsequent importation into a PV simulation tool.

The interoperability of software regarding 3D model generation, export and import options into different PV tools strongly varies, primarily due to differences in file formats, modelling methods, and data structures among the eight assessed tools. For instance, tools such as BIMsolar and Solarius PV, which are BIM-based, support importing IFC files. On the other hand, standalone PV tools like PVsyst and PV*SOL are compatible with COLLADA (.dae) format files, which can be exported from Sketchup and Rhino. Only SAM among the tools analysed in this study does not support the import of 3D models. Detail and quality of imported models also varies. During the export and import of 3D models, issues such as information loss, mesh simplification, and geometric distortion may occur. For example, when COLLADA files are imported into PV*SOL, the model shows distorted and unclosed surfaces. Additionally, when importing the model, it is important to verify that the coordinate system of the imported model correctly aligns with the simulation environment of the PV tools. For example, when PVsyst receives COLLADA files exported from Rhino, the model needs to be rotated 180° in Rhino in advance. The correct orientation – especially of a curved building – is not always easy to control in the tools. Consistent orientation and alignment are vital for accurately positioning components and shading analysis.

3.2. Weather data and solar resource inputs

When simulating PV systems, the weather data input significantly influences the final simulation outcomes. Typically, there are two primary methods for incorporating weather files. The first method utilizes the built-in weather database within simulation tools, which selects weather data from the nearest weather stations based on the project's geographical location. These files are commonly in Typical Meteorological Year (TMY) format, which aggregates measured weather data from a period of 20 years to a TMY. Alternatively, with specific tools,

Table 1
Electrical description of each subsystem.

System Location Total system installed power		Roof 75.46 kW	Canopy 14.976 kW	Façade 122.808 kW
Total number of PV modules		308	78	714
Monitored power		48.51 kW	9.984 kW	88.236 kW
PV module electrical specifications at standard test conditions (data sheets)	Maximum Power, *Pm*	245 W	192 W	172 W
	Open circuit voltage *Voc*	37.4 V	29.28 V	26.8 V
	Short circuit current *Isc*	8.76 A	8.54 A	8.86 A
	Voltage at the maximum power point *Vmp*	30.2 V	24.48 V	21.4 V
	Current at the maximum power point *Imp*	8.11 A	7.84 A	8.08 A
PV sub-array configuration	Number of sub-arrays and module configuration (s: series, p: parallel)	3 sub-arrays (22 s x 6p, 22 s x 6p, 22 s x 2p)	1 sub-array (26 s x 3p)	5 sub-arrays (32 s x 6p, 29 s x 3p, 34 s x 6p, 34 s x 6p, 26 s x 1p)
Inverters configuration	33 kW inverter	1NV1-1# inverter, 1NV1-2# inverter	—–——	1NV4-1# inverter, 1NV4-3# inverter, 1NV4-4# inverter
	17 kW inverter	—–——	—–——	1NV4-2# inverter
	12 kW inverter	1NV1-3# inverter	1NV3-1# inverter	—–——
	8 kW inverter	—–——	—–——	1NV4-5# inverter

users can import weather files from external sources, offering greater flexibility in weather data selection. Beyond TMY files, this function allows for incorporating on-site monitored meteorological data or even future forecast meteorological data.

In practice, simulation of PV yield during the project planning phase is relying on weather data of the past instead involving predictions into the future. Currently, energy simulations are typically conducted using TMY weather files [17]. Although the past long-term average annual solar radiation may differ from actual climate values [18], leading to disparities between generated and measured data, it aligns with the real industry practice. Therefore, in this study, due to the incorporation of the Meteonorm 8.1 weather database into SAM, PVsyst, and PV*SOL, and the capability of Skelion, BIMsolar, and Ladybug Tools to import external weather files, it was decided to use Metronome 8.1 weather data for these tools. The nearest station to the building's location in Meteonorm 8.1 database is Xiangzhou, which is about 50 km distance from the building's location. The weather measurement period spans the years between 1996 and 2015. Solarius PV and INSIGHT for Revit use their built-in weather databases, namely Meteonorm 7.1 and Autodesk Climate Server because they cannot import weather files. To illustrate the limitations of using TMY to predict power generation during project planning, we include the comparison monthly global horizontal irradiation data (*GHI*) of Meteonorm TMY with measured data by Solcast [19], a provider of satellite-based global weather data, for the year 2020 in Fig. 3.

Since the Autodesk's weather file are difficult to be exported, it is not included in the comparison. The Meteonorm 8.1 TMY weather file, utilized by most tools in this study, indicates a GHI of 1387 kWh/m2/year, and Solarius PV's Meteonorm 7.1 a GHI of 1376 kWh/m^2/year. In contrast, Solcast reports a significantly higher solar radiation amount for the year 2020, at 1487 kWh/m^2/year. Due to climate change and environmental changes weather patterns might be a subject of change. The measured data from Solcast shows about 7 % higher GHI-irradiation for the year 2020 than the Meteonorm average TMY, while Solcast itself names estimates the standard deviation for annual GHI measurement for all sites worldwide to be within +/- 2.47 % [19]. This discrepancy highlights the disparity between the use of TMY data and actual solar irradiance data for one specific year. Differences between the TMY weather data files provided by professional databases, which are commonly used for planning and simulation of PV and BIPV systems, and the actual data for single years cause significant uncertainties. This is a recurrent problem in PV system simulation. This study aimed to minimize the impact of this uncertainty on the comparison between simulations carried out with different tools by using the same Meteonorm 8.1 weather data input for tools that can use it. Nevertheless, differences in the treatment of weather data between tools might account for a significant portion of the observed solar yield differences. Since there was no scientifically measured on-site weather data for the year 2020 at the building's location, this study does not aim to determine which tool is the most accurate at predicting PV energy yield. Instead, it presents the typical differences that occur between different tools even after attempting to normalize and homogenize all the input parameters as much as possible.

3.3. PV module and inverter data inputs

PV modules and inverters are the foundational components of solar

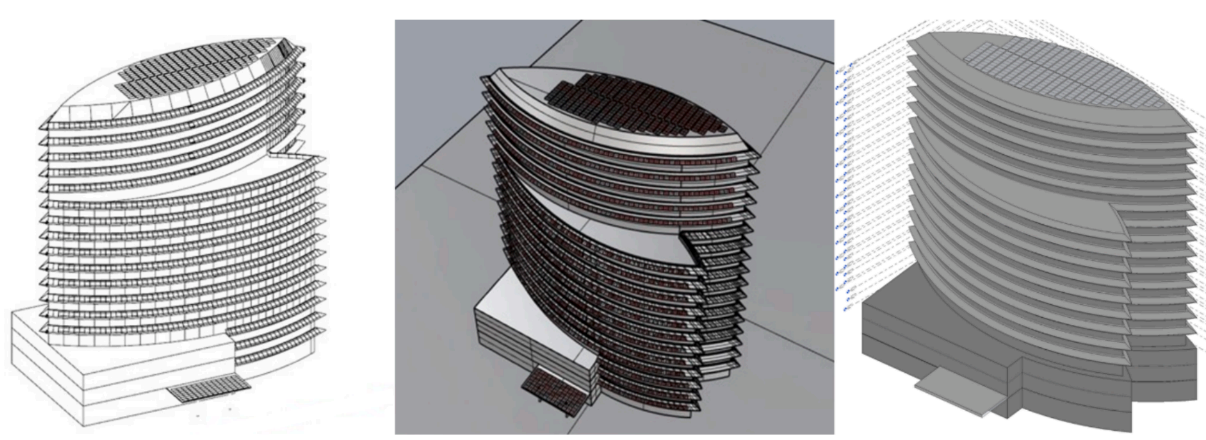


Fig. 2. Different 3D models of the building.

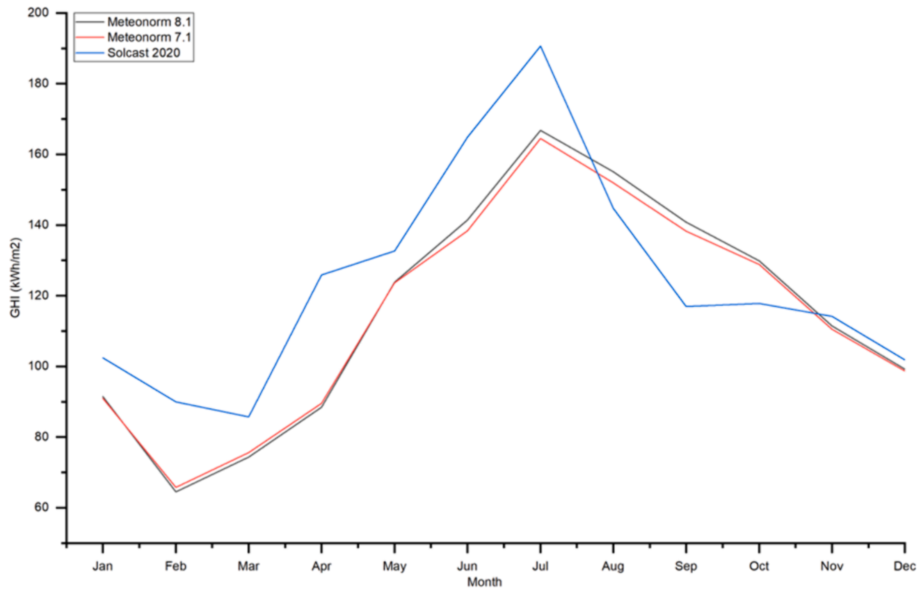


Fig. 3. Monthly GHI data comparison between measured data of Solacast for 2020 and Meteonorm TMY.

PV power generation systems, and accurately inputting their technical parameters is crucial for PV system simulation [20]. Standalone PV tools typically feature extensive PV modules and inverter libraries, allowing users to select specific models from these databases. However, the comprehensiveness and availability of these libraries vary significantly. Only BIMsolar's component database is specific to BAPV and BIPV products.

In the case of BIPV systems, components often require high levels of customization. For instance, the components used in this study's project are customized and not available in standard libraries. In such scenarios, users can create custom components by inputting their parameters through built-in editors. PV*SOL, Skelion, SAM, BIMsolar, and Solarius PV offer this functionality, though Skelion's component parameters are relatively simplified, and often limited to represent power rating parameters.

PVsyst and PV*SOL allow users to import PAN and OND files, which are exchange formats for PV-modules (PAN) and inverters (OND). For this study, the custom PV-modules specific user-defined module data sets were represented by basic tables in the project documentation, which was used to create PAN-files and OND-files to provide the same input data. However, it is worth noting that project documentations, as it was the case in this study, might not always provide all necessary component specifications for simulations, such as temperature coefficients of Isc and Voc, or the thickness and weight of PV panels. In such cases, assumptions are made based on similar modules. PV*SOL accepts PAN and OND files created by PVsyst, but it's essential to acknowledge that PAN files may lack certain parameters required by the PV*SOL model, such as the information of bypass diodes or the solar cell-string direction within the module. In this case, assumptions were made based on similar modules when data is incomplete for PV*SOL.

Unfortunately, Ladybug Tools and INSIGHT, constrained by their limited detailed electrical modelling capabilities, do not support user-defined input of PV system components' detailed specification.

3.4. System layout and array configuration

To examine the modelling capabilities of each tool, for this study, the layout of the BIPV system and the interconnections between modules should be modelled based on the electrical design drawing of the system. The PV modules are arranged on the surface of the building with specified inclination and azimuth angles, and the interconnection between the modules and the connections between module strings and inverters are defined.

In Ladybug Tools and INSIGHT, the layout of PV modules depends on their respective host platforms, making the design of BIPV component layouts straightforward. Rhino represents PV panels as 'surface', while Revit utilizes 'mass' elements. However, neither platform defines the electrical behaviour between strings during this process.

For standalone PV tools, the module layout process involves secondary design since they cannot inherently recognize PV modules within imported 3D models. Thus, the architectural model serves as the 3D-template for 'attaching' modules to geometric surfaces. However, the complexity of façade geometry, especially curved surfaces with unique orientations for each row, presents challenges for placing PV modules in standalone PV tools.

Some tools offer visual and interactive module arrangement processes, facilitating swift design and setup of PV panels using 3D modelers. Solarius PV, for instance, allows users to design multiple 'PV fields' individually on the building surface, each containing 6 or 7 modules. Similarly, PV*SOL enables users to create 'PV fields' atop the existing building model surface to place PV modules. BIMsolar, operating in its 'BAPV' mode in this case, requires the creation of groups of 2/3/4 modules to complete the module layout on the geometrical surfaces of the façade, one-piece layouts for the roof and canopy. Skelion, functioning independently of the host platform, places PV panels by creating 'groups' on the model's geometrical surfaces, like BIMsolar's approach. In contrast, SAM and PVsyst do not offer visualization or interactive processes for module arrangement.

When defining an array configuration, standalone PV tools have limitations on the number of orientations of the modules within a string. To address this limitation, the different azimuth angles corresponding to the unique curvature of the façade are averaged into a total of eight different orientations by PVsyst. SAM's restrictions are even more stringent, allowing up to four subarrays in a simulation. Therefore, for SAM, the eight parts of the façade are further divided into two sets, each handling four subarrays, to achieve a comprehensive modelling of the façade system. However, these measures cannot model 100 % of the strings as given by the skyscrapers façade PV-system. Consequently, the string and inverter layouts have to undergo a redesign process. In the case of PVsyst, the inclusion of inverters with diverse capacities is necessary to enable the seamless execution of the entire simulation process. For SAM, the assignment of different inverters to distinct subarrays is not supported. Hence, a crucial step involves choosing the appropriate inverter for the façade system from SAM's internal database. Due to problems with placing “PV fields” on the curved surface and the difficulties of the 3D-model import for PV*SOL, a sensitivity study was carried out to show that the biggest yield difference is not between the different orientations in the façade but between top rows and partially shaded middle rows in the façade. Therefore, for PV*SOL, it is decided to model only a few mini strings in the middle field with module inverters and calculate from those the potential yield of the overall monitored modules of the façade system.

3.5. POA irradiance and shading evaluation

Simulating solar irradiance accurately on the plane-of-the-array (POA) is essential for reliable PV system simulation outcomes. The global irradiance reaching a tilted surface consists of three parts: direct, diffuse, and ground-reflected irradiance [21]. During our study, we faced a notable challenge: the models used for calculating irradiance on the POA, taking into account both distant and nearby shading as well as albedo effects, are not all transparently disclosed. The owners of these models often keep the details confidential to protect their intellectual property rights on their unique algorithms and calculation methods. The value of ground albedo in this simulation study is set to 0.2, which is a common default value [22].

Most standalone PV toolkits simulate irradiance on inclined surfaces from any direction by initially using global irradiance. They employ decomposition and transposition models to determine the irradiance on the plane-of-the-array (POA) [23]. Various decomposition models are popularly used to break down the global irradiance into its solar components. Subsequently, transposition models calculate the POA irradiance from its horizontal value for each of these components. PV*SOL offers a selection of transposition models. For this study, the Hay and Davies model [24] is selected. Skelion, SAM, and Solarius PV are all based on the Perez model [25]. PVsyst proposes either the Hay and Davies or the Perez model. For this study, the Perez model was used to align with most other tools used.

For BIPV, the analysis of partial shading is a key factor affecting the simulation results. In this study, external shading is excluded from the simulation due to the absence of tall buildings near the skyscraper. However, the complex geometry of the BIPV system on the building façade results in a significant amount of self-shading. Additionally, the canopy system located in the low area of the building is affected by shadows caused by the building itself. Furthermore, the roof modules may face mutual shading between each other during flat standing west sun.

Most existing tools that include shading analysis typically rely on two general approaches to simulate the shading geometry. The first approach involves the use of projection algorithms, view factors, or numerical methods. This method is effective for simulating a 3D scene as long as the scene is composed of a sufficiently low number of polygons [26]. PVsyst, Skelion, and PV*SOL can perform 3D shading analysis based on imported 3D models and visualize the shading factor for each PV module or area. PV*SOL takes the partial shading of solar modules into account in relation to the cell string direction within the module and visualizes on demand the shade percentage on the modules surface. SAM utilizes built-in plotting functions to draw 3D shapes and simulate irradiance loss through a shadow calculator. Solarius PV allows users to visually evaluate the effect of shadows on PV modules but shading factors need to be manually set in a table, based on experience of the user or other simulation results.

The second approach employs ray tracing algorithms, which are capable of handling very complex shading scenarios. The computational resources required by these algorithms depend on the number of rays that need to be traced. This number increases significantly with the desired accuracy and the complexity of the scene. Ray tracing is considered a technology that can better handle radiation simulation under complex partial shading conditions [27]. BIMsolar, Ladybug Tools, and INSIGHT are based on geometric ray tracing. BIMsolar uses its genuine ray tracing core based on Monte Carlo ray-tracing method to simulate solar radiation interaction with complex urban environments, notably its effects, including the total irradiance components (direct, diffuse, reflected) distribution on each geometrical surface, on each module, and overall dissipated power contribution for every time step. Ladybug Tools utilizes the backward ray tracing tool RADIANCE as simulation engine, while BIMsolar adopts a hybrid approach combining ray tracing with rasterization. Similarly, INSIGHT utilizes a hybrid methodology combining ray tracing with radiosity. Ladybug Tools set a grid size with 1x1m to define the test points on the surface, representing the number of virtual sensors required for backward ray tracing. Ray tracing technology tracks the path of light through a scene, considering the interaction of light with objects in the scene, and automatically accounting for the effects of shadows [28]. Therefore, the irradiance simulated by ray tracing technology represents the irradiance received by the surface of the PV panel, without the need for correction by superimposing shadow factors. In addition, all three tools can visualize irradiance simulation results in 3D model.

A third alternative is also emerging, but it is out of the scope of this study. Today, virtually all graphics systems are equipped with a specialized Graphics Processing Unit (GPU) designed to perform specific graphics functions efficiently. Among the key features offered by GPUs is rasterization, the process of converting vector graphics into a grid of pixels or dots for display on a screen or for printing, which enables the simulation and visualization of shadows resulting from the complete obstruction of the direct component of solar irradiance [29].

3.6. PV energy conversion simulation

The energy output simulation of PV systems depends on the PV performance model used, which can be categorized into empirical models and physical equivalent models. Additionally, PV energy generation can be calculated using analytical formulas.

The physical model is based on a single or two-diode equivalent circuit to predict the PV module’s current–voltage (IV) curve and obtain the system’s output power [30]. To depict the operation of a PV module, SAM, PVsyst, and BIMsolar employ single diode models, whereas PV*SOL utilizes the two-diode model for c-Si modules. For the equivalent circuit model, the tools require more parameters of the PV module to be entered [31].

On the other hand, empirical models describe maximum power values under actual working conditions [32]. Solarius PV’s power generation simulation and Skelion’s built-in models are based on empirical models. They estimate PV power output using POA irradiance and conversion efficiency under standard test conditions (STC) combined with temperature correction [33]. However, system losses for Skelion and Solarius PV are based on empirical inputs.

For Ladybug Tools and INSIGHT, the geometric-based analysis workflow does not model the electrical behaviour of the entire PV system. Instead, the PV system is represented by a series of planar surfaces at their original positions, and Ladybug Tools and INSIGHT act as solar irradiance simulation tools. In this study, the incident solar irradiance simulation results of Ladybug Tools are based on hourly time steps, while INSIGHT is based on monthly. The energy yield is calculated by Eq. (1) [34].

$$E_p = P^* \frac{H_T}{G_{STC}} {}^*PR \tag{1}$$

Where, ‘P’ is Monitoring System capacity (kW); ‘H_T’ is the total solar radiation on the modules surface (kWh/m2); ‘G_{STC}’ is the solar irradiance in standard test conditions (kW/m2); ‘PR’ is Performance ratio of the PV system.

3.7. PV system losses

Simulating energy loss in a PV system is inherently complex, but considering all contributing factors is crucial for designing and installing a properly sized system and to determine the solar yield. Tools based on the equivalent circuit model in this study typically incorporate functions for simulating PV system losses.

For BIPV systems, two significant loss mechanisms merit attention. The first is electrical mismatch loss stemming from uneven irradiance across the array due to different orientation or due to partial shading. PVsyst, BIMsolar, and PV*SOL offer capabilities to account for series mismatch losses during simulation. Another critical mechanism is temperature loss, as PV system performance declines with increasing PV cell temperature. Thermal modelling of BIPV modules considerably impacts the PV systems' yield predictions [10]. SAM, PVsyst, BIMsolar, and PV*SOL have built-in temperature models to evaluate the modules' temperature, an essential input parameter for the equivalent circuit model. However, given the typically limited space behind BIPV cladding systems, ventilation is often limited, resulting in higher module temperatures [35]. In general, accurately assessing the temperature of BIPV arrays poses a challenge; temperature models for ground-mounted PV plants may not adequately simulate BIPV module temperatures [36]. PV*SOL offers for that reason to choose between free-standing green fields, roof-top, and built-in PV modules. Additionally, simulation tools can take into account other losses, such as the ohmic losses of wires. PVsyst and PV*SOL can consider more losses, such as Incident Angle Modifier (IAM) and spectral losses. They also offer options for setting some losses manually. For instance, in this study, module mismatch loss and soiling loss are set to be 2 % and 1 %, respectively in all PV subsystems.

For tools unable to directly simulate system losses, the setting of system losses relies on user experience or outputs from standalone PV tools. Skelion and Solarius PV offer tabs for manually entering system losses. INSIGHT and Ladybug Tools require estimated loss values to be applied in calculations. PVsyst can break down and provide detailed outputs of losses in various parts of the entire system. Therefore, the system losses for Skelion and Solarius PV's manual input, as well as Ladybug Tools and INSIGHT's yield calculation are derived from PVsyst losses simulation results, resulting in 19.8 % for the roof, 23.5 % for the canopy, and 27.0 % for the façade.

Overall, to minimize the sources of uncertainty affecting the comparison between simulations using different tools, input parameters such as weather data, PV module key specifications (shown in Table 1), and case array configurations (shown in Fig. 1) were consistent as much as possible during the simulation process. However, each tool has its own function features and limitations that lead to obstacles in maintaining consistent input. The detailed simulation process summarize table between tools is shown in Table 2.

4. Results and deviations analysis

Based on the simulation process, the corresponding functionality comparison of the eight tools is shown in Appendix 1.

Statistical metrics such as Relative Deviation, Mean Bias Deviation (MBD), and Root Mean Square Deviation (RMSD) have been used to assess the deviation of the eight simulation tools results to the monitored data. MBD provides insights into the direction of the deviation, where negative values indicate underestimation and positive values signify overestimation. Smaller RMSD values indicating that the simulated results are more consistent with the measured data. MBD and RMSD are annotated as rMBD and rRMSD to facilitate the interpretation of results [37]. These indicators have their own limitations. It is essential to supplement them with analysis by examining the patterns of the monthly energy output curves.

Table 2
Summary of the simulation process in each tool.

Steps	Skelion	SAM	PVsyst	BIMsolar	Ladybug Tools	PV*SOL	Solarius PV	INSIGHT
Building geometry modelling	Create 3D Model	Create simplified 3D Model	Import 3D Model in COLLADA format	Import 3D Model in Skp format	Create 3D Model	Import 3D Model in COLLADA format	Import 3D Model in IFC format	Create 3D Model
Weather data inputs	Input from Meteonorm 8.1	Built-in Meteonorm 8.1	Built-in Meteonorm 8.1	Input from Meteonorm 8.1	Input from Meteonorm 8.1	Built-in Meteonorm 8.1	Built-in Meteonorm 7.1	Built-in Autodesk Climate Server
PV module and inverter data inputs	Manual input PV module power rating	Manual input detailed specifications	Input detailed specifications via PAN/OND files	Manual input detailed specifications	No input	Input detailed specifications via PAN files and inverter template	Manual input detailed specifications	No input
System layout and array configuration	Reposition but not define array configuration	Reposition and reconfigure façade system array	Reposition and reconfigure façade system array	Reposition and configure case system array	No array configuration defined	Reposition and reconfigure façade system array	Reposition and configure case system array	No array configuration defined
POA irradiance	Perez model	Perez model	Perez model	Ray tracing	Ray tracing	Hay & Davies model	Perez model	Ray tracing
Shading evaluation	Shading factor analysis based on building geometry	Shading calculator based on simplified geometry	Shading factor analysis based on building geometry	Ray tracing	Ray tracing	Near shade calculation based on building geometry	Manual input shading factor	Ray tracing
PV energy conversion simulation	Built-in empirical model	Built-in equivalent circuit model	Built-in equivalent circuit model	Built-in equivalent circuit model	Calculation based on formula	Built-in equivalent circuit model	Built-in empirical model	Calculation based on formula
PV system losses	Manual input based on PVsyst results	Simulation	Simulation	Simulation	Manual input based on PVsyst results	Simulation	Manual input based on PVsyst results	Manual input based on PVsyst results

$$MBD = \frac{\sum_{i=1}^{n}(S_i - M_i)}{n} \quad (2)$$

$$rMBD = \frac{\sum_{i=1}^{n}(S_i - M_i)}{\sum_{i=1}^{n}(M_i)} \quad (3)$$

$$RMSD = \sqrt{\sum_{i=1}^{n}(S_i - M_i)^2/n} \quad (4)$$

$$rRMSD = \frac{\sqrt{\sum_{i=1}^{n}(S_i - M_i)^2/n}}{\overline{m}} \quad (5)$$

Where, 'M_i' is the monitored value of power generation; 'S_i' is the simulated value from each tool; 'n' is the number of observations and '$\overline{m}$' is the average value of all monitored data.

As mentioned in section 3.2, it is noted that TMY data can obviously be exactly identical with on significantly differ from the irradiation conditions of the yield-monitoring year 2020. This study focuses on the results based on the Meteonorm 8.1 TMY data and cannot be universally applied to results based on other weather data. In the following result analysis section, the names of tools are anonymized, and the number and colour of each tool are consistent in all displayed figures. Tools 1 to Tool 6 all use the Meteonorm 8.1 TMY weather file.

4.1. Annual analysis

Fig. 4 illustrates each tool's annual energy yield simulation results and 2020 monitoring data. It also depicts the relative deviation compared to the monitored solar power generation in 2020. The annual results are expressed in kWh/kW to facilitate comparison across the three BIPV subsystems. The red line represents the actual energy generation of the three BIPV subsystems.

The maximum differences of the simulated yields between the eight tools for the BIPV-systems compared to the measured yield of 2020 as 100 % are as shown in Fig. 4 (i.e. Roof: 12,38 %, Façade: 25.77 %, Canopy: 16.25 %). When assessing the simulated PV energy yield of the rooftop system, all tools exhibit reasonable results, with a deviation rate of less than 10 %. Notably, the discrepancies between simulation results using Meteonorm 8.1′s tools are insignificant for the rooftop PV system. Conversely, the performance of the canopy system's annual results diverges due to shading effects, with one tool showing annual relative errors exceeding 10 %. There is a considerable disparity in the simulation results for canopy systems when using Meteonorm 8.1 tools,

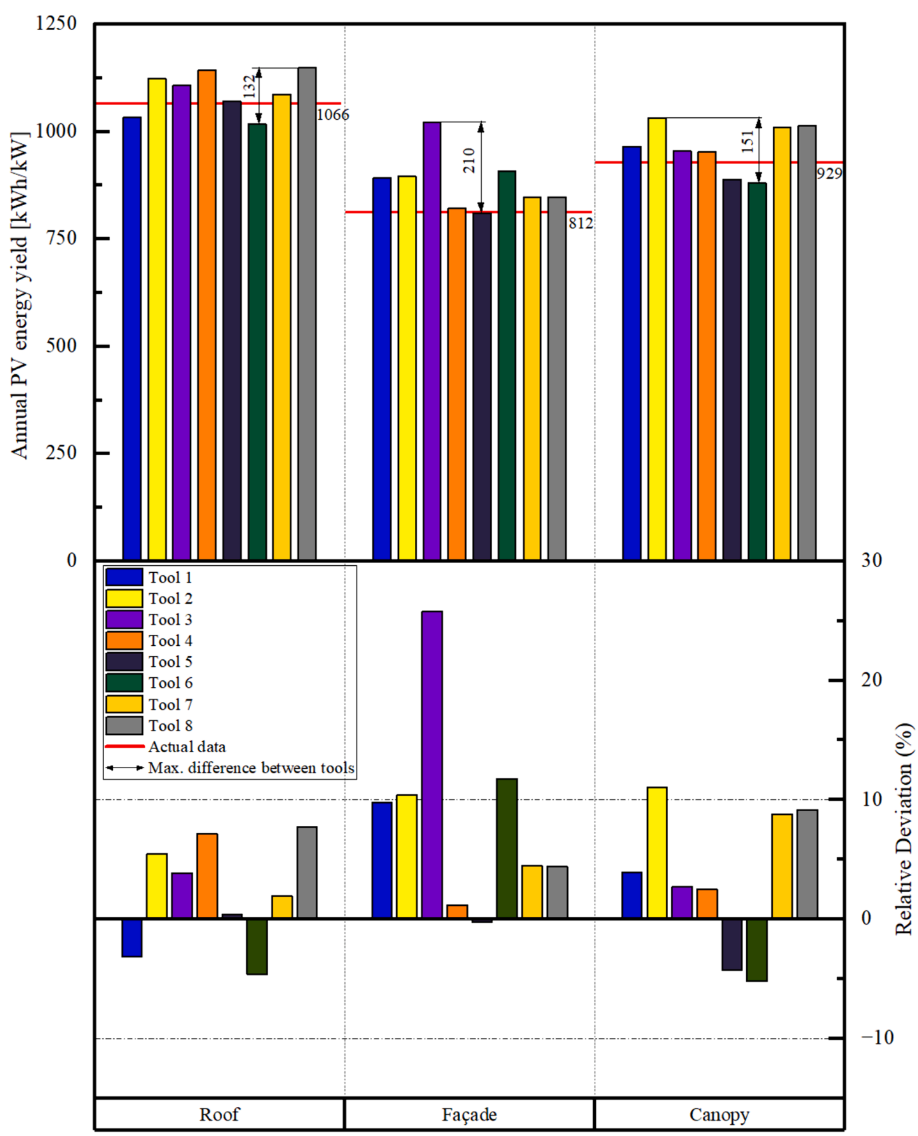


Fig. 4. Cross tool comparison of annual PV energy yield simulated with TMY-data and measured yield of 2020 values for three systems.

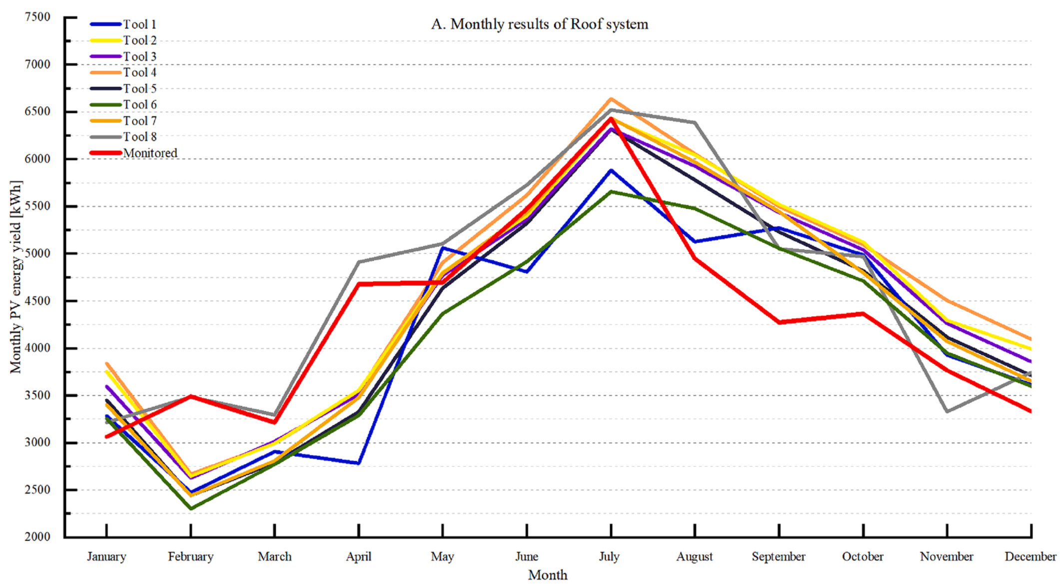
attributed to differences in shadow handling.

Due to the significant self-shading effect of the south-facing folded façade, the façade system's results reveal significant variation among the results of the eight tools. It is worth noting that the deviation of the results of Tool 5 is very small, at 0.2 %. Although this result is calculated based on Eq. (1), as no secondary design is required, Tool 5 shows reasonable results compared to other tools also using the same weather file. Furthermore, Tool 5 demonstrates relatively close results across all three systems, indicating its proficiency in handling diverse scenarios, including complex partial shading, because accurate simulation of irradiance is fundamental for the entire simulation process.

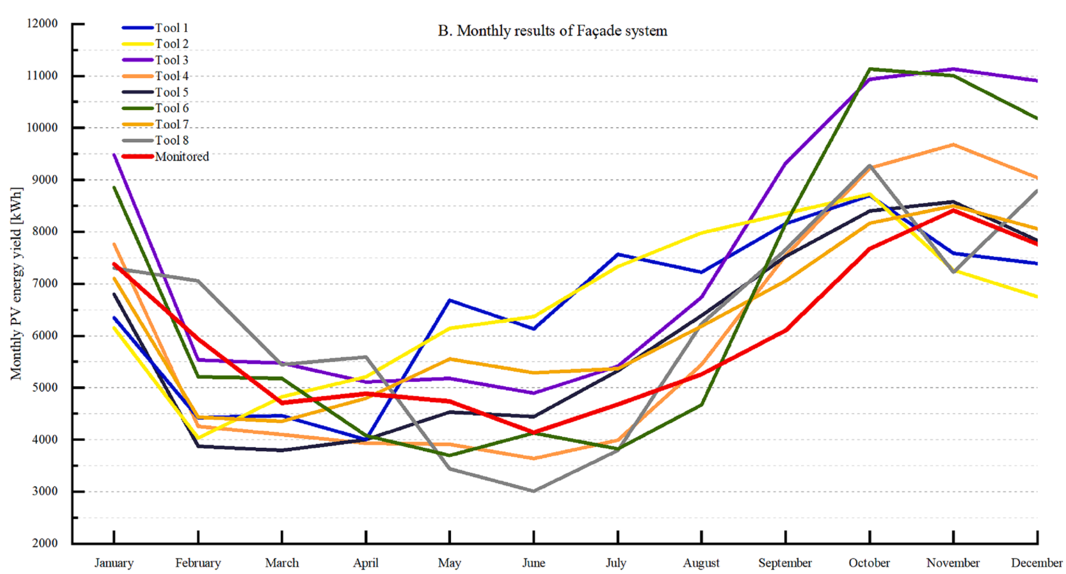
4.2. Monthly analysis

Fig. 5 a, b and c are displaying the monthly PV energy generation of both monitored and simulated data. Fig. 6 shows the statistical results of monthly results. Consistent with the annual results, all tools provide acceptably close results to the simulation results for rooftop systems. For canopy systems, one tool fails to provide reasonably acceptable simulation results, indicating that this tool may be less suitable for modelling the PV output of canopy systems with shading. For the façade system, based on indicators and combined with analysis of monthly curve trends and patterns, three tools provided simulation results that are close to the monitoring data, and they are BIM-based tools.

The comparison revealed the simulations for the façade differ the most from the monitored data. The differences associated with the transposition of solar irradiance can be much greater on such a vertical surface. A primary factor contributing to the notably greater discrepancies in predictions made by transposition models for vertical surfaces, compared to low-tilt surfaces, is the substantial contribution of diffuse

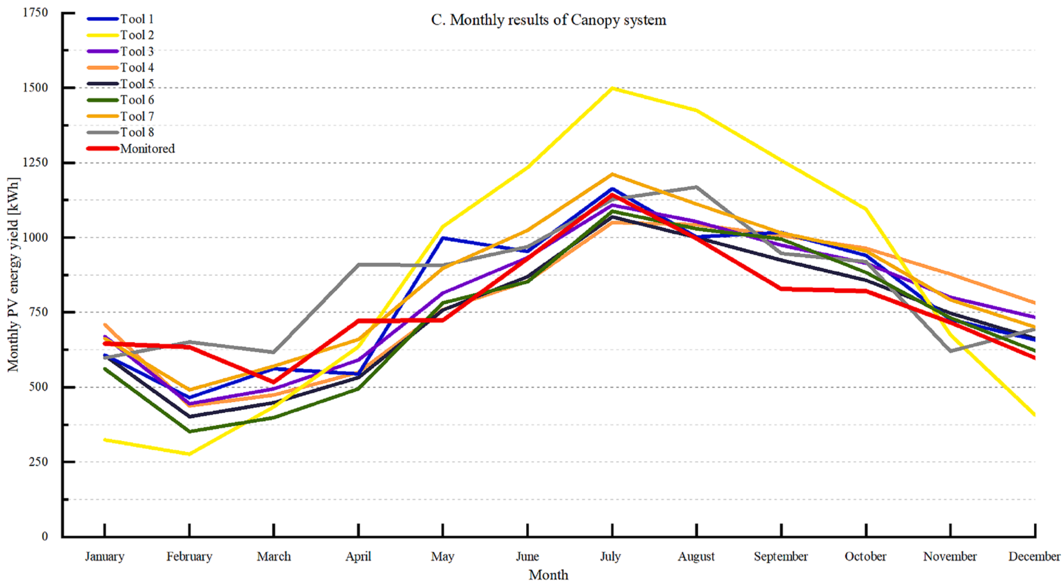


(a) Roof system



(b) Façade system

Fig. 5. Monitored and simulation monthly values of three systems.



(c) Canopy system

Fig. 5. (*continued*).

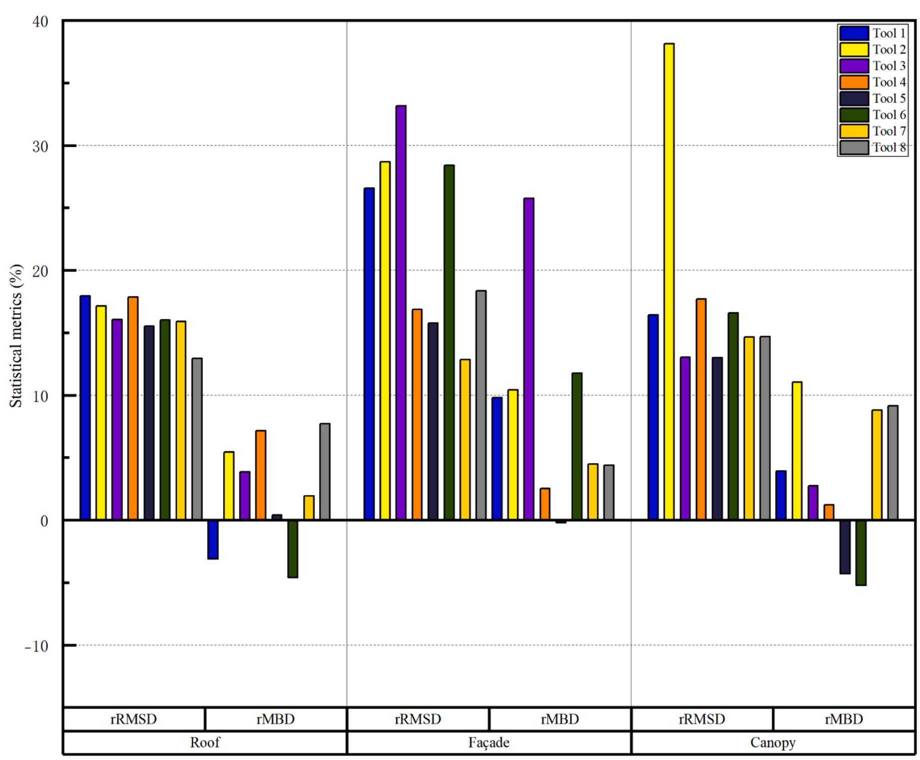


Fig. 6. Statistical metrics of Monthly results.

radiation reflected from the foreground or other surrounding objects. This reflected component can constitute a significant, and occasionally the dominant, portion of the total diffuse radiation (both skyward and reflected) incident on these surfaces. To date, most transposition models have not adequately addressed the quantification of diffuse reflected irradiance, with only a few exceptions noted, such as those documented in [38]. Façades are also often affected by a significant amount of complex shading, which, on the one hand, causes a decrease in solar irradiation and, on the other hand, increases electrical mismatching losses due to partial shading phenomena that provoke inhomogeneous light distribution on the PV cells.

Several factors contribute to the complexity and sensitivity of this shading effect analysis, which is a crucial point for BIPV. The site's latitude is close to the tropics, leading to smoother seasonal shading profiles than at higher latitudes. The system's geometry results in partial shading on many days throughout the year. Although this partial shading is relatively small in geometric terms, it causes significant electrical losses. It is because when approximately 10 % of a module is shaded, at least one-third of the module ceases to produce energy. This scenario occurs frequently during the summer when the sun is higher and the irradiation is greater, resulting in substantial PV energy losses due to partial shading. Given the case modules, each barely over 1 m high, every centimetre in the 3D shading model is critical. A few centimetres can determine whether a significant portion of the PV output is lost, which illustrates the importance of high-quality 3D models containing BIPV modules. However, when importing the complex curved 3D model, mesh simplification and geometric distortion usually occur. Furthermore, since the case has a curved façade with various inclinations, some PV tools face difficulties and limitations in simulating BIPV on this curved façade, resulting in the reconfiguration of the façade system strings during the simulation process, which also brings uncertainties. In conclusion, simulating BIPV on curved façades is a highly complex task requiring very accurate input data and tools.

5. Suggestions for future bipv research and development

BIPV simulation tools are critical for driving the design and the performance analysis of PV systems integrated into buildings. This study aims to identify trends and insights to foster the advancement of BIPV through data-driven approaches. Here are some suggestions for improving simulation tools based on the experience of using multiple simulation tools in this case study:

- **Data exchange and interoperability:** While most PV tools support the import of 3D models, the available data formats are limited. Standalone PV tools require manually repositioning PV modules on the surface of the imported 3D model, which does not truly represent BIPV and entails redundant work. In the future, PV simulation tools should be capable of “reading” imported building models to automatically identify placed PV modules that already contain PV module information and specifications. Additionally, PV tools lack the capability to export digital output to other simulation tools. Open industry-standard data exchange formats, such as IFC file, can facilitate smoother workflows and enable multidisciplinary integration in BIPV projects.
- **Rich Product Database:** Among the three plug-ins that were used, no one offers a built-in product database. Additionally, while standalone PV tools typically include product databases, only one is designed explicitly for BIPV products, including a custom design BIPV-module generator, which is essential for the potential of BIPV-adaptation to architectural designs. Having a rich and regularly updated product database is essential for simplifying the simulation process. Simulation tools can enhance accuracy in BIPV project planning by providing access to comprehensive product information. It enables users to compare the performance of various products easily.
- **Accurate and fast solar radiation simulation:** An accurate and rapid solar radiation simulation method is the basis for accurately evaluating BIPV performance. Standalone PV tools typically use simple geometrical models to evaluate the irradiance on the POA. However, this approach may be an ‘outdated’ approach for BIPV systems facing complex shading conditions in urban environments. Although ray trace-based methods may be relatively advanced, Ladybug Tools’ hourly irradiance simulation often takes much time. INSIGHT and BIMsolar’s ray tracing methods have a significant speed advantage. Accurate and fast solar radiation simulation can provide precise simulation results and improve the efficiency of the BIPV simulation process, enabling users to adjust the simulation in time.
- **Electrical Performance Analysis:** For some BIM-based tools, detailed electrical simulations require collaboration with other specialized tools. Thus, an embedded equivalent circuit model is essential for enabling comprehensive electrical performance analysis of the BIPV system. As for standalone PV tools, one area for improvement involves removing restrictions on PV module orientation within the string. This enhancement would provide users with greater flexibility in configuring BIPV systems. Furthermore, optimizing the system loss mechanism represents another crucial aspect requiring attention.
- **Cloud simulation and service:** Due to the complexity of façade BIPV systems, the simulation took a lot of time. BIPV simulation tools could benefit from leveraging cloud computing infrastructure to accelerate simulations. Cloud-based services also offer flexibility and collaboration for BIPV design and analysis by enabling distributed computing and collaboration. Multiple users can access and share simulation tasks and data, facilitating teamwork and information sharing.
- **Pending research topics**: This study has highlighted some critical aspects of BIPV modelling that require further research. Among the most pertinent issues are the need for improved modelling of solar irradiance transposition on vertical surfaces, which has rarely been the focus of existing studies; enhanced modelling of PV cell temperature, taking into account the wind speed profile near the building and around BIPV arrays; the effects of multiple array orientations on PV power output, including considerations for electrical mismatching losses; and the potential differences in the typical assumptions used for PV energy losses in standard PV versus BIPV systems. Specifically, the impact of multiple array orientations on PV power output can be significant when the façade is curved. A curved façade results in varying angles of incidence for solar irradiation, leading to uneven light distribution across the PV arrays. This uneven distribution can affect the overall efficiency and power output of the system, as different parts of the array receive varying amounts of sunlight throughout the day.
- **Investigation of other BIPV case studies:** The BIPV installation chosen for this study illustrates a significant proportion of the typical difficulties encountered while attempting to model a BIPV system using state-of-the-art simulation tools. However, while the general philosophy and outcomes of this exercise may be largely applicable to other similar BIPV cases, different BIPV modelling case studies may present unique challenges specific to each case, potentially leading to conclusions that differ partially or substantially. For this reason, further investigations of similar cases are both necessary and encouraged.

6. Conclusion

This study elucidates the typical challenges encountered when a group of individuals with reasonable expertise endeavours to model a real and complex BIPV system. It takes on a complex BIPV installation comprising three subsystems as a case study to assess the capability of eight simulation tools in representing BIPV systems, planning them, and evaluating the BIPV system performance. The endeavour is constrained not only by the capabilities and specificities of the available market tools but also by the scarcity and limitations of data typically accessible for such installations. This scenario represents a common challenge in the field, highlighting the practical difficulties in accurately simulating BIPV systems with the limited data that are often the norm for these kinds of installations. Through this exploration, we provided valuable insights into the practical aspects of BIPV system modelling, underscoring the nuanced understanding required to navigate the intricacies of such projects effectively.

Standalone PV tools based on equivalent circuit models have unparalleled advantages for a detailed electrical performance simulation. However, their process involves repetitive design work and does not accurately describe the BIPV project because they consider the PV modules attached to the building and not building-integrated. Based on monitored energy yield data, this study analyses the usability of the tools’ simulation results based on TMY weather files when planning projects. Each of the eight tools demonstrated the ability to obtain reasonable annual and monthly PV energy generation predictions for rooftop systems. However, for complex façade systems, BIM-based tools offer clear advantages.

Overall, standalone PV tools' limited 3D modelling capabilities and algorithm models restrict their modelling capabilities when encountering complex BIPV façade projects. Additionally, while good at 3D modelling, certain BIM-based tools and plug-ins lack standalone capabilities for detailed electrical simulations, highlighting the necessity to boost their capacity for BIPV system electrical modelling.

The selection of weather and solar resource data significantly impacts energy forecasting. PV simulation tools vary in their handling of solar resource input data; some operate as a "black box" and lack flexibility, accepting only specific data formats, such as TMY, or only GHI. Others are more versatile, accepting multiple years of data and different solar irradiance components. During this comparison study, simplifications were necessary to find common ground between the tools, which led to the exclusive use of TMY weather data for simulation and comparison with one year's measured yield. A limitation of this approach is that it does not leverage the potential accuracy improvements from using measured weather data from ground stations and solar yield data over several years. Future research could address this by incorporating such measured data to enhance result accuracy.

CRediT authorship contribution statement

Rebecca Jing Yang: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Conceptualization. **Yusen Zhao:** Writing – original draft, Software. **Sujan Dev Sureshkumar Jayakumari:** Software. **Astrid Schneider:** Writing – review & editing, Software. **S. Prithivi Rajan:** Writing – review & editing, Software. **Jonathan Leloux:** Writing – review & editing, Software. **Philippe Alamy:** Writing – review & editing, Software. **Gavin Prasetyo Raharjo:** Writing – review & editing, Software. **Fedele Rende:** Writing – review & editing, Software. **Tharushi Samarasinghalage:** Writing – review & editing. **Ana Marcos Castro:** Writing – review & editing. **Nuria Martin Chivelet:** Writing – review & editing, Methodology. **Shin Woei Leow:** Writing – review & editing. **Pabasara Wijeratne:** Writing – review & editing. **Yingwen Li:** Resources. **Ling Zhang:** Resources. **Chao Wu:** Resources. **Xin Deng:** Resources. **Duo Luo:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

all data used has been shown in the paper

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Appendix

Appendix 1:. Overview of functionalities of eight tools regarding compatibility and usability in planning data exchange, built-in databases, and detail of simulation

Function		Skelion [39]	SAM [40]	PVsyst V7 [41]	BIMsolar [42]	Ladybug Tools [43]	PV*SOL [44]	Solarius PV [45]	INSIGHT [46]
Type of tools		Plugin	Standalone	Standalone	Standalone	Plugin	Standalone	Standalone	Plugin
Import model	BIM-based simulation	○	○	○	●	●	○	●	●
	Import 3D model	●	○	DAE, 3DS	SKP, IFC, gbXML, IDF	●	DAE, OBJ, blend, 3DS, Iwo, stl, ply ms3d	DWG, IFC, Skp,OBJ, 3DS	●
	Import of 3D landscape Surrounding	●	○	○	●	●	●	●	●
	Export of 3D-model including PV / BIPV	●	○	○	○	●	○	●	●
Weather data	Built-in global weather database	●	●	●	■	●	●	●	●
	Import EPW format weather file	●	●	●	●	●	■	○	○
PV Modules and Inverters data	Built-in PV/Inverter Database	○	●	●	●	○	●	●	○
	Import customized component specifications	Built-in editor	Built-in editor	PAN/OND files	Built-in editor	○	PAN/OND files	Built-in editor	○
	Electrical parameter requirements	Module Rating Power	Detailed electrical specifications	Detailed electrical specifications	Detailed electrical specifications	Module Rating Power/Efficiency	Detailed electrical specifications	Detailed electrical specifications	Module Rating Power
BIPV layout configuration	Interactive placement	●	○	○	●	●	●	●	●
	Modelling on curved surfaces	■	■	■	●	●	■	●	●
	Modules with multiple orientations in one string	●	■	■	●	●	■	●	●
	Detailed Electric PV-system planning	○	○	●	●	○	●	●	○
Solar radiation simulation	Method of near shade evaluation	Shading factor	Shading calculator	Shading factor	Ray-tracing approach	Ray-tracing approach	Det. Shading calculation	Shading factor (Manual input)	Ray-tracing approach
	Irradiance / shading factor visualization	●	○	○	●	●	●	○	●
Losses	Electrical losses simulation	○	●	●	●	○	●	○	○
Energy generation	Module's temperature model	●	●	●	●	○	●	●	○
	Models for simulating the Electric DC output	Empirical model	Single diode model	Single diode model	Power coefficient & Single diode variant models	Equation calculation	Two diode model	Empirical model	Equation calculation
Simulation result	Energy generation output	Monthly	Hourly	Hourly	Hourly	Hourly	Hourly	Monthly	Monthly
	Export of detail simulation report	●	●	●	●	○	●	●	○

●Available function; ○ Unavailable function; ■ Available with difficulties.

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