2025 5th International Conference on Artificial Intelligence and Industrial Technology Applications (AIITA)

Research on Cloud-Edge Collaborative Building Photovoltaic Simulation Design System Based on Microservice Architecture

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***Abstract*—In response to the absence of specialized software tools for designing and simulating building photovoltaic(PV) systems in China, and the significant reliance on foreign software in related engineering projects, which are not well-suited to the scenarios of China's building PV demonstration projects, this paper presents the design and development of a cloud-edge collaborative building PV simulation design system based on microservice architecture. The system replaces the traditional monolithic architecture with a microservice architecture. Based on the simulation business requirements of building PV systems, seven loosely coupled and independently deployable microservices are identified, and a simulation process for building PV systems is designed to facilitate multi-professional collaborative design and parallel simulation functions. To further enhance the simulation efficiency of building PV systems, this paper introduces a cloud-edge collaborative online scheduling strategy, which comprises microservice sorting, task sorting, and task allocation. Finally, the feasibility of the proposed system has been demonstrated through system visualization applications and pilot engineering practices.**

Keywords- microservices; building photovoltaic; simulation design; online scheduling; priority

I. INTRODUCTION

The vigorous development of photovoltaic(PV) power generation applications in the construction field is a key technical path to implement the national energy conservation and carbon reduction strategy[1]. The development of Building Integrated photovoltaic (BIPV) applications is an important technical path for the construction field to achieve the goals of carbon peaking and carbon neutrality[2]. BIPV takes various forms[3], and the system involves multiple links such as generation, storage, grid connection, and consumption. The solar energy resources and loads are not synchronized, and there is a two-way coupling effect between buildings and PV[4]. Traditional design methods have not comprehensively considered the impact on building functions, performance and safety, which has affected the efficient and reliable application of building PV in buildings and restricted the further increase of the installation ratio of building PV in China. Therefore, it is urgent to break through the fine design and simulation software for building PV systems to better meet the needs of BIPV applications.

At present, for building PV systems in the large-scale promotion and start-up stage[5], in the international context, building PV system simulation design software has emerged as a crucial support tool for PV system design and planning. For example, the PVsyst software from the University of Geneva in Switzerland can offer certain data and design solutions for simulating PV power station systems[6]. The Archelios software from Trace Software in France is a professional PV design and output calculation software[7], capable of conducting full-cycle three-dimensional design for grid-connected, off-grid, and distributed PV systems. Nevertheless, these traditional foreign building PV design software exhibit single functions and inadequate performance, lacking refined design processes and simulation strategies, and are not well-suited to the scenarios of China's building PV demonstration projects.

Currently, China's building PV systems primarily rely on the design technology system and tools of ground PV systems. For example, during the "12th Five-Year Plan" and "13th Five-Year Plan" periods, the Institute of Electrical Engineering at the Chinese Academy of Sciences specifically developed

This work is supported by National Key R&D Program of China (SQ2022YFB4200018)
979-8-3315-0976-7/25/$31.00 ©2025 IEEE

centralized ground PV power station engineering design software[8] and high-performance simulation and virtual reality design platforms for large-scale PV systems[9, 10]. Additionally, the China Electric Power Research Institute established multiple PV performance testing platforms. However, there is a dearth of dedicated software tools for building PV system simulation design, leading to a significant reliance on foreign software in related engineering projects. Regarding the coupling effects between buildings and PV systems, Reference [11] investigated the multi-physics field coupling among heat, structure, and internal air flow in the new membrane material PV-ETFE air pillows of building-integrated PV [11], and Reference [4] explored the coupling effect between PV power generation and phase change heat storage[4]. Nevertheless, research on the multi-physics field coupling effects of different types of BIPV components remains limited.

In response to the above problems, this paper proposes a cloud-edge collaborative building PV simulation design system based on a microservice architecture. It elaborates on the overall architecture, functional modules, simulation processes, and cloud-edge collaborative online scheduling strategies of the system, as well as presents the system's visualization and its application status in pilot projects.

II. SYSTEM DESIGN SCHEME

A. Research Thoughts

In recent years, the market of BIPV has developed rapidly, with an expanding market size, increasingly complex system structure, and characteristics such as large data volumes and long simulation time[12]. The traditional system development models using single architecture face a series of problems such as high coupling degree between functional modules, difficulties in maintenance, upgrading and expansion, and outdated and single technology selection[13].

Therefore, this paper first studies the microservice architecture of the building PV simulation design system, dividing the system into multiple tasks[14], then conducting cloud-edge collaborative online scheduling management for these split tasks, and finally achieving multi- disciplinary collaborative design and simulation functions to reduce the complexity of system development, use, maintenance and expansion[15].

Secondly, this paper studies the cloud-edge collaborative online scheduling strategy. According to the diversified, dynamic and differentiated characteristics of tasks in the building PV simulation design system, a cloud-edge collaborative online scheduling strategy is proposed, composing microservice sequencing, task sequencing and task assignment.

B. Overall System Architecture Design

In response to the need for accelerated integration of the building PV industry with digital technology and the demand for multi-disciplinary collaborative design and parallel simulation, the system adopts a microservice architecture to build a cloud-edge collaborative building PV simulation design system, providing a solution for multi-disciplinary cloud-edge collaborative simulation and design of building PV systems.

The system employs a "microservice" technical architecture, constructing a five-layer architecture consisting of the resource layer, data layer, service layer, interface layer, and access layer[16], providing technical and service capabilities step by step progressively from bottom to top, ultimately forming seven application services: project management, component management, system design, mechanical load simulation, multi-physics field coupling simulation, system joint operation simulation, and comprehensive quantitative evaluation. The overall architecture of the cloud-edge collaborative building PV simulation design system based on microservices is shown in Figure 1.

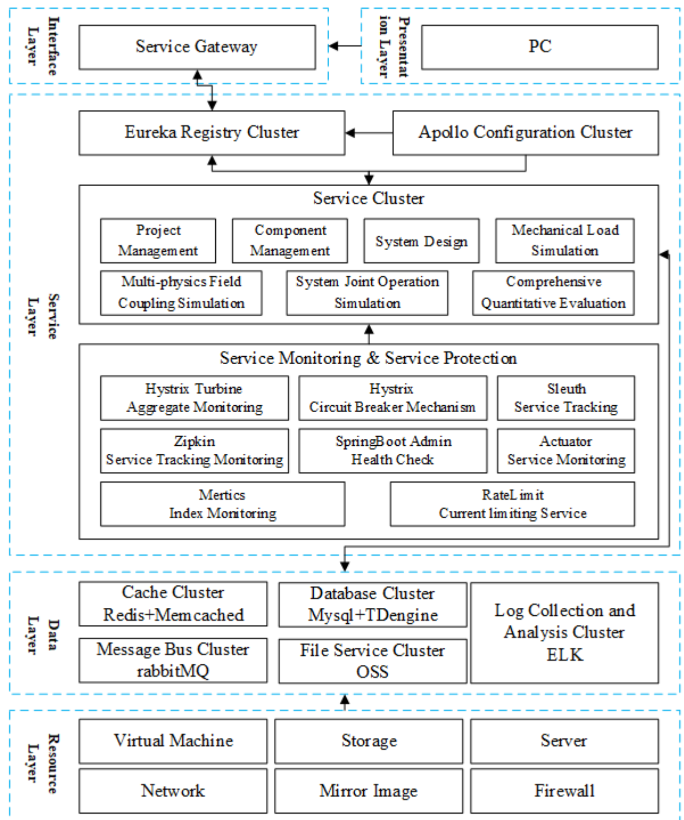

Fig 1 Overall architecture of building PV simulation design system

1) Resource Layer: Utilizing technologies such as server virtualization and containerization, it builds networks, computing, and storage resources, providing efficient infrastructure resources for the system's operation.

2) Data Layer: This layer Establishes logical, storage, and physical models of building PV system data, builds a data management platform, realizes unified, standardized and systematic management of data, enhances data interaction and sharing capabilities, and provides reliable data support for the service layer.

3) Service Layer: Responsible for the implementation of business logic, data processing, and transaction control, providing seven application services to meet the comprehensive needs of building PV simulation design system.

4) Interface Layer: Through verification and authorization mechanisms, determining the user's access rights to the system, ensuring data security, effectively preventing unauthorized access and operations, and safeguarding the stability and security of the system.

5) Presentation Layer: This layer Provides computer applications for building PV designers and engineers, supporting multi-disciplinary collaborative design and parallel simulation. It improves design efficiency and quality by offering intuitive tools and interfaces.

C. *System Function Design*

Aiming at the simulation and design business requirements of building PV system, this paper designs seven functional modules in the system, and divides them into independent microservices according to the principle of business function and performance requirements, which are independent of each other and work together as follows:

1) Project management: Responsible for the basic information management of the project, covering the functions of creating, opening, modifying and deleting the project.

2) Component management: Focus on the management of building PV components, PV modules, inverters, batteries, off-grid controllers and other components.

3) System design: According to different types of building PV systems, complete the selection of key equipment, series and parallel design of arrays, loss model and operation strategy parameter setting.

4) Mechanical load simulation: Perform mechanical load calculation for different types of building PV components, and output load stress results.

5) Multi-physics coupling simulation: For different types of building PV components, to achieve light-electric-thermal multi-physics coupling calculation, output the thermoelectric performance of the system.

6) System joint operation simulation: Realize the simulation calculation of system loss and power generation in the whole life cycle, providing prediction for the economic operation and power generation efficiency of the system.

7) Comprehensive quantitative evaluation: Comprehensive evaluation of system power generation performance, building PV coupling performance, building energy efficiency, economic viability and environment impact, to provide scientific basis for decision-making and optimization.

D. *System Simulation Flow*

The Building PV simulation design system involves multiple disciplines such as HVAC, architecture, electrical engineering, and new energy. During the system design phase, HVAC professionals provide building loads, architectural professionals import the 3D model of the building and select the building surfaces where PV panels can be installed, and electrical engineering professionals establish PV arrays and design PV system. In the system simulation phase, new energy professionals set the simulation duration and step size for system simulation. In the system scheme evaluation phase, multi-disciplinary users continue to improve the design scheme according to the comprehensive quantitative evaluation index until it meets the design requirements.

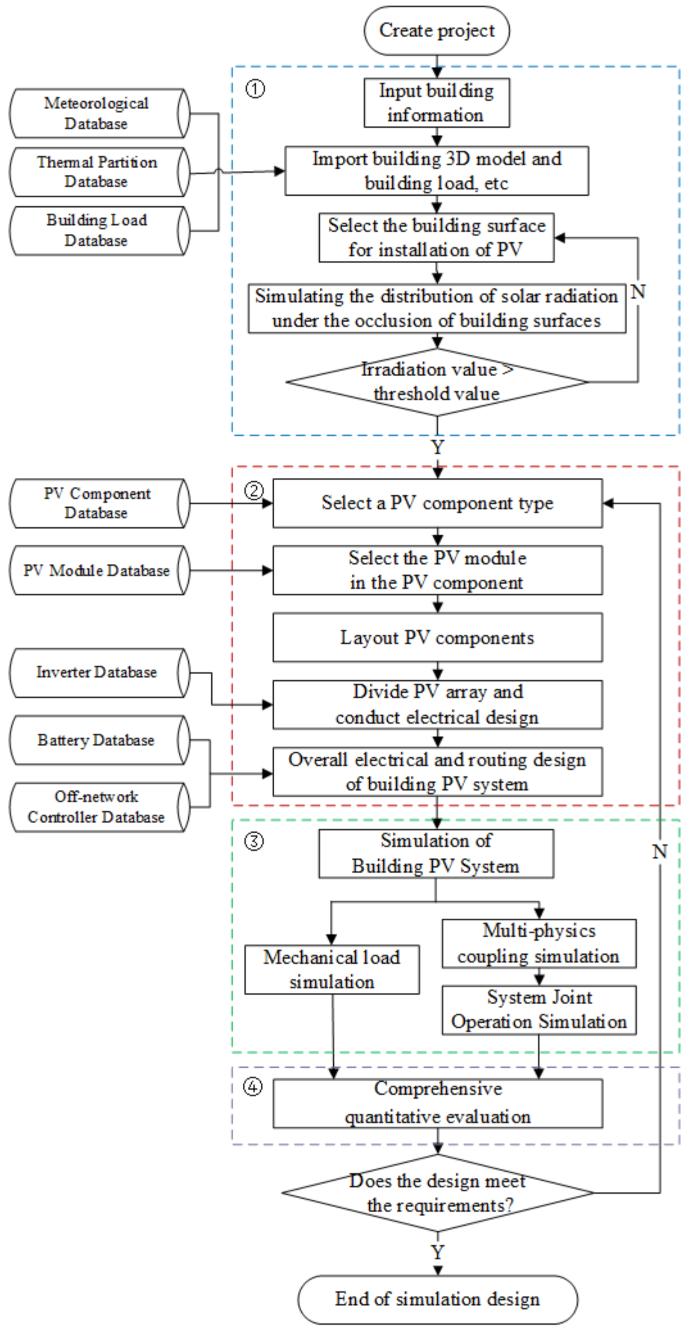

Fig.2 Simulation flow chart of building PV system

The simulation process of multi-professional cloud-edge collaborative building PV simulation design system proposed in this paper mainly includes four stages: region determination, system design, system simulation and comprehensive evaluation, as shown in Figure 2. The details are as follows:

1) Region Determination Stage: Users first input the basic building information, and import the 3D model, building load,

meteorological and thermal zones. Then, users select the potential PV installation on the imported 3D model and evaluate the solar radiation distribution considering shading effects. If the radiation value is greater than the threshold value, the process proceeds to the next stage of system design.

2) System Design Stage: Based on the outcomes from the region determination stage, users choose appropriate building PV components and modules, followed by layout design for these components. PV arrays are then divided and integrated into the electrical design. Once all array electrical designs are completed, an overall electrical and routing design for the entire building PV system is conducted, and finally form the whole station scheme.

3) System Simulation Stage: Users input the simulation duration and step size, and select the appropriate simulation model. The mechanical load simulation and multi-physics coupling simulation can be calculated in parallel, but the system joint operation simulation must be based on the results of multi-physics coupling simulation to ensure the accuracy.

4) Comprehensive Evaluation Stage: Upon obtaining the simulation results, users comprehensively evaluate the system's power generation performance, building PV coupling performance, building energy efficiency, economic viability and environmental impact. If the evaluation results meet the design requirements, the simulation concludes. Otherwise, adjustments are made starting from the system design phase to optimize the design scheme.

III. Cloud Edge Collaborative Online Scheduling Policy

In order to improve the efficient operation and rational utilization of resources of the building PV simulation design system, accounting for task differentiation, diversification, and dynamism, as well as the volatility of the system deployment environment, we adopt the task scheduling strategy outlined in Reference [17]. A cloud-edge collaborative online task scheduling strategy for building PV system is proposed, which is composed of microservice sorting, task sorting and task assignment[18]. Its core objective is how to optimize task execution order and time under resource constraints, and reduce task queuing and resource occupation time[18, 19].

A. *Microservice Priorities*

The task of building PV simulation design system under microservice architecture is composed of many microservices, that is, the completion of building PV system task depends on several microservices. Therefore, prioritizing microservices is essential to ensure mission-critical execution and proper allocation of resources[20].

If there is a cooperative relationship between microservices, their execution order cannot be exchanged. For example, the system design microservice must be executed before mechanical load simulation microservice. If there is a parallel relationship between microservices, that is, multiple microservices are carried out at the same time, such as executing multi-physical coupling simulation and mechanical load simulation at the same time, the execution order of parallel microservices will also affect total processing delay. Therefore, Formula 1 is used to estimate the priority of each microservice in the task of building PV system, optimizing resource utilization and improving system efficiency.

$$\mathrm{p}(i) = \left(\sum_{n=1}^{n=N} t_{i,n}^{m} + \sum_{n=1}^{n=N} c_{i,n}^{m} + \sum_{n=1}^{n=N} w_{i,n}^{m}\right) / N + \max_{s_j^m \in R(s_i^m)} \left(d_{i,j}^{m} + r_{i,j}^{m} + p(j)\right) \tag{1}$$

Where: $p(i)$ is the scheduling priority of s_i^m; s_i^m and s_j^m represent two microservices respectively, and s_j^m depends on s_i^m. $t_{i,n}^m$ indicates the execution time of s_i^m. $c_{i,n}^m$ indicates the CPU usage of s_i^m. $w_{i,n}^m$ indicates the memory usage of s_i^m. N indicates the number of executions. $d_{i,j}^m$ is the amount of data generated by s_j^m depending on s_i^m; $r_{i,j}^m$ is the amount of resources that s_j^m depends on s_i^m.

B. *Task Priority*

After defining the microservice priority relationship in the previous section, it is also necessary to determine the priority relationship among multiple system tasks to ensure that critical tasks are prioritized.

This paper proposes a fuzzy logic algorithm to determine task priority, which considering multiple factors that have a significant impact on task execution performance, including data volume, execution time, task type and required resource load (such as memory, CPU, storage space), etc. The process is shown in Figure 3 below, and specific steps are described as follows.

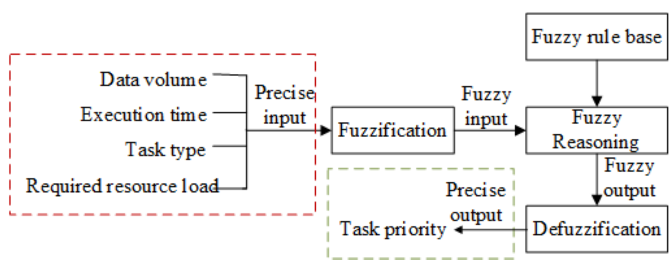

Fig.3 Task priority flow chart

1) Fuzzification: System inputs are transformed into fuzzy membership function, which describe the degree to which input variables belong to each fuzzy set[21]. Considering the wide distribution and high volatility of the data in this system, as well as the high requirement for accuracy, this paper adopts Gaussian membership function[22] to achieve fuzzy processing, and its calculation formula is as follows:

$$u(x) = e^{-\frac{(x-c)^2}{2\sigma^2}} \tag{2}$$

Where: $u(x)$ is membership degree; x is the input or output variable; c is the center of the distribution; σ is the standard deviation. The inputs include data volume, execution time, task type and required resource load, with corresponding linguistic variables defined as follows: Data volume can be small, medium, or large; Execution time can be long, medium, or short; Task types can be urgent, important, or daily. Required resource load can be high, medium, or low. The output is task priority, represented by the linguistic variables highest, high, medium, low, and lowest.

2) Fuzzy Reasoning: This process calculates fuzzy output according to fuzzy rules and fuzzy input. In this system, fuzzy rules are formulated using "if-then" logical structures. with four membership functions, each having three linguistic variables, 81 fuzzy rules can be combined to comprehensively describe the fuzzy relationship between these input variables and task priority.

3) Defuzzification: This process converts fuzzy output into precise value. Common defuzzification methods mainly include the centroid method, area center method and mean maximum method[21]. In this system, the centroid method is selected for defuzzification calculation, and the final accurate output value is determined by calculating the centroid position of the fuzzy output set. Task priorities in the system can be calculated by formula (3).

$$q = \frac{\int xu(x)dx}{\int u(x)dx} \tag{3}$$

Where: q indicates the task priority.

C. Task Assignment

After defining the task priority relationship in the previous section, in order to ensure efficient task completion, optimal resource utilization and minimized total task execution time, this system designs a task resource matching algorithm based on task requirements and resource availability. The core principle is to maximize resource utilization and enhance task execution efficiency through precise task-resource matching[23].

Specifically, the resources required by system tasks mainly include key indicators such as server network bandwidth, memory occupancy, CPU usage and disk load ratio. In order to assign tasks to the most matched resources, the task-resource matching algorithm proceeds as follows: The Task and Resource classes are created to represent tasks and resources in the system, with unique IDs and weight attributes defined for each. The weight attributes of the task are the task priority mentioned in the previous section, reflecting the importance and urgency of the task, and the weight attributes of the resource are set according to the resources required by the task and the execution situation. Based on those weights, all matching degrees between tasks and resources are calculated. Finally, according to the calculated matching degree, the optimal task-resource matching pair is selected. The system allocates the task to the corresponding resource for execution, thereby improving overall task execution efficiency and resource utilization.

IV. SYSTEM VISUALIZATION APPLICATION AND ENGINEERING PRACTICE

A. Visualization Application

The first version of the system described in this paper has been developed, with the system design page shown in Figure 4. The left column of the figure clearly displays the functional modules contained within the system.

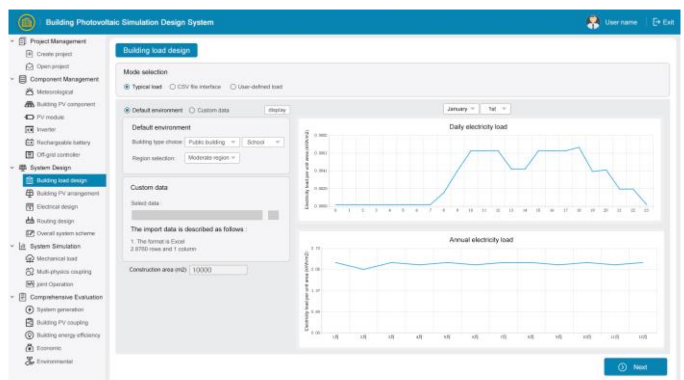

Fig.4 Screenshot of the page of the "System Design" page

TABLE I. THE FUNCTION COMPARISON BETWEEN THIS SYSTEM AND PVSYST SOFTWARE

Comparison item	***System***	***PVsyst software***
Import 3D building model	Support	Nonsupport
PV component database	Yes	No
Building specific PV module database	Yes	No, the component database lacks technical features such as fire and waterproofing ratings, bezels, glazing, and connections
Support the building PV technology route	Add-on, wall-mounted, embedded, tile and sunshade	Add-on, wall-mounted, sunshade
The surface of the building supports multiple installation forms at the same time	Yes	No
Building surface arrangement PV	The orientation of the PV module can be automatically obtained after the PV module is arranged on the building surface	After estimating the best inclination and azimuth of PV modules, PV is arranged on the surface of the building
Design and simulation of building PV system with various types of PV system	Support, user can set different PV arrays to different systems in the design phase	Nonsupport, at the beginning of the design, users must choose the type of grid or off-grid, before they can enter the system design
Multi-physics coupling simulation	Support	Nonsupport

TABLE II. COMPARISON OF THE IMPLEMENTATION OF PILOT PROJECT CASES

Comparison item	***The power simulation value of the system is compared with that of PVsyst software***	***The power simulation value of the system is compared with the empirical operation data of the pilot project***	***Comparison of PVsyst software's power generation simulation value with the experimental operation data of the pilot project***
Mean relative error	1.89%	4.73%	6.41%

To evaluate the proposed system's capabilities, a comparison with the international mainstream PVsyst software is presented in Table 1. It is evident from the table that this system has significant advantages in 3D building model import, PV components and building specific PV modules addition, building PV technology route support, multiple types of PV system design and multi-physical field coupling simulation. However, PVsyst software provides more comprehensive loss analysis for PV systems[6], the function that will be incorporated into future versions of this system.

B. *Pilot Project Practice*

In order to verify the feasibility and effectiveness of the designed cloud-edge collaborative building PV simulation design system based on microservices architecture, this paper uses a 38.2kWp wall-mounted building PV demonstration system as an example. Located in Xi 'an, Shaanxi Province, the building is an industrial structure with 735m^2 of embedded PV installed on its facade. The PV module consist of 120 gold components with rated power of 245W and 39 cyan components with rated power of 225W, and is equipped with 4 grid-connected energy storage inverters with rated output power of 6kW.

The proposed system and PVsyst software were utilized to simulate the power generation of this case. The average relative error between the simulated power generation value of the proposed system, the empirical operation data of the pilot project, and the simulated power generation value of PVsyst software was calculated. As shown in Table 2, the generation power simulation error of the system in this paper and the PVsyst software is 1.89%, indicating that the simulation results of both are closely aligned with minimal difference. To further verify the reliability of the system simulation in this paper, compared with the empirical operation data of the pilot project, the generation power simulation errors of the system in this paper and the PVsyst software are 4.73% and 6.41% respectively, indicating that the system simulation results in this paper are closer to the actual operation data and exhibit higher accuracy.

V. CONCLUSIONS

To meet the urgent needs of large-scale construction and fine design and simulation of building PV system in China, this paper designs and develops a cloud-edge collaborative building PV simulation design system based on microservice architecture. This paper analyzes the overall architecture and functional modules of the system, proposes the process of multi-disciplinary collaborative design and parallel simulation, and designs a cloud-edge collaborative online scheduling strategy for building PV system tasks based on the task scheduling mechanism under the microservice architecture, effectively improving the efficiency of system simulation.

The application results of system visualization and pilot projects demonstrate that the building PV simulation design system can realize the design and simulation of kilowatt-level PV system in different typical building environments, thereby promoting the development and application of building PV technology.

To verify the usability of the system, this paper only uses a kilowatt-level demonstration project as a simulation case. However, real-world building PV systems also include megawatt-level demonstration projects. Future research will continue to study the optimization scheduling algorithm of tasks and resources to meet the needs of more complex building PV system simulation.

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