R&D and Application of Distributed Photovoltaic Simulation Planning Platform

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Abstract. Aiming at the problem that it is difficult to realize accurate and efficient design of distributed photovoltaic system, a distributed photovoltaic simulation planning platform is developed, which makes use of digital means to carry out rapid planning and design of distributed photovoltaic system in the early stage of the project, to improve the efficiency of the design in the early stage of the project and to carry out the prediction of the performance of the distributed photovoltaic system and analysis of indexes, so as to reduce the design error. This paper firstly introduces the overall architecture of the distributed PV simulation planning platform, then respectively for the distributed PV system design basis and the calculation of the system key indexes for a detailed description, and combined with the actual project to verify its reliability, the results show that the simulation planning platform fully support the distributed photovoltaic business of the pre-project planning and design.

Keywords: Solar energy, Distributed photovoltaic, Simulation planning, Digital twin

1 Introduction

With the introduction of the "dual carbon" goal, the global energy structure transformation and sustainable development concept is deeply rooted in people's hearts, the photovoltaic (PV) industry, as an important part of the new energy field, has been highly valued by governments and enterprises, and the PV industry in China has increased from 893 MW to 48.2 GW in the past decade or so [1]. Compared with centralized PV systems, distributed PV systems have lower investment costs and are easy to be integrated in existing buildings, while distributed PV systems produce harmonic currents during operation, which do not pose adverse physical effects on neighboring users [2], and will account for an important market in the future [3-4].

Traditional distributed PV design relies on artificial experience or simple control strategies, making it difficult to realize accurate and efficient design of PV systems. At the same time, when the proportion of self-consumption exceeds the building's self-consumption of electricity, it is necessary to configure the energy storage system, thus increasing the investment cost of distributed PV systems and bringing more difficulties to the planning and design of distributed PV systems. In the rapid development of

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photovoltaic industry, how to achieve intelligent regulation, optimize design and ensure stable and efficient operation of PV system has become a key issue to be solved.

Multi-level and wide-field research has been carried out at home and abroad for the design of photovoltaic systems. The PVSyst software designed and developed by Dr. André Mermoud of Geneva University, Switzerland, has perfect functions and rich databases, which is suitable for PV researchers and senior engineering designers; the HOMER Pro software, which originated from the U.S. National Renewable Energy Laboratory and was later commercially developed by HOMER Energy, can be applied to a variety of off-grid and grid-connected power system evaluation and design, focusing on system optimization and sensitivity analysis, and applicable to wind, light, storage, gas, biomass and other forms of energy. Wang Mengxue et al. compared the planning functions, energy service types and platform features of 10 representative simulation platforms, and categorized the 10 platforms in terms of application scenarios, research methods and model types, providing targeted references for the selection of integrated energy simulation and planning platforms[5]; Kaiqi Ma has sorted out the technical routes and technical difficulties of integrated energy research from three levels: system, model, and calculation, which is of good guidance for the planning and construction of the subsequent integrated energy dynamic simulation system[6]; the photovoltaic power generation simulation model, booster station simulation model, power grid simulation model, and equipment 3D visualization model built by Zhengmao Dong et al. on the CyberSim power diagram simulation platform can simulate the operation processes of starting and stopping power stations, normal operation, fault handling, transmission and substation system inspection, and gate reversal, which can greatly improve work efficiency when used in conjunction with actual systems[7].

The current research on distributed PV overall lacks a simulation platform that can meet the pre-planning and design needs of PV business. Based on the current research, this paper proposes a distributed photovoltaic simulation planning platform with comprehensive functions and a wide range of applicability, which utilizes digital means to carry out rapid design planning for photovoltaic power generation systems at the pre-project stage, thus enhancing the design efficiency of distributed photovoltaic systems, as well as carrying out performance prediction to reduce design errors, thus providing guidance for the pre-design of distributed photovoltaic platforms.

2 Distributed PV Simulation Planning Platform

2.1 Distributed Photovoltaic System Structure

Distributed photovoltaic system refers to a photovoltaic power station in the distribution network, close to the user load side, with a relatively small installed capacity and decentralized installation, which converts solar energy into electric energy by using photovoltaic modules, with self-generation and self-consumption as the primary mode, and with excess power going online and being locally consumed as the main mode, and is designed to tailor power supply to meet the specific user's power demand, and to effectively promote the economic and efficient operation of the existing distribution network.

As shown in Figure 1, the equipment of distributed photovoltaic system mainly includes photovoltaic cell module, converter, DC distribution cabinet, inverter, transformer and so on. Its mode of operation is in the solar radiation, solar modules will be converted into solar energy, through the converter centralized into the distribution cabinet, by the inverter inverse into alternating current to supply the building's own loads, excess or insufficient power through the connection to the grid to regulate.

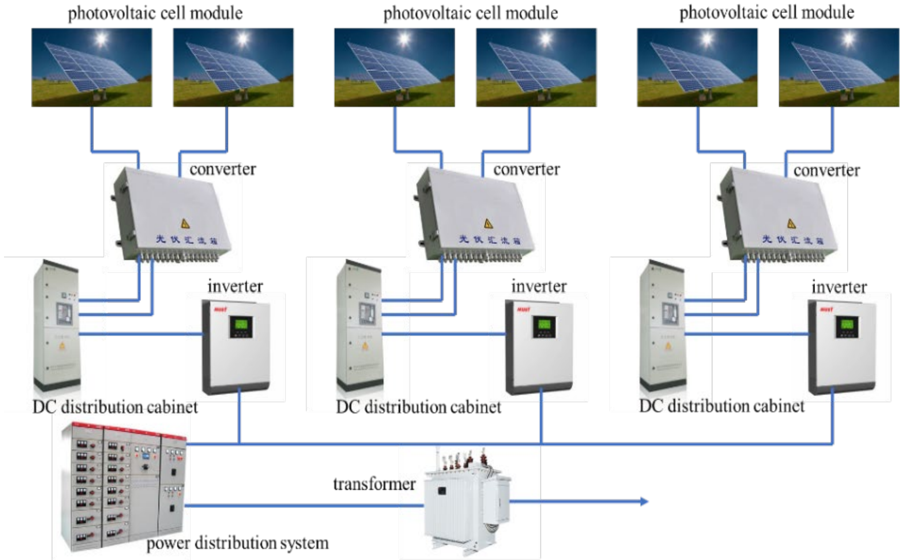

Fig. 1. Distributed photovoltaic system structure.

2.2 Platform Architecture

The distributed photovoltaic (PV) simulation and planning platform developed in this paper includes four modules: PV planning and design, online modeling, parameter optimization and backend service:

Photovoltaic planning and design as the main part of the realization, can complete the load analysis, array design, key components selection and key indicators of the calculation function; Online modeling enables the system to have online modeling capability through graphic rendering technology and browser modeling tools in the Web environment; Parameter optimization obtains the equipment, meteorology, and solar panel layout information at the design stage through the database as input parameters for multi-objective optimization, and performs objective optimization on the PV system model to obtain the optimal solution; The backend service uses model compilation servitization technology and model compilation containerization technology to seal the model compiler, run it as a Docker container, and provide corresponding interfaces to provide modeling, compilation, and simulation capabilities externally, and Figure 2 shows the specific architecture of the platform.

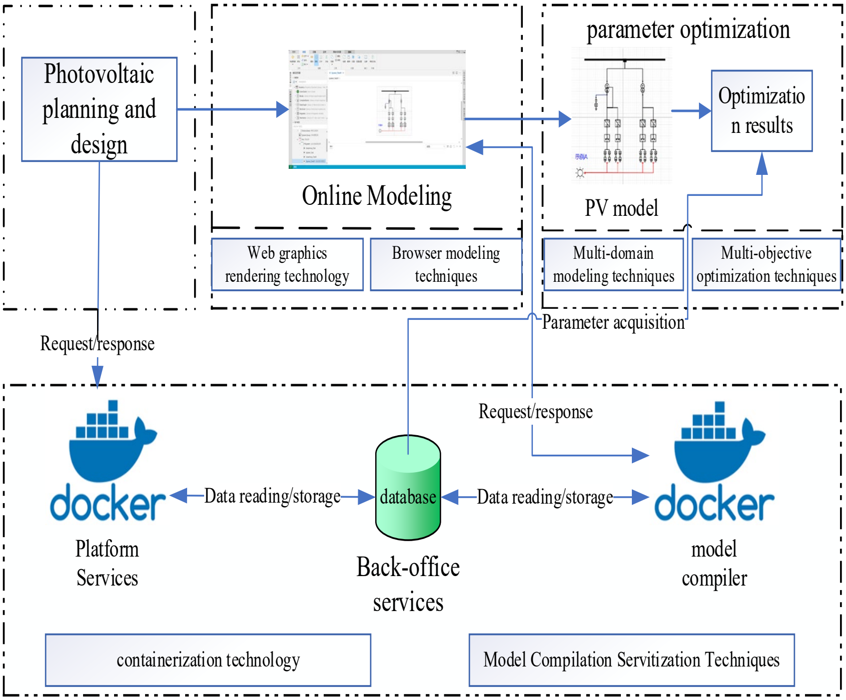

Fig. 2. platform architecture.

This article focuses on the photovoltaic planning and design module of the simulation platform in response to the difficulty of realizing accurate and efficient design of distributed photovoltaic systems.

3 Photovoltaic Planning and Design Functions

3.1 Load Analysis

The goal of load analysis is to guide the energy system construction and equipment selection, using the historical data method, based on the historical load situation, the annual, monthly, typical day, hour-by-hour load forecast. The simulation platform provides four load types for load analysis: no self-consumption of electricity, monthly electricity consumption, day-by-day configuration and hour-by-hour or daily electricity consumption, and the process of analyzing the specific loads of each type is shown in Figure 3.

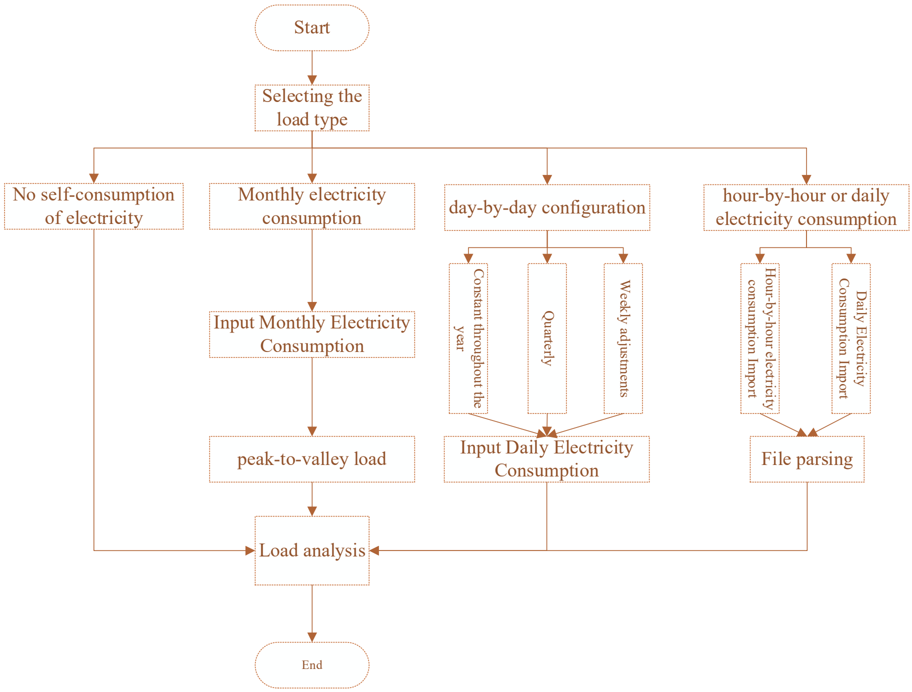

Fig. 3. Historical Data Method Load Analysis Process.

3.2 Array Design

3.2.1. Solar Panel Selection and Arrangement.

Solar panel selection is based on the results of load analysis and plant site information and combined with module manufacturers, rated power, size and other information for screening, and then determine the series-parallel arrangement of solar panels.

First determine the number of solar panels in series, the principle is that the open-circuit voltage after series connection is lower than the maximum input voltage of the inverter, and the operating voltage is in the range of the maximum power point tracking voltage of the MPPT (mounted between the solar panels and the inverter as an intermediate link in the optimization and regulation of electrical energy).

The maximum open circuit voltage is lower than the maximum DC input voltage of the inverter:

$$N \le \frac{V_{\mathrm{dc\,max}}}{V_{\mathrm{oc}} * [1 + (t - 25) * K_V]} \tag{1}$$

The operating voltage should be in the middle range of the inverter MPPT voltage:

$$\frac{V_{mppt\,\min}}{V_{pm}*[1+(t'-25)*K_V']} \le N \le \frac{V_{mppt\,\max}}{V_{pm}*[1+(t-25)*K_V']} \quad (2)$$

where K_V is the open-circuit voltage temperature coefficient of the PV module, K_V' is the temperature coefficient of the operating voltage of the PV module, N is the number of PV modules connected in series (N is rounded up), t is the extreme low temperature under the working conditions of PV modules , t' is the extreme high temperature under the working conditions of PV module, $V_{\mathrm{dc}\max}$ is the maximum permissible DC input voltage of the inverter, $V_{mppt\,\max}$ is the maximum value of the MPPT voltage of the inverter, $V_{mppt\,\min}$ is the minimum value of the MPPT voltage of the inverter, V_{oc} is the open-circuit voltage of the PV modules, V_{pm} is the working voltage of the PV module.

Once the number of series connections is determined, the power is determined at the same time and the number of parallel connections is calculated by the maximum input power of the inverter.

$$M \le \frac{P_e}{P_m * N} \quad (3)$$

Where, P_e is the rated power of the inverter, P_m is the peak power of PV modules, M is t the number of PV modules connected in parallel (rounded).

3.3 Key Component Selection

3.3.1. Inverter Selection.

Inverter selection based on manufacturers, inverter power rating, size information for screening, the same site can be a variety of models of inverter selection, inverter power determination method based on distribution power

$$P = \mathrm{N}_{MPPSET} * (P_{\mathrm{Norm}} / \mathrm{N}_{MPP}) \quad (4)$$

where P is the distribution power, N_{MPPSET} is the number of MPPT settings, P_{Norm} is the nominal AC power, N_{MPP} is the total number of MPPTs.

The ratio of the installed capacity of the PV array to the rated capacity of the inverter is the capacity-matching ratio, which generally does not exceed 1.2, so the minimum value of the total inverter capacity can be taken as the following formula:

$$P\_\min = P\_install / 1.2 \quad (5)$$

where $P\_\min$ is the minimum inverter capacity and $P\_install$ is the installed capacity of the PV array.

3.3.2. Transformer Selection.

Transformer selection based on the transformer output voltage level, according to the "PV power plant design specifications" can be divided into voltage: 400V, 10kV, 35kV, and then determine the transformer capacity, selecting the transformer capacity needs to be considered transformer reactive power:

$$S_{\text{tan}sformer} = P_{convertor\_\max} / PF / K \tag{6}$$

Where $S_{\text{tan}sformer}$ is the transformer's recommended apparent power, $P_{convertor\_\max}$ is the maximum active output power of the inverter, PF is the transformer power factor, K is the margin factor, generally take 0.8~0.9.

The eligible transformers are combined so that the total final transformer capacity meets the requirements:

$$S_{total} = S_{t1} + \cdots + S_{\text{tn}} \tag{7}$$

where S_{total} is the total transformer capacity, S_{tn} is the nth transformer capacity.

3.4 Key Indicator Measurement Functions

3.4.1. Generation of Electricity.

Power generation is one of the important indicators of distributed PV systems, and the formula for calculating power generation and annual power generation hours is as follows:

$$E_p \leq \frac{H_A}{E_S} * P * K = H_A * A * \eta * K_e \tag{8}$$

Where K_e is the integrated efficiency coefficient of the distributed photovoltaic system, H_A is the total horizontal solar irradiation, which shall be the product of the average daily total horizontal solar irradiation of each month and the number of days in a month when calculating the monthly power generation, E_p is the grid-connected power generation, E_S is the irradiance under the standardized conditions, A is the total area of the photovoltaic modules within the calculation range, and η is the conversion efficiency of the modules, which is determined by the data provided by the manufacturer.

Calculate the annual power generation over the operating life of the power generation system based on the above formula and the module decay coefficient, which is provided by the manufacturer and is categorized into first year decay and linear decay over a period of 30 years. The formula for calculating the power generation in the second and subsequent years of the power generation system is as follows:

$$E_{p1} = E_p * (1 - k_1) \tag{9}$$

$$E_{pn} = E_{p(n-1)} * (1 - k_n) \tag{10}$$

where E_{pn} is the generation in the nth year of the operation period, $E_{p(n-1)}$ is the generation in the previous year, and k_n is the attenuation coefficient for the current year.

3.4.2. Self-generated Self-utilization Rate.

"Self-generation and self-consumption, surplus power on-grid" is an important working mode of distributed PV systems, especially for distributed PV projects on industrial and commercial rooftops [8-9], and the self-generation and self-consumption rate is one of the important indexes for this kind of projects, i.e., the ratio of the portion of the electricity generated by distributed PV systems that is consumed by the users after the completion of distributed PV systems to the total amount of electricity produced.

The monthly self-generation rate is calculated as follows:

$$I_M = \frac{\min(E_{PJ}, P_{PJ}) + \min(E_{PF}, P_{PF}) + \min(E_{PP}, P_{PP}) + \min(E_{PG}, P_{PG})}{E_{PJ} + E_{PF} + E_{PP} + E_{PG}} \tag{11}$$

Where I_M is the monthly self-generation and self-consumption rate; E_{PJ} is the power generation at the peak moment; E_{PF} is the power generation at the peak moment; E_{PP} is the power generation at the flat moment; E_{PG} is the power generation at the trough moment; P_{PJ} is the load at the peak moment; P_{PF} is the load at the peak moment; P_{PP} is the load at the flat moment; P_{PG} is the load at the trough moment.

The annual self-generation rate is calculated as follows:

$$I_Y = \frac{\sum_{1M}^{12M}(\min(E_{PJ}, P_{PJ}) + \min(E_{PF}, P_{PF}) + \min(E_{PP}, P_{PP}) + \min(E_{PG}, P_{PG}))}{\sum_{1M}^{12M}(E_{PJ} + E_{PF} + E_{PP} + E_{PG})} \tag{12}$$

where I_Y is the annual self-generation and self-consumption rate.

3.4.3. Comprehensive Electricity Tariff.

The composite electricity price varies considerably from project to project, but can be calculated in a uniform manner:

$$W_Z = W_X * I_Y + W_B * (1 - I_Y) \tag{13}$$

$$W_X = W_Y * Z \tag{14}$$

Where W_Z is the consolidated electricity prices, W_X is the agreed electricity prices, W_B is the benchmark feed-in electricity prices, W_Y is the customer electricity prices, and Z is the discount.

3.4.4. Energy Saving and Emission Reduction Benefits.

Energy saving and emission reduction is one of the important indexes to measure the performance of new energy [10-11], the average annual power generation is converted into standard coal for power supply and calculated to reduce the emissions, and the calculation contains the annual standard coal carbon saving, SO_2 emission reduction, NO_X emission reduction and CO_2 emission reduction. The relevant calculations are based on the Energy Research Institute of the National Development and Reform Commission, and the specific requirements are shown in Table 1.

Table 1. Emissions from consumption of 1 kWh of electricity.

CO_2 emissions	SO_2 emissions	NO_X emissions
0.997 kg	0.03 kg	0.015 kg

The calculation method for each energy saving and emission reduction indicator is as follows:

Annual saving of standard coal = average annual power generation * 10,000 * 304.9 / 1,000,000, of which, the standard coal consumption for power supply is calculated as 304.9 g/kW·h.

Annual reduction of CO_2 emissions = average annual power generation * 10,000 * 0.0997/1000.

Annual reduction of SO_2 emissions = average annual power generation * 10,000 * 0.03/1000.

Annual reduction of NO_X emissions = average annual power generation * 10,000 * 0.015/1000.

4 Example

Taking a 4.5MW distributed PV project of a company in Hubei as an example, the distributed PV simulation planning platform proposed in this paper is simulated and verified to determine whether the platform has guiding significance for the pre-design of distributed PV projects, and the data are obtained from the actual project.

4.1 Distributed Photovoltaic System Design

In the simulation platform, the historical load is used as the data source for load analysis, and the historical monthly peak and valley time power consumption is input to simulate the power consumption of the site. The maximum input capacity of the project is 4.5144 MWp. Considering the convenience of system installation and maintenance, the solar cell array consists of one 0.9396 MWp, one 0.8316 MWp, one 0.2484 MWp, one

1.3284 MWp, one 1.1664 MWp, and a total of five sub-systems, which are arranged on the roofs of five different plants. The number of series connection is calculated as 26, while the number of parallel connection is calculated as 12. The project is a medium-sized PV power generation system, if the inverter capacity is small, the number of equipment is large, which will increase the investment and maintenance workload in the later stage, and if the inverter capacity is too large, if an inverter fails, the power generation system loses too much power generation and is not conducive to the flexibility of the arrangement, and the final use of the 175kW string inverter. The transformer is calculated by the platform and adopts three sets of 1000kVA and one set of 1250kVA. The project has been in operation for many years, and the distributed PV system designed in the simulation planning platform needs to be modified within the range allowed by the calculation to ensure consistency with the actual and simulation.

4.2 Simulation Verification

Verify the reliability of the simulation planning platform by comparing the actual power generation, self-generation and self-consumption rate, comprehensive electricity price, energy saving and emission reduction benefits and other important indexes calculated in the simulation planning platform with those in the actual platform.

After the project is connected to the grid, the first year's power generation is 4,463,000 kWh, the first year's utilization hours are 988.62 h. During the 25-year operation period, the average annual power generation is 4,162,500 kWh, the average annual utilization hours are 922.04 h, and the total power generation is 104,061,800 kWh. Comparing the actual power generation data with that of the data in the simulation and planning platform, and the results of the comparison are as shown in Table 2. The error of power generation increases with the increase of power generation years, and the error of power generation in the 25th year reaches the maximum value of 2.05%, which still meets the error requirements.

Table 2. Power generation error

Years	Utilization hours(h)		Error	Power generation (million kWh)		Error
	Actual	simulation		Actual	simulation	
1	988.62	996.50	0.80%	446.3	449.86	0.80%
2	983.08	991.02	0.81%	443.8	447.39	0.81%
3	977.53	985.57	0.82%	441.29	444.92	0.82%
4	971.98	980.15	0.84%	438.79	442.48	0.84%
5	966.43	974.76	0.86%	436.29	440.04	0.86%
6	960.88	969.39	0.89%	433.78	437.62	0.89%
7	955.33	964.06	0.91%	431.28	435.22	0.91%
8	949.79	958.76	0.94%	428.77	432.82	0.94%
9	944.24	953.49	0.98%	426.27	430.44	0.98%
10	938.69	948.24	1.02%	423.76	428.07	1.02%
11	933.14	943.03	1.06%	421.26	425.72	1.06%

12	927.59	937.84	1.11%	418.75	423.38	1.11%
13	922.04	932.68	1.15%	416.25	421.05	1.15%
14	916.49	927.55	1.21%	413.74	418.73	1.21%
15	910.95	922.45	1.26%	411.24	416.43	1.26%
16	905.4	917.38	1.32%	408.73	414.14	1.32%
17	899.85	912.33	1.39%	406.23	411.86	1.39%
18	894.3	907.31	1.45%	403.72	409.60	1.46%
19	888.75	902.32	1.53%	401.22	407.35	1.53%
20	883.2	897.36	1.60%	398.71	405.11	1.61%
21	877.66	892.43	1.68%	396.21	402.88	1.68%
22	872.11	887.52	1.77%	393.7	400.66	1.77%
23	866.56	882.64	1.86%	391.2	398.46	1.86%
24	861.01	877.78	1.95%	388.69	396.27	1.95%
25	855.46	872.95	2.04%	386.19	394.09	2.05%
average	922.04	933.42	1.23%	416.25	421.38	1.23%

The project's power generation accounts for 70.6% of the total power generation, 23.6% of the power generation in the usual section, and 5.8% of the power generation in the valley section. Based on the fixed time-sharing tariff in 2022: peak time 1.1358623 yuan/kWh; peak time 0.9480245 yuan/kWh; normal time 0.6473666 yuan/kWh; valley time 0.3360381 yuan/kWh. Power sales agreement with the power consumption unit, with a discount of 10% to the calculation of its composite unit price, the project's selling price for electricity is: $0.8416 \times 90\% = 0.7574$ yuan/kWh, and the consumption ratio is 90%. 90% = 0.7574 yuan/degree, the rate of consumption is considered according to 90%, and the remaining 10% surplus electricity is considered according to the benchmark feed-in tariff of desulfurization coal-fired power plant in Hubei Province of 0.4161 yuan/degree, and the comprehensive price of electricity is: $0.7574\times90\%+0.4161\times10\% = 0.7232$ yuan/degree. Therefore, the actual self-generation and self-consumption rate of the project is 90%, and the comprehensive electricity price is RMB 0.7232/kWh. The self-generation and self-use rate calculated by the simulation planning platform is 89.81%, and the comprehensive electricity price is 0.723 yuan/kWh. The error analysis is shown in Table 3.

Table 3. Error in the calculation of self-generation and self-consumption rates and comprehensive electricity price.

Parameter name	Unit	Actual	simulation	Error
self-generation and self-consumption rate	%	90%	89.79%	0.23%
comprehensive electricity price	yuan/kWh	0.7232	0.7226	0.08%

The annual on-grid power generation capacity of the project is 4.1625 million kWh. Compared with the coal-fired power plant, with the standard coal consumption of 304.9g/kWh for power supply, it saves 1269.15 t of standard coal per year, and reduces the emission of sulfur dioxide (SO_2) by about 0.67t, nitrogen oxides (NO_X) by about 0.75t, and carbon dioxide (CO_2) by about 3463.20t. The simulation results of the planning platform are compared with the actual results, and the error analysis is shown in Table 4.

Table 4. Error in the calculation of energy saving and emission reduction benefits.

Parameter name	Unit	Actual	simulation	Error
Annual coal savings	t	1269.15	1300.06	1.23%
Annual CO_2 emissions reduction	t	3463.2	3411.12	2.66%
Annual SO_2 emissions reduction	t	0.67	0.71	5.9%
Annual NO_X emissions reduction	t	0.75	0.76	1.3%

Under the premise of ensuring that the distributed photovoltaic system designed in the simulation planning platform is consistent with the actual project, the errors of the ten-year power generation, self-generation and self-consumption rate, and the comprehensive tariffs calculated in the simulation platform are within the acceptable range, and at the same time, energy-saving and emission reduction benefits can be obtained, and in a comprehensive point of view, the distributed photovoltaic simulation planning platform can satisfy the project's pre-project planning and design.

5 Conclusion

In this paper, for the distributed photovoltaic system is difficult to realize the problem of accurate and efficient design, developed a distributed photovoltaic simulation planning platform, respectively, for the platform for how to carry out the design of distributed photovoltaic system and the system key indexes calculated in detail, and then combined with the actual project to verify the practical value of the simulation platform.

The simulation results show that: the maximum error in the calculation of 25-year power generation is 2.05%, the error in the calculation of self-generation and self-consumption rate is 0.23%, the error in the calculation of the comprehensive electricity price is 0.08%, the error in the calculation of the annual coal saving is 1.23%, the error in the calculation of the annual reduction of CO_2 emissions is 2.66%, the error in the calculation of the annual reduction of SO_2 emissions is 5.9%, and the error in the calculation of the annual reduction of CO_2 emissions is 1.3%. In summary, the designed distributed PV simulation planning platform can provide guidance value for the pre-design of the project.

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