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Study on the performance characteristics of the substation PVASHP system based on TRNSYS

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Abstract. Taking the substation building as the research object, DeST software is used to simulate the annual building load of the case building, and the load results are connected to the TRNSYS software. At the same time, the G ENOPT software is used to optimize the solar inclination and azimuth, and the system simulation model of solar photovoltaic-air source heat pump is established and the data analysis is carried out. The results show that the peak cooling load of the substation building occurred on July 24th, The numerical value is the 49.28kW, The annual cumulative cooling load of the building is 20165.59 kW·h; Based on Hooke Jeeves algorithm, the optimal inclination of photovoltaic panels is 44.18° and the optimal azimuth is 11.69°; Typical days, The highest peak power of the air source heat pump appears at 1 a.m,Its peak power is 7.47 kW, The COP peak was 3.67; Within the typical week, Solar photovoltaic efficiency shows stable periodic changes, Peak aking around 12:00 noon, Its peak efficiency is 18.14%; There is a significant linear distribution relationship between the solar photovoltaic power generation capacity and the solar radiation, Its linear correlation coefficient was 0.85. Compared with the single air source heat pump system, the composite system saves 18.33% energy and has good application effect.

Keywords: Transformer substation;air source heat pumps;multi-energy complementarity; pattern search algorithms; Numerical simulation

1. Introduction

In order to give full play to the advantages of the “solar PV-air source heat pump” system, the optimal selection of key parameters has become the key. At present, the optimization research methods for solar photovoltaic solar thermal air source heat pump system are mainly divided into two forms: experiment and simulation. Among them, Gao Changwei (2017) [1] combined with the design case of office buildings, designed an air source heat pump heating system with solar power generation and mains complementarity, and carried out a case study of “simulation + experiment”, the results show that the load voltage and current waveform distortion rate in the operation of the composite system is small, which can ensure the stable operation of the system and improve the economy at the same time. Zhang Meng (2022) [2] used TRNSYS software to establish a simulation model of the solar-air source heat pump energy supply system, and the system parameters were used as the optimization variables, and the parameters were optimized by combining the Coordinate Search algorithm to achieve a comprehensive improvement in the operation efficiency of the system. Yang Haihong (2020) [3]took green farmhouses in cold regions of China as an example, and realized the comprehensive energy supply of rural single-family houses by deepening the comprehensive integration of building ontology energy-saving technology, solar energy and air source heat pump combined heating, and photovoltaic power generation technology, which has excellent application benefits. ChenZ (2023) [4] proposed a distributed energy system integrating light/heat and air source heat pumps, and evaluated the thermodynamic and economic performance of the system in the form of simulations over four typical days, and the results showed that the annual cost savings of the system were US$24.22/m².Nicoletti F (2022) [5] established an integrated energy supply system combining heat pumps and photovoltaics to achieve sustainable heating/cooling, in which the data were introduced from the standard components in the Energy Plus calculation code for modeling, and the results showed that the capacity design of the battery should depend on the local climatic characteristics as well as the size of the photovoltaic power plant. ZhangC (2023) [6] pointed out that the building-integrated photovoltaic/heating system is a basic system to ensure the stability of the space thermal environment, and proposed a photovoltaic/heat pump system based on the building facade. The results show that the higher the water temperature of the system, the greater the value of heat loss.

2. Mathematical model

2.1. Air source heat pump model

(1) Mass flow rate of the refrigerant

$$q_{m,\mathrm{com}} = \frac{\eta_v q_{V,\mathrm{th}}}{v_{\mathrm{suc}}} \tag{1}$$

In formula: $q_{m,com}$ for the refrigerant mass flow rate, kg / s; η_v is the volume efficiency; $q_{V,th}$ for the theoretical transmission volume, m^3/s; v_{suc} for the inspiratory ratio volume, m^3/kg.

(2) Evaporator

$$Q_{\mathrm{eva}} = q_{m,\mathrm{com}}(h_1 - h_4) \tag{2}$$

In formula: Q_{eva} for heat for evaporator, kW; h_1 is the outlet enthalpy value of the evaporator, kJ/kg; $h_4$is the inlet enthalpy value of the evaporator, and the kJ/kg.

(3) Condenser

$$Q_{\mathrm{con}} = q_{m,\mathrm{com}}(h_2 - h_3) \tag{3}$$

In formula: Q_{con} for the condenser heat release, kW; h_2 is the inlet enthalpy value of the condenser, kJ/kg; $h_3$is the outlet enthalpy value of the condenser, and the kJ/kg.

(4) Dwelling valve

$$h_3 = h_4 \tag{4}$$

In formula: h_3, h_4 is the anteroposterior enthalpy value of the throttle valve, kJ/kg.

(5) Compressor

$$W_{com} = q_{m,\mathrm{com}}(h_2 - h_1) \tag{5}$$

In formula: W_{com} for the compressor power consumption, kW; $h_1$for the compressor inlet enthalpy value, kJ/kg; $h_2$is the compressor outlet enthalpy value, kJ/kg.

(6) Isoentropy compression efficiency of the compressor

$$\eta = 0.874 - 0.0135\frac{p_2}{p_1} \tag{6}$$

In formula: p_1 for the compressor inlet pressure, the MPa; $p_2$for the compressor outlet pressure, the MPa.

(7) Heating coefficient

$$COP = \frac{Q_{\text{con}}}{W} \tag{7}$$

Where: COP is the heating performance coefficient of the system; W is the system power consumption, kW.

2.2. Mathematical model of photovoltaic modules

(1) Photovoltaic energy balance equation

$$P_{pv,\text{in}} = P_{pv,\text{elect}} + P_{pv,loss} \tag{8}$$

In formula: $P_{pv,in}$ Solar energy obtained for photovoltaic modules, W; $P_{pv,elect}$ for the photoelectric conversion of power of photovoltaic modules, W; $P_{pv,loss}$ for the lost energy, W.

(2) Radiation received on the surface of the battery

$$P_{pv,\text{elect}} = \eta_0 G S_c \tag{9}$$

In formula: P_{elect} is the product of glass transmittance and absorption of cell surface; is the efficiency of photoelectric conversion; $S\eta_{0c}$is the total area of photovoltaic modules, m^2.

(3) Photoelectric conversion efficiency

$$\eta_0 = \eta_{pv}\left[1 - \gamma\left(T_p - T_r\right)\right] \tag{10}$$

η_{pv}Where: it is the photoelectric conversion efficiency of photovoltaic modules at room temperature, and it is the photovoltaic temperature variation factor; $T\gamma_p$for the photovoltaic operating temperature, °C; T_r for the reference temperature, the °C.

2.3. The DeST load calculation model

The basic method for DeST to solve the building thermal process is the state space method, which is characterized by the difference in space while keeping continuous in time. The simulation object with relatively uniform temperature in internal space is regarded as a temperature node alone, and the thermal balance equation of indoor air is as follows:

$$\rho_a c_{\text{pa}} V_a j\omega T_a = \sum_j h_{\text{in}} f_j\left(T_{j1} - T_a\right) + c_p \rho G(T_o - T_a) + Q_{\text{iner}} + Q_{\text{hvac}} \tag{12}$$

c_{pa} ρ_a $V_a G$In the specific heat capacity of the air, indicating the density of the air, is the volume of the air volume through penetration and natural ventilation; is the part of the indoor heat production into the indoor air by convection; is the heat provided by the indoor air conditioning. Q_{inner} Q_{hvac}

3. Building load calculation based on DeST

3.1. Model modeling

When carrying out primary planning and energy saving design of substation, it is necessary to consider the size of the building load from the building body. The DeST software is used to focus on the building load situation. The single-floor building area of the substation building is 1,501 m^2, 1 floor with a height

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of 10.3m. The design site is Ningbo, China, and the climate area is hot summer and cold winter. The schematic diagram of DeST building model is shown in Figure 1.

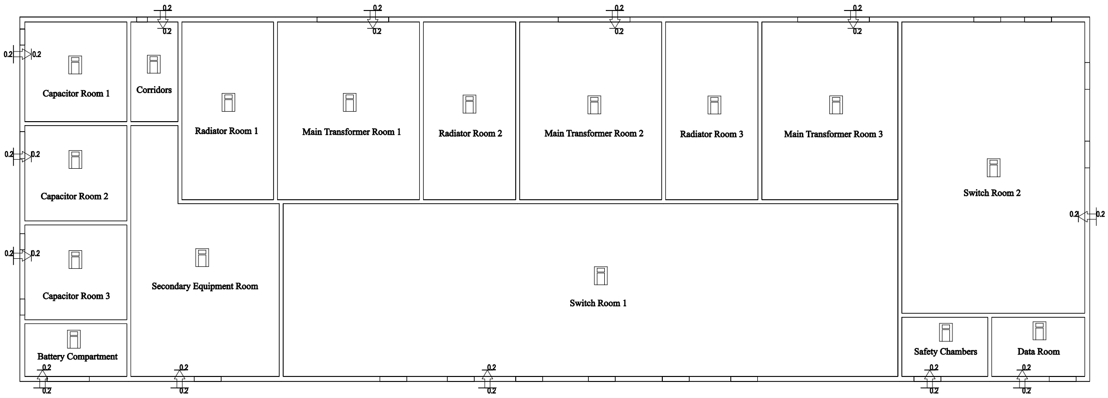

Figure 1. Schematic representation of the DeST model

3.2. Description of the model parameters

DeST adopts the method of dynamic model of building thermal process, comprehensively considers the heat storage and release of building envelope structure and objects, including the long wave radiation heat exchange between the internal surface and the convection of the room. The room thermal balance method carries out the simulation of 8760 hours throughout the year, and finally the annual load of the building and the thermal parameters of the envelope structure are as shown in Table 1.

Table 1. Thermal parameters information of the envelope structure

Building name	exterior wall ($W/m^2 \cdot K$)	exterior window ($W/m^2 \cdot K$)	roof ($W/m^2 \cdot K$)	South corner (°)
converting station	1.0	3.2	0.65	270

The room rate of indoor personnel refers to the actual survey results of the substation, and the heat dissipation of lights is 75W / m^2, The per capita fresh air volume is 30m^3/ (h · p), set the lighting time and equipment utilization rate according to the personnel rate. The ventilation times in the room is 0.5 ach.

3.3. Annual load calculation results of the building

After the comparative analysis of the scheme, the annual construction load simulation was conducted on the optimized optimal scheme combined with DeST software, and the annual dynamic load results of the optimal scheme are shown in Figure 2.

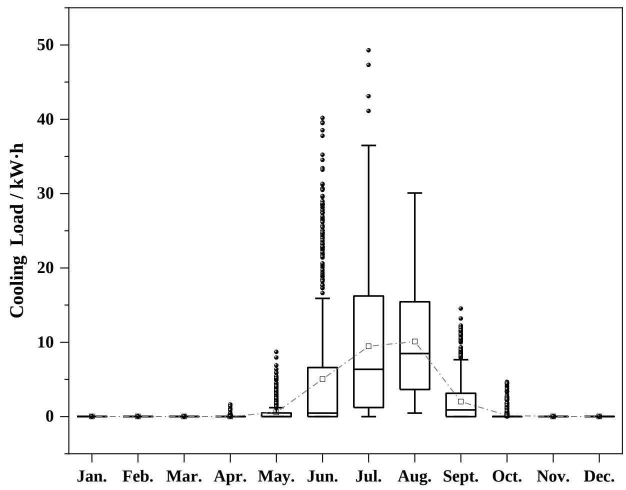

Figure 2. Results of building cooling load successively

According to the analysis of Figure 2, the peak cooling load occurred on July 24, and the value was 49.28kW, and the annual cumulative cooling load of buildings was 20165.59 kW · h.

4. Optimal calculation of photovoltaic panel parameters based on Genopt

4.1. Optimization method

The photovoltaic power station model is built in the T RNSYS software, and the variable parameters can be optimized through the Hooke Jeeves algorithm built into Genopt and TRNSYS. Among them, the artificial intelligence Hooke-Jeeves algorithm is a smooth and non-linear "mode search method"[7], Has a strong local search ability and search ability fast characteristics. In the optimization calculation, the optimization variable is first selected and the initial value and change range of the variable are set, and then the target function and optimization algorithm are selected to continuously transform the value of the variable until the algorithm converges, and the optimization is completed [8].

4.2. Optimization variables

Considering the actual factors such as building area and installation location, the photovoltaic module inclination and azimuth of photovoltaic module are selected as optimization variables. According to GB 50364- -2018 Application Technical Standard for Solar Energy System in Civil Buildings and the engineering design experience of Ningbo city, the change range of optimization variables is determined. The schematic diagram of the model is shown in Figure 3.

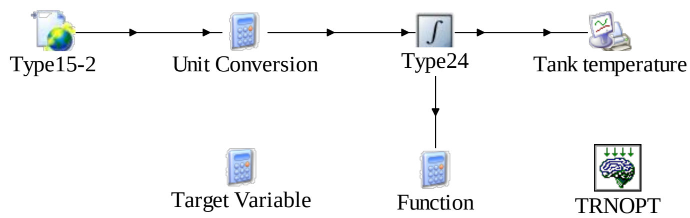

Figure 3. Shows the TRNSYS optimization model based on the "Hooke-Jeeves" algorithm

The generated BUI file and all the DCK file contain the information of the system. The BUI file and DCK file are called through Genopt to transfer the input value of each variable to T RNSYS for simulation calculation[9], During the continuous iterative calculation process, the optimal parameter set is finally obtained. The parameter range of the solar azimuth is (-10°, 10°), the parameter range of the

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inclination is (30°, 60°), and the objective function is the highest radiation received by the overall surface of the module, realizing the synchronous optimization of the inclination Angle and azimuth. The schematic diagram of the calculation results is shown in Figure 4.

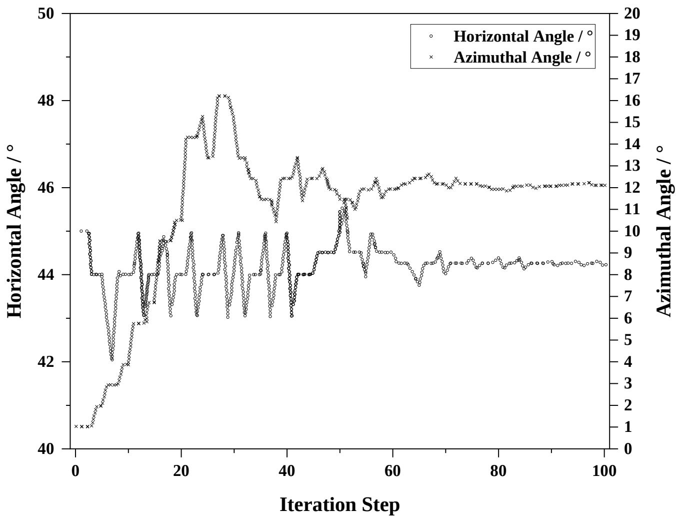

Figure 4. Iteratively calculates the optimization process

Judging from the data results in Figure 4, it can be seen that the Hooke-Jeeves algorithm uses continuous parameter iterative calculation. In the process of iterative calculation of the optimized variables, the iterative state reaches a stable and stationary state when the calculation reaches 65 steps, and the optimal solution is obtained for the optimized variables. At this time, the optimal inclination Angle is 44.18°, and the optimal azimuth Angle is 11.69°.

5. Based on the "PV-ASHP" model based on TRNSYS

5.1. System operation principle

The "PV-ASHP" model is built through TRNSYS simulation software, in which the system modules in the simulation platform mainly cover Type 152 meteorological parameter module, Type 114 water pump module, Type 682 load access module, Type 141 start-stop time control module, Type 47 battery module, Type 158 water tank module, Type 941 air source heat pump module, Type2b controller module, Type 94 solar photovoltaic panel module, etc.

In order to facilitate the calculation, the following setting: circulating medium is single phase, uniform, normal property, incompressible fluid; the pipe is filled with circulating medium, and the working condition of circulating pump remains stable[10]; There is no energy loss during the circulating medium transmission process, and the simulation system is shown in Figure 5.

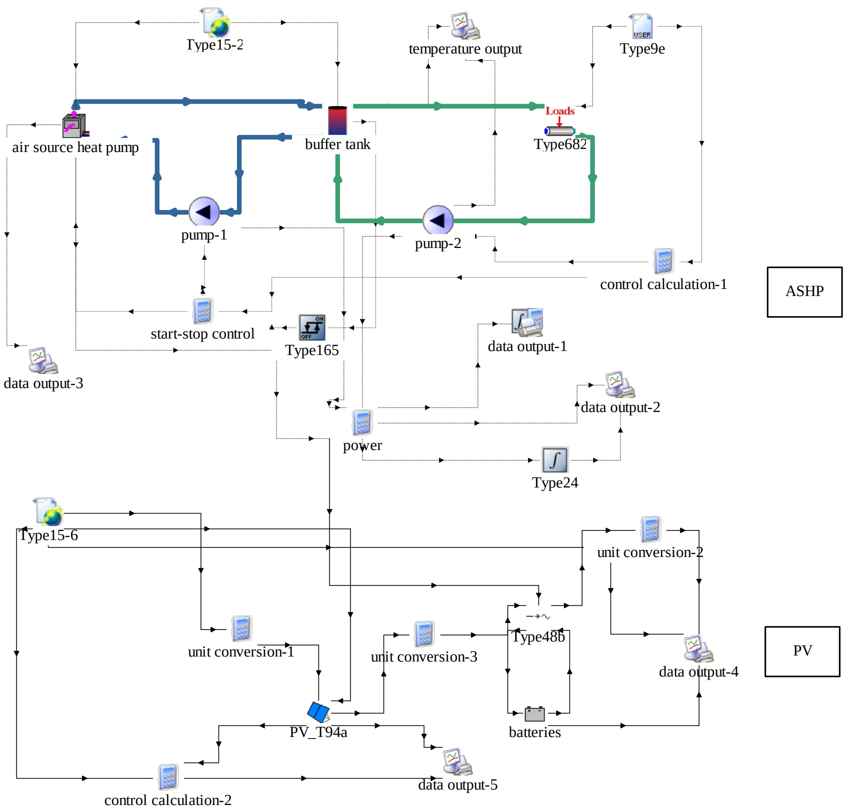

Figure 5. Shows the "PV-ASHP" model based on the TRNSYS

5.2. System operation strategy

The signal by $T_{f,o}$ and the temperature difference at the bottom of the heat storage tank is $T_{f,I}$ carry out temperature difference control, and the temperature difference parameter is 5°C. When the temperature difference is more than 5°C, the circulating pump is opened and the unit starts to operate; when the temperature difference is less than 2°C, the circulating pump is closed, the heat pump unit operates at the same time, and the unit determines the operation state of the system every 7.5min.

In the recharge control strategy of air source heat pump battery, when the battery is not discharged, the municipal power supplement begins; in the battery charge and discharge control strategy, when the remaining photovoltaic power generation is not used up and the SOC (capacity) of the battery is less than 80%, the battery starts to charge; when the SOC is greater than 90% or there is no excess power generation, the charging is stopped.

5.3. Typical daily system operation results

(1) ASHP system power simulation

In the analysis and study of A SHP system performance, August 15 was selected as a typical day for data analysis, and the changes of air source heat pump power, water pump power and system COP were mainly discussed from the system side. The change trend of the data within the typical day is shown in Figure 6.

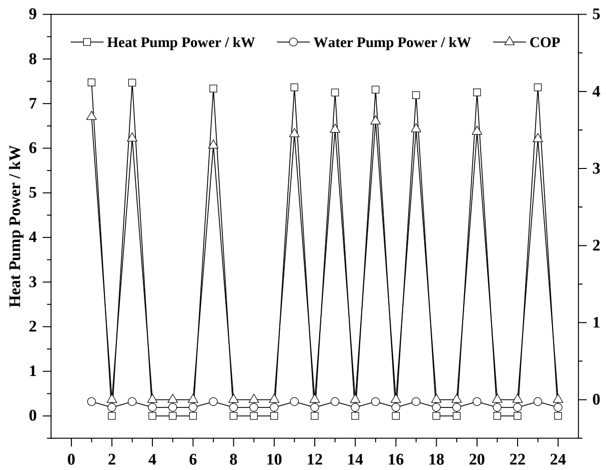

Figure 6. Typical daily operation results of the ASHP system

As can be seen from the analysis of Figure 6, we can see that due to the existence of the energy storage tank, the overall operation of the heat pump system shows an intermittent operation trend, which can better save power resources compared with the traditional continuous operation conditions. In the time range from early morning to early morning, the room can maintain a stable environmental state through its own heat storage, and the unit is shut down for a long time. At the same time, the peak power of the air source heat pump is at 1 am, and its peak power is 7.47 k W. The COP value showed a synchronous change trend with the unit, with a peak COP value of 3..67

(2) PV system efficiency simulation

The power consumption of the air source heat pump is mainly supplied by the photovoltaic power generation. When the real-time photovoltaic power generation power is not enough to meet the demand of the air source heat pump, the power grid will be supplemented to meet the stable operation of the heat pump. Therefore, the PV system efficiency directly determines the operation stability of the system[11], The efficiency of PV system is analyzed by the operation cycle from August 1st to August 7th, and the simulation results of PV system efficiency are shown in Figure 7.

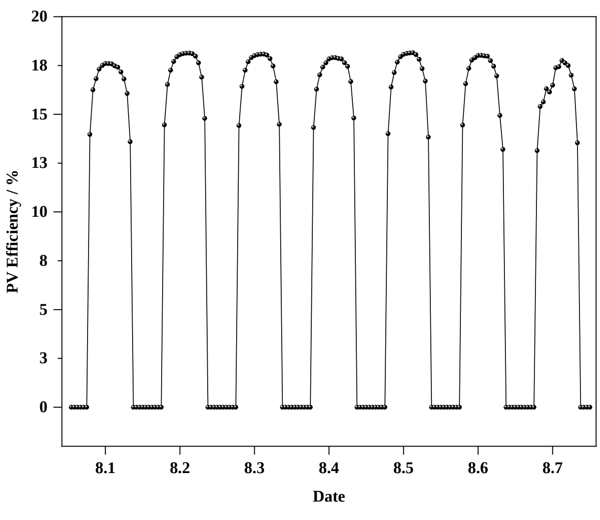

Figure 7. A. Simulation of the PV system efficiency

Through the data analysis in Figure 7, it can be seen that the operation of PV system has significant periodicity. With the increase of solar irradiance, the photovoltaic efficiency is also gradually increasing, basically reaching the peak around 12 noon, and the peak efficiency is 18.14%, and the operation is relatively stable. Compared with the single A SHP system without PV system, the composite system saves 18.33% compared with the initial building, which has good energy saving effect.

6. Analysis of the influence law of solar radiation on power generation

PV system running power is directly affected by solar irradiation, to explore the relationship between solar irradiance and PV system output value, the typical cooling season in July, 8, September and linear correlation value of solar radiation value, the generating power and numerical distribution relationship between solar radiation value as shown in figure 8.

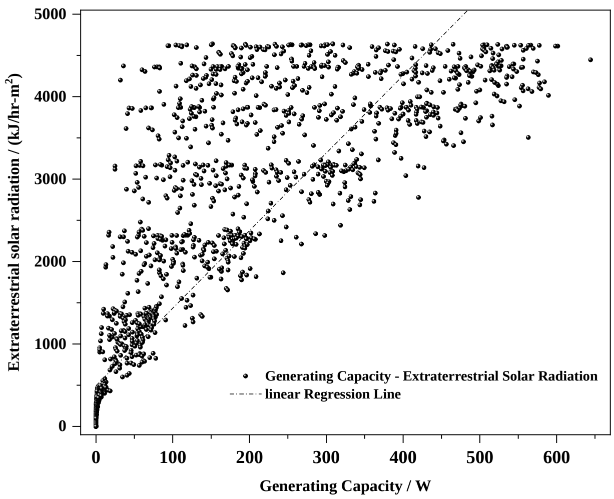

Figure 8. Numerical distribution relationship between power generation capacity and solar radiation

Through the analysis in Figure 8, we can see that there is a significant linear distribution relationship between power generation capacity and solar radiation. The empirical model fitted according to the parametric model requirements of linear regression is shown as follows.

$$y = 9.41x + 494.89(R2 = 0.85) \tag{12}$$

Where, y- -solar radiation, kJ / (hr-m^2); X- -Power generation power, W.

7. Conclusion

Multi-energy complementarity is a crux way to integrate resources, energy and energy demand, and to alleviate the contradiction between energy supply and demand. In the study of this paper, the specifications parameters and operational characteristics of the thermal environment of the substation are combined in depth, and a set of photovoltaic air-source heat pumps coupled with photovoltaic systems is designed to be able to utilize solar energy resources in depth. By using DeST energy consumption software and TRNSYS simulation software to simulate and analyze the design scheme, and derive the hour-by-hour cold negative load of the design building in Ningbo area. The solar photovoltaic - air source heat pump system model was established using the TRNSYS simulation platform, which realizes energy complementarity and makes up for the deficiencies of the traditional single-system operation. Through the simulation, it can be seen that the cumulative annual cooling load of the building is 20,165.59 kWh, the optimal tilt angle of the optimal PV panels is 44.18°, the optimal azimuth angle is 11.69°, the peak power of the composite system is 7.47 kW, and the peak COP is 3.67. The PV panels operate in a more stable manner, and there is a significant linear correlation between the power generation and solar radiation, which has a better application results. The PV panels operate more stably, and there is a significant linear correlation between power generation and solar radiation, which

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has a better application effect and lays the foundation for commercialization and its popularization and application.

References

[1] Gao Changwei, Liu Xiaoming, Huang Chong Yang. Research on air source heat pump heating system for solar power generation [J]. Science, Technology and Engineering, 2017,17 (13): 177-181.
[2] Zhang Meng, Hao Xuejun, Tong Zheng. Solar photovoltaic solar thermal air source heat pump energy supply system optimization simulation [J]. Gas and Heat, 2022,42 (09): 17-21.
[3] Yang Haihong, Tian Bin, Mi Ying ying, etc. Design and operation of multi-energy complementary system for green farm houses in severe cold areas [J]. Building Energy Saving, 2020,48 (03): 35-39.
[4] Chen Z, Su C, Wu Z, et al.Operation strategy and performance analyses of a distributed energy system incorporating concentrating PV/T and air source heat pump for heating supply[J].Applied Energy, 2023, 341: 121125.
[5] Nicoletti F, Cucumo M A, Arcuri N.Cost optimal sizing of photovoltaic-battery system and air–water heat pump in the Mediterranean area[J].Energy Conversion and Management, 2022, 270: 116274.
[6] Zhang C, Chen L, Zhou Z, et al.Heat harvesting characteristics of building façades integrated photovoltaic /thermal-heat pump system in winter[J].Renewable Energy, 2023, 215: 118909.
[7] Yuan Jing, Wang Xuan, Ma Li, etc. Research on rural house photovoltaic-air source heat pump combined heating technology in Chengde area [J]. Building Science, 2023,39 (08): 241-245.
[8] García-Gáfaro C, Escudero-Revilla C, Flores-Abascal I, et al.A photovoltaic forced ventilated façade (PV-FVF) as heat source for a heat pump: Assessing its energetical profit in nZEB buildings[J].Energy and Buildings, 2022, 261: 111979.
[9] Herrando M, Coca-Ortegón A, Guedea I, et al.Experimental validation of a solar system based on hybrid photovoltaic-thermal collectors and a reversible heat pump for the energy provision in non-residential buildings[J].Renewable and Sustainable Energy Reviews, 2023, 178: 113233.
[10] Li Z, Huang X.Simulation analysis on operation performance of a hybrid heat pump system integrating photovoltaic/thermal and air source[J].Applied Thermal Engineering, 2022, 200: 117693.
[11] Wang J, Xu S, Ma G, et al.Emergy analysis and optimization for a solar-driven heating and cooling system integrated with air source heat pump in the ultra-low energy building[J].Journal of Building Engineering, 2023, 63: 105467.