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Analysis of the Complementary Property of Solar Energy and Thermal Power Based on Coupling Model

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ABSTRACT

To further improve the traditional coal-fired power generation, lower the pollutant emission, and comprehensively implement the energy saving and emission reduction policy, the view that the solar-assisted coal-fired power generation system is the complementary and integrated power system of clean energy and traditional fossil energy has been put forward in the paper. Due to the complexity of solar-assisted coal-fired power generation system, the unified integration principles of the system haven't been established yet. On the basis of the energy conversion happened in the solar-assisted coal-fired power generation system and the simple coal-fired power generation system, a physical model of two different power input of the power generation system is established, the instantaneous photoelectric efficiency expression of solar-assisted coal-fired power generation system is obtained, and the major factors that affect the solar-assisted coal-fired power generation system are concluded. The results provide the practical in-progress solar-assisted coal-fired power generation system with a basic theoretical basis. Therefore, on the one hand, the solar-assisted coal-fired power generation system helps the large-scale and low-cost development and exploitation of solar thermal power systems; on the other hand, it accelerates the implementation of energy saving and emission reduction policy in traditional coal-fired power plants. It is an effective solution to the problems of ever-increasing environmental pollutions and the limited traditional fossil energy supplies.

INTRODUCTION

Energy is the lifeblood of the national economy. It is closely related to the livelihood of people and the survival of human being. It is of great significance to the sustainable development of a society. Being the most important component of energy resource structure, coal is the most stored fossil fuel worldwide and is distributed more evenly all over the world than other fuels (like gasoline and natural gas). Considering the storage of coal and the economic situation worldwide, the role of coal would have no substantial transformations over a long period of time in the future. In terms of the Chinese power system, the coal-fired units occupied more than 70% of the total power units and approximately 60% of the total coal consumption. Therefore, coal-fired power plants would be one of the major power supplies in China over a long period of time in the future (Zhai et al. 2015). In recent years, the Chinese government has introduced a series of energy consumption control policies and environmental protection requirements, which brings not only new challenges but also limitations to the development of coal-fired power plants. Coal-fired power plants are under great pressure of energy saving and emission reduction (Yu et al. 2015).

Therefore, introducing the photo-thermal system to the regular coal-fired power plants for composing a photo-coal complementary power generation system would utilize the advantages of wide adjustment ranges of power units, making it unnecessary to apply the heat accumulation and turbine systems of solar thermal power plants. In addition, the solar-assisted coal-fired power plants would lower the coal consumption of coal-fired units and relieve the fossil energy shortages on the one hand; if the solar power supply is in scarce need, on the other hand, the coal-fired units are able to supply the power separately, which would effectively solve the problem of intermittency of solar power application, lowering the investment costs of developing and utilizing the solar power. Meanwhile, compared with other renewable resources, solar thermal power system takes the heat as the medium of intermediate energy, making it relatively easy to couple with the coal-fired power system.

PAST RESEARCH

The photo-coal complementary power plant is the integrated energy system of the solar energy collector system and coal-fired power plant. Researches on the complementary

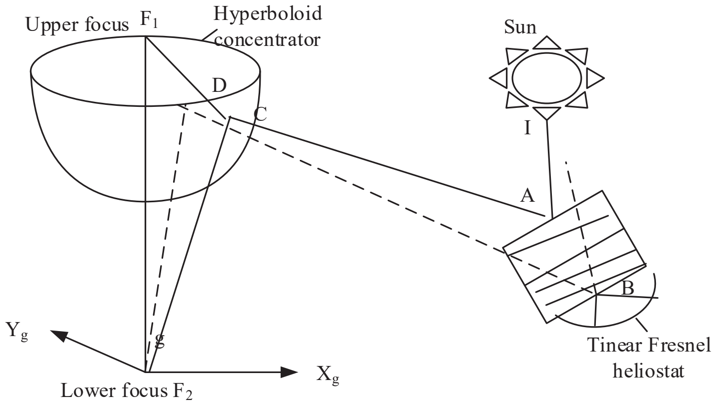

Fig. 1: Principle diagram of point-line coupled focusing solar energy collector system.

system shall focus on the solar energy collector system, the coal-fired power system, and the coupling correlation as well as the corresponding properties between the two systems. Both domestic and foreign scholars have done researches on them. A study explored the photo-coal complementary power system and its operation mode; they analysed the heat-economy of solar power application in coal-fired power units in terms on different grounds or with different capacities (Loew et al. 2016). Recent study discussed the factors that affect the selection of solar radiation during the designing process of the solar power field in compounded power units; besides, they took solar resources of three different places as examples to calculate the optimal design value of solar radiation and obtained the correlation between the solar resource and the optimal design value (Singh et al. 2015). Based on a thermal circulation boiler of a 300MW power unit, a research calculated the properties of wall circulation of given 40 different operating modes (Li et al. 2016). A study also analysed the impacts of solar power utilization on wall circulation in 2015, their calculation and analysis showed that solar power utilization has obvious impacts on the evaporation point and under-heating of drum water (Wu et al. 2015). A research integrated the solar power and the boilers of biomass power plants based on the fundamental theories of solar-assisted coal-fired power plants, replacing some parts of heaters in biomass power stations with solar power and realizing the utilization of complementary power generation system (Yong et al. 2017). Based on the limitations of current researches on the combination of solar power and the coal-fired power plants, a previous research took the design conditions as the reference condition and put forward that the reference conditions shall be the actual operating conditions of the combination of solar power and the coal-fired power plants in 2017 (Wang & Jie 2017). In 2017, Wu & Zhen (2017) established an optimized comprehensive integration model of the topological structure and parameters of the solar power-coal integrated thermal power system and conducted simulation analysis on huge amounts of integration plans. A previous study built the compounded power system of coal-fired power units and solar energy collector in 2017; from the theoretical perspective, they analysed the thermodynamic performance and the heat-economy (Wei et al. 2017). You et al. (2018) also discussed the factors that affect the selection of solar radiation during the designing process of the solar power field in compounded power units; besides, they took solar resources of three different places as instances to calculate the optimal design value of solar radiation and obtained the correlation between the solar resource and the optimal design value.

MATERIALS AND METHODS

Optics is the foundation of the solar energy collector system, while the absorbing surface radiation heat flow boundary condition based on the optical properties is the precondition of photo-thermal conversion analysis. Therefore, based on the dual-axis tracker wire non-reflecting condenser, a point-line coupled focusing solar energy collector system is proposed and the basic structure and operating principles of the major optical components of the system are explained.

Fig. 1 shows the operating principles and the structure of the point-line converging focusing solar energy collector system based on the Tinear Fresnel heliostat. The system mainly consists of dual-axis tracker wire non-reflecting condenser, BD reflector, and CPC receiver. As Fig.1 shows, the focal point F1 on BD reflector is the object point; the incoming sun rays (IA and IB) are focused to the BD reflector on the top of the tower by the Tinear Fresnel heliostat with the focal points being C and D respectively; then, the sun rays are re-focused to the CPC receiver which locates at the near-ground focal point F. Consequently, a photo-thermal energy conversion process is completed. In the system, the Tinear Fresnel heliostat is a line-focusing condenser, BD reflector, and CPC condenser are all point-focusing condensers. Therefore, the system is called point-line converging focusing heat collector system. The Tinear Fresnel heliostat with dual-axis tracker wire possesses the advantages of good resistance to wind damage and simple structure of traditional Tinear Fresnel condenser; in terms of the differences of tracking modes between the two kinds of condensers, the Tinear Fresnel heliostat is of more compact layout and less land occupation compared with a traditional heliostat.

Regular coal-fired power systems mainly consist of a boiler, steam turbine, and regenerative heater. These components are attached to pipes successively, and transport the working fluids of heat transfer and work applied. The steam generated in the boiler first works in the high-pressure cylinder of steam turbine; then the steam discharged from the high-pressure cylinder goes into the regenerative heater for re-heating; the reheated steam then successively goes to the mid-pressure cylinder and low-pressure cylinder to work and the exhaust steam is discharged into the condenser and is condensed into steam condensate; the steam condensate is pumped into each low-pressure regenerative heater successively by the condensate pump, and is transported to each high-pressure regenerative heater in succession through feedwater pump. Consequently, it enters the boiler again and starts a new circulation. The energy balance model of the coal-fired power system is established in accordance with the first law of thermodynamics. The boiler is the major device to achieve the transmission of fuels from chemical energy into thermal energy; its heat balance equation is:

$$m_c \times q_s \times \eta_b = m_{ms} \times (h_{ms} - h_{iw}) + m_{rs} \times (h_{ro} - h_{ri}) \ldots(1)$$

In the equation, m_c is the fuel mass, kg/s; q_s is the fuel calorific capacity, kJ/kg; is the thermal efficiency of the boiler; m_{ms} is the steam flow at boiler outlet, kg/s; h_{ms} is the steam specific enthalpy at the boiler outlet, kJ/kg; h_{iw} is the feedwater specific enthalpy at boiler inlet, kJ/kg; m_{rs} is the reheated steam flow, kg/s; h_{ro} is the steam specific enthalpy in regenerative hot section, kJ/kg; h_{ri} is the steam specific enthalpy in regenerative cold section, kJ/kg.

Superheated steam generated in the boiler expands and works in the steam turbine, as the following equation shows:

$$w = m_s \times (h_{si} - h_{so}) \times \eta_i \qquad \ldots(2)$$

In the equation, w is the work applied by steam in a steam turbine, kJ/s; m_s is the steam flow of steam turbine, kg/s; h_{is} is the steam specific enthalpy at steam turbine inlet, kJ/kg; h_{so} is the steam specific enthalpy at steam turbine outlet, kJ/kg.

RESULTS AND DISCUSSION

Analysis of the Thermal Properties of Solar Power Photo-coal Complementary Demonstration Power Plant

In the system flow of the photo-coal complementary demonstration power plant, the solar power is utilized to replace certain low-pressure cylinder in terms of heating steam condensate in the regenerative system; the steam condensate reheated by solar power is re-fed into the de-aerator for circulation, while the replaced steam continues to work in the steam turbine. Consequently, solar thermal power is output in the form of electricity.

For convenient analysis, the major devices and the energy transmitting processes of the solar energy photo-coal complementary power plant are simplified in accordance with the functions, as shown in Fig. 2. The simplified photo-coal complementary power plant consists of 4 major subsystems and 8 enthalpy flows. The 4 major sub-systems are respectively: (1) boiler preheating, evaporating and super-heating subsystem; (2) turbine power subsystem; (3) solar power oil-water heat exchange subsystem; and (4) heat exchange subsystem.

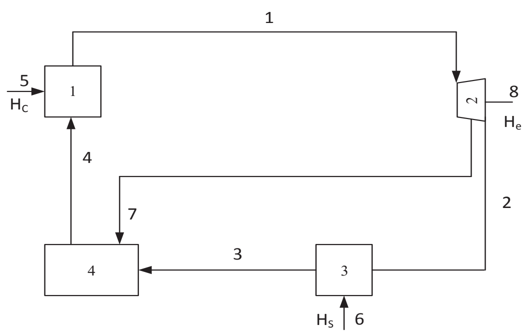

Fig. 2: Chart of simplified solar energy photo-coal complementary power plant system.

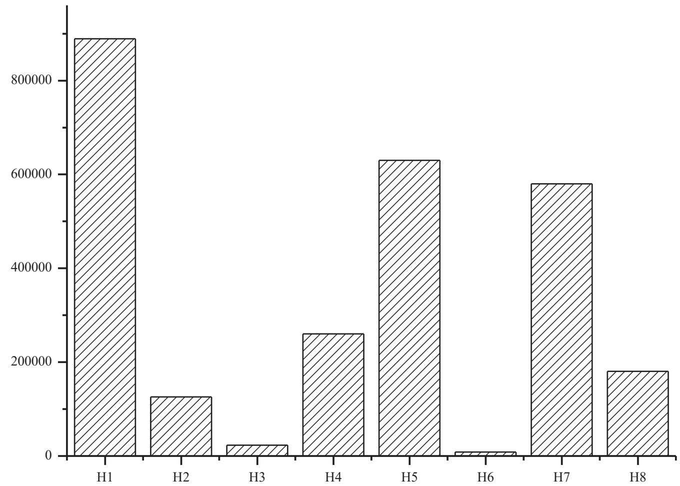

Fig. 3: Enthalpy flow value of each unit in demonstration power plant.

Table 1: Proportion of solar energy in the demonstration power plant.

The proportion of solar energy a	%
a_1	0.1
a_2	0.1
a_3	6.3
a_4	0.34
a_5	0
a_6	100
a_7	0.1
a_8	0.1

Through the simulation model of solar energy photo-coal complementary power plant established before, the parameter distribution properties of major devices of the system in the complementary powering operating mode are analysed. Based on the simplified system structure demonstrated in Fig. 2, the corresponding thermodynamic parameters of the system are calculated. The values of enthalpy flow of the demonstration power plant are shown in Fig. 3, and the proportion of solar energy is shown in Table 1.

Of all the enthalpy flows and the proportion of solar energy in the demonstration power plant, it can be inferred from Fig. 3 and Table 1 that the proportion of solar energy in total thermal enthalpy of the 6th enthalpy flow reaches 100%, i.e. the solar power occupied 100% in the solar energy enthalpy flow. The proportion of solar energy in enthalpy flows gradually decreases as the steam-water system circulates. The 8th enthalpy flow H8 shown in Fig. 3 represents the enthalpy value of the power generated by the steam turbine power unit; the solar energy occupies 0.10% of the enthalpy flow. It shows that under the operating mode of the photo-coal complementary demonstration power plant, the solar energy occupies 0.10% in the total energy output. More precisely, if the rated power of the complementary demonstration power plant is 50MW, the solar power output would be 0.05 MW, and the coal-fired power output would be 49.95 MW.

Research on Operation Properties of Solar Energy Photo-coal Complementary Power Plant with the Heat Collector

In accordance with the perennial meteorological data of the photo-coal complementary demonstration power plant, the annual direct solar radiation of the site is calculated to be 1970 kWh/m^2, and the horizontal total radiation is calculated to be 1699 kWh/m^2. Solar radiation intensity on a typical summer day is selected to explore the operation modes and properties of the complementary power plant. The time-variant solar radiation intensity on the typical summer day is shown in Fig. 4.

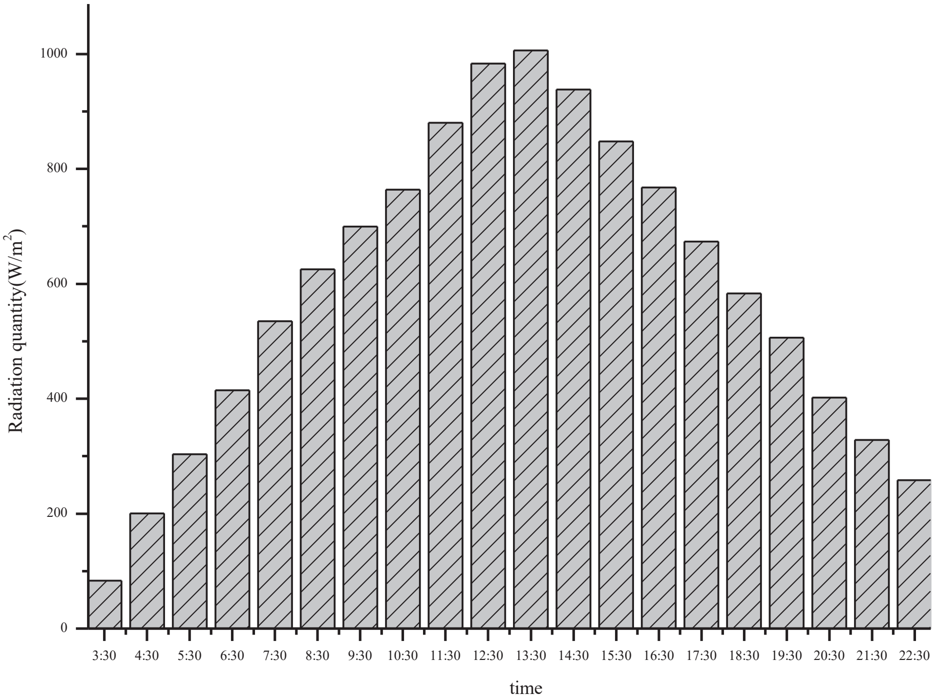

Fig. 4: Chart of time-variant solar radiation intensity on a typical summer day.

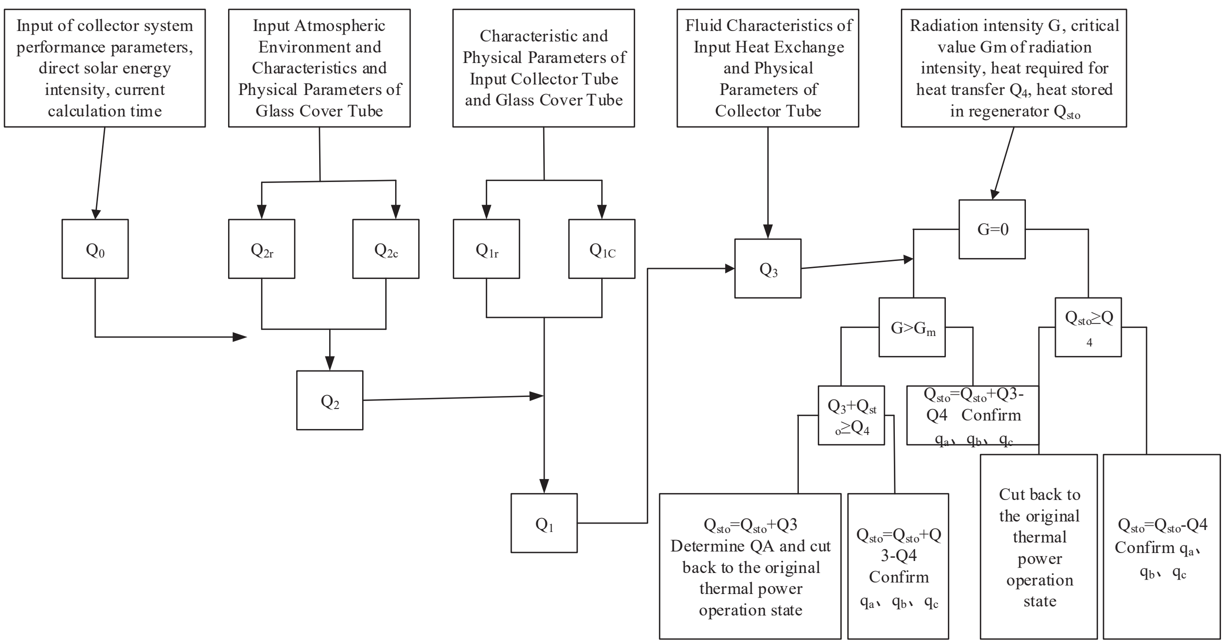

Fig. 5: Solar energy side operation strategy of solar energy coal complementary power station.

It can be inferred from the solar radiation distribution chart (Fig. 4) that the sun rises after 5:30 a.m. on the day; since then, the solar radiation intensity gradually increases in accordance with the time, and reaches the maximum at 12:30-13:30 in the noon. After 13:30, the radiation intensity decreases sharply; the sun sets at 20:00 and the radiation intensity is zero.

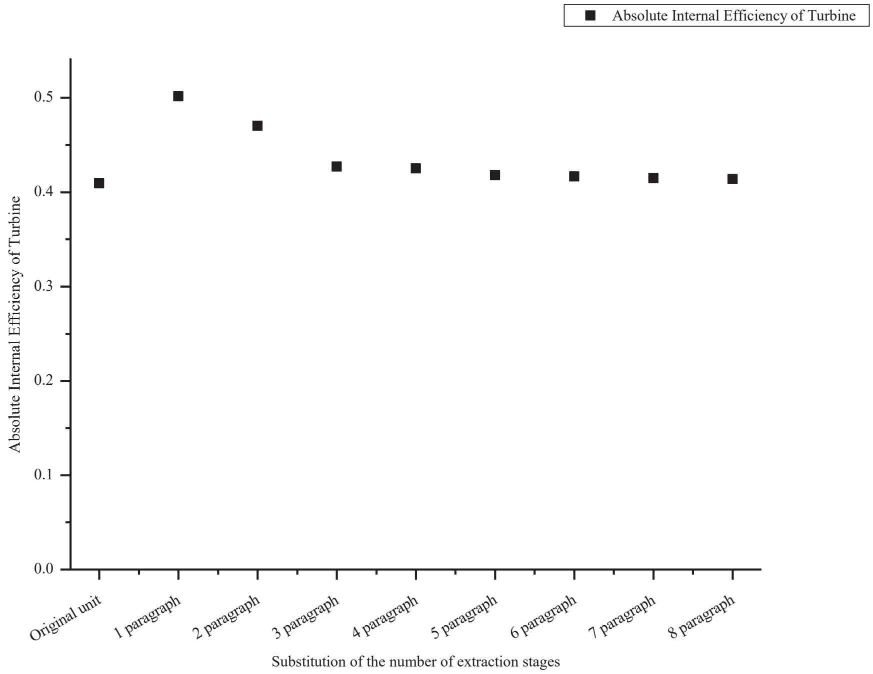

Fig. 6: Absolute internal efficiency of steam turbines with integrated modes.

Due to the intrinsic fluctuation property of solar radiation, when the solar energy photo-coal complementary power plant is in stable operation, the solar power demanded by the coal-fired power units is constant, then the corresponding total solar radiation intensity of demanded solar power G_m is defined as the radiation threshold. In accordance with the total radiation intensity, the actual operation mode of the photo-coal complementary power plant with heat collector are categorized into following 3 categories: (1) the total radiation intensity is higher than the threshold; (2) the total radiation intensity is lower than the threshold; and (3) the radiation intensity is zero. Under the 3 operation modes, the operation control strategies of the complementary power plant are shown in Fig. 5.

Analysis of the Radiation Properties of the Photo-coal Complementary Compounded Power System

The section mainly focuses on the analysis of the integrated properties and the thermodynamic properties of the capacity expansion solar steam direct generation system and the coal-fired power units under different integrated modes of single radiation intensity. The analysis follows the principle of "proper temperature and gradient utilization of energy". Certain amount of steam condensate is collected at the condensate pump outlet; after being pressurized by the booster, it is heated by the heat collector fields to certain section of steam extraction parameter, and then returns to the thermal system of the coal-fired power unit; in the thermal system, it is mixed with the steam extraction for getting heated in the heater; meanwhile, the drain generated in capacity expansion evaporator possesses the same pressure as superheat steam, therefore, it is basically the same as the pressure of drain generated in the replaced heater. The replaced steam extraction continues to work in the steam turbine, increasing the system power output. The inlet steam flow, pressure, and temperature are directly related to the steam extraction parameter when solar steam is inlet into different sections of the coal-fired power units. Therefore, the steam extraction flow of the unit varies, which would cause the parameter variations and the property variations in terms of thermodynamic properties and heat-economy in the compounded power system. Based on the 600 MW coal-fired power unit, the operation modes of replacing the 8 steam extraction sections are simulated. Calculations are based on the parameters of the steam turbine unit, the heat collector field, and the compounded system. The variation tendency of thermodynamic properties of the coal-fired power unit aided by capacity expansion evaporative parabolic trough solar power collector system is explored.

Suggestions on the Development of Photo-coal Complementary Power Plant Industry

In recent years, solar thermal power has attracted broad attention and been progressed. As a kind of renewable energy, solar thermal power possesses lots of advantages, such as good power quality and suitable for being built in desolate Northeastern China, etc. However, the solar thermal power industry in China hasn't been industrialized yet; in addition, its supporting system still needs improving and its price policy hasn't been issued. Therefore, the comprehensive promotion and large-scale application of solar thermal power are relatively difficult in China. Due to the sharp decrease in the construction cost of solar photovoltaic (PV) power generation, the return on investment of solar PV power generation is much higher than that of solar thermal power. Thus, in accordance with the development of photo-thermal industries in China, the balanced development of solar thermal power and solar PV power, and the project development of power supply corporations, it is suggested that governmental departments decide the sample solar thermal power price as soon as possible to attract investments on the solar thermal projects, as well as pushing forward the organized development of the solar industry in China.

CONCLUSION

The objective of the present work is to explore the photo-coal complementary compounded power generation system by means of theoretical researches, numerical modelling and simulation calculations, etc. The capacity expansion evaporative solar power direct evaporation generation system is proposed. The general calculation equation of photo-coal complementary compounded power generation system is obtained. The rated radiation and radiation variation model of the photo-coal complementary power system is established. The thermodynamic properties, the operational laws and the impacts of solar-assisted heating system on the performance of the power unit are discussed and explored. Besides, the technical economy and the commercial opportunity of the system are analysed, providing a new approach to optimize the energy structure in China. In summary, the major achievements are demonstrated as follows:

Based on analysing the solar resource properties of the demonstration plant site, the heat collecting properties of the system under the conditions of designed operation modes, array spacing variation, axial installation angel variations and loss of vacuum of heat collecting pipes of the parabolic trough solar power collector system are analysed theoretically. Besides, the environment-variant mechanism and properties of the heat collecting system are also analysed. Next, through analysing 3 typical power generation properties of the solar power system and the solar radiation resources of the demonstration power plant, the environment adaptabilities of different technologies of the solar power system including heat collecting properties are discussed. From the perspective of technology selection, based on demonstration power plant site, the power capacities and systematic heat collecting properties of both trough and tower systems are analysed given the same operating performance, the same heat collecting area, the same collecting hours, and the same installed capacity.

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