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# Analysis of CO<sub>2</sub> Abatement Cost of Solar Energy Integration in a Solar-Aided Coal-Fired Power Generation System in China

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**Abstract:** Utilization of renewable energy, improvement of power generation efficiency, and reduction of fossil fuel consumption are important strategies for the Chinese power industry in response to climate change and environment challenges. Solar thermal energy can be integrated into a conventional coal-fired power unit to build a solar-aided coal-fired power generation (SACPG) system. Because solar heat can be used more efficiently in a SACPG system, the solar-coal hybrid power system can reduce coal consumption and CO<sub>2</sub> emissions. The performance and costs of a SACPG system are affected by the respective characteristics of its coal-fired system and solar thermal power system, their coupling effects, the solar energy resource, the costs of the solar power system, and other economic factors of coal price and carbon price. According to the characteristics of energy saving and CO<sub>2</sub> emission reductions of a SACPG system, a general methodology of CO<sub>2</sub> abatement cost for the hybrid system is proposed to assess the solar thermal energy integration reasonably and comprehensively. The critical factors for carbon abatement cost are also analyzed. Taking a SACPG system of 600 MW in Jinan, Shandong and in Hohhot, Inner Mongolia in China as an example, the methodology is further illustrated. The results show that the efficiency of solar heat-to-electricity should be high and it is 0.391 in the scheme of SIH1 in Hohhot, and that the designed direct normal irradiation (DNI) should be greater than 800 W/m<sup>2</sup> in order to make full use of solar energy resources. It is indicated that the abatement cost of a SACPG system depends significantly both on the cost of solar power system and its relevant costs, and also on the fuel price or the carbon prices, and that the carbon abatement cost can be greatly reduced as the coal prices or CO<sub>2</sub> price increase. The methodology of carbon abatement cost can provide support for the comprehensive assessment of a SACPG system for its design and optimal performance.

**Keywords:** solar-aided coal-fired power generation system; assessment methodology in solar-coal hybrid systems; solar energy integration; CO<sub>2</sub> emission reductions; abatement cost

## 1. Introduction

Improving the share of renewable energies and the efficiency of electricity power generation are the critical strategies to mitigate climate change and environment challenges, especially for China's power supply, on the basis of the energy endowment and the high proportion of coal-fired power generation [1,2]. The efficiency of a coal-fired unit can usually be improved by its energy-saving retrofit and its optimal operation. The efficiency of coal-fired power generation can also be improved by increasing the number of the units with large capacities and optimally dispatching them in the power system. The Chinese government has implemented a series of policies and measures for

developing the units with large capacities and suppressing the ones with small capacities [3], demand side management, energy-efficient retrofit or energy-efficient dispatching [4], and they have achieved a good effect on the efficiency improvement of coal-fired power generation. If these measures continue to be carried out to adjust the power unit structure of coal-fired power units and optimize their operational parameters, their potential for energy saving and pollutant emission reductions will decrease. In order to further promote the energy saving and carbon emission reductions of coal-fired power generation, the solar energy is hybridized with a conventional coal-fired power unit (i.e., a solar-aided coal-fired power generation (SACPG) system) is significant and realistic due to the large share of coal-fired power generation in China. However, the performance of a SACPG system and its mechanism of solar-coal hybridization have not been fully analyzed, along with its evaluation criteria [5–10].

Solar thermal energy is the one of the clean, abundant, free energy sources, and the high solar insolation can be received in the northwest areas of China [5,11]. A solar thermal power system is one of potential renewable energy generation technologies, but it is usually costly to build and run due to the intermittency and low intensity of solar thermal energy [5,6]. The combination of a solar thermal power technology with a conventional coal-fired power system may be one of the effective ways to balance the intermittency of the solar energy through the adjustment ability of the power output of the coal-fired power system. A SACPG system is a solar-coal hybrid system and it may improve the efficiency of the solar thermal power generation because of the high parameters of the conventional coal-fired power system [12]. Based on the technical characteristics of solar thermal power generation, it can share parts of the equipment of the coal-fired power system, so that its initial investment may decrease, and the coal consumption by the SACPG system may decrease due to the solar energy integration [5].

The working principles of solar thermal energy power systems are described according to their requirements of utilization, and their technical characteristics, such as their types, efficiency, and cost, are discussed in literature [13,14]. The combination of an existing coal-fired power unit with solar thermal energy is one proven strategy to reduce the coal consumption and the relevant pollutant emissions, and the previous studies about the integration of solar thermal energy into the conventional fossil fuel power units have been reviewed in literature [15–24]. Based on energy conservation theory, the second law of thermodynamics, the thermo-economic theory or economic theory, the solar energy integration in a SACPG system and its operation are analyzed and some evaluation methods of the solar heat contribution are put forwards [7,25–27], in order to disclose the solar energy integration principles through the cases of solar-coal hybrid systems [8,28,29]. These studies mainly focus on the solar thermal energy integration of the parabolic trough collectors in which the solar thermal energy may substitute part or all of the extraction steam from the turbine to heat the feedwater [30]. Recently, studies about a SACPG system with the integration of the solar tower power system have been gradually increasing [8,31,32]. The methods to assess solar heat integration in a SACPG system are centered either on the solar heat from the solar collector field, or the change of the main steam in the turbines, or the coal consumption and CO<sub>2</sub> emission reductions, or the energy and exergy economic analysis [9,33].

Besides, the related incentive policies and measures for solar energy may also have an important effect on the solar-coal hybrid system [7,25,34]. The power output in a SACPG system may be divided into two parts which are allocated to coal and solar thermal energy, so the solar-coal hybrid system can gain subsidies or other funding support which is granted to renewable energies [34]. The operation strategies for a SACPG system should be planned and their effects should also be estimated on the basis of its expected operation under the circumstances of different relevant policy scenarios [35,36]. These strategies may include the selection of the solar energy integration topologies and determination of the hybrid scheme.

However, in the abovementioned studies on a SACPG system, most of them mainly focus on integration methods, the analyses of performance optimization based on specific units or certain schemes of solar thermal energy integration [8,37–39], along with the economic factors of initial

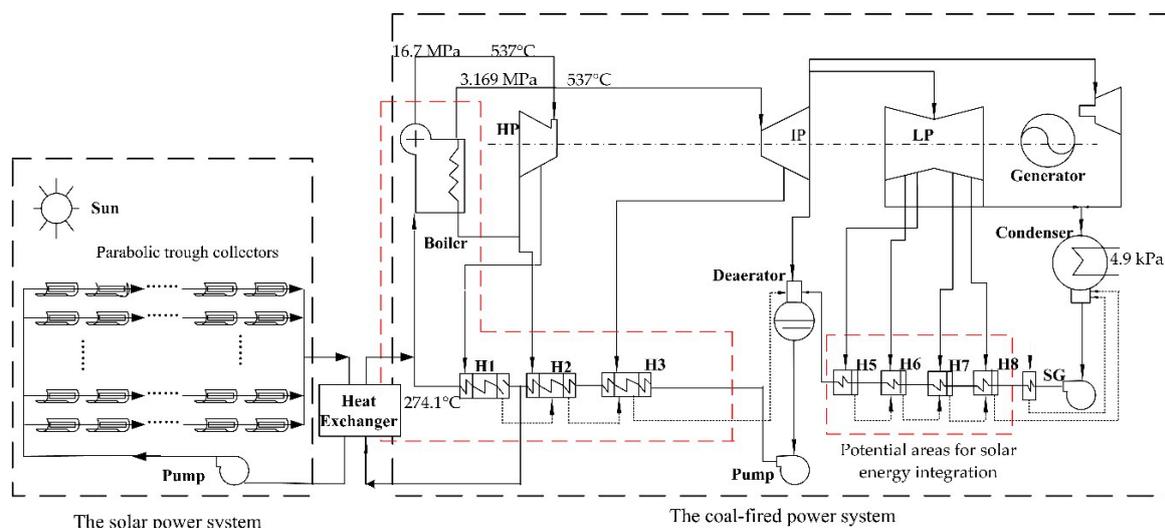
investment of the solar power system and its environment benefits (i.e., energy saving and CO<sub>2</sub> emission reductions), while part of the key factors and their variation impacts, including both direct normal irradiation (DNI) and electrical load, as well as carbon price or fuel price, are neglected in these studies and they cannot provide a general detailed methodology of the solar thermal integration to assess the performance of a SACPG system. A SACPG system is a feasible hybrid solar-coal power generation technology with high efficiency [34,40]. In order to promote the development of a SACPG system, it is crucial to understand the key factors of the performance and cost of solar thermal energy integration, whose drivers remain both technology- and market-specific [41]. The technologies of the solar energy integration, solar resource endowments, its related market structure and incentive policies, play an important role in the cost of building a SACPG system.

In this paper, we will examine in depth the performance and cost of a SACPG system and build a methodology to assess the solar thermal energy integration reasonably and comprehensively according to its characteristics of energy saving and CO<sub>2</sub> emission reductions. The methodology may be valuable both for the design and performance of a SACPG system, and for policy makers to make incentive policies and measures for its development. The rest of the paper goes as follows: We present in Section 2 the illustration of SACPG systems and analysis of its key factors. The abatement cost of a SACPG system is analyzed and its methodology is built, then the qualitative analysis of the key factors are carried out in Section 3. In Section 4, the application of the model is further explained through a case study of a SACPG system with the comparison of solar energy integration. We summarize the key finding about the model and put forward the conclusions in Section 5.

## 2. Description of a SACPG System and Its Key Factors

### 2.1. SACPG Description

The solar energy power system in a SACPG system can be usually coupled with the regenerative Rankine cycle with a steam-reheating process in a coal-fired power system [8,10], resulting in the reductions of coal consumption and the related pollutant emissions. The solar energy power systems with parabolic trough collectors and the solar tower power system are two promising technologies among solar thermal power generation technologies to build the SACPG systems. The solar energy power system with parabolic trough collectors has been used for grid-connected power generation commercially; however, the solar tower power generation system is in the process of project demonstration [42,43]. The SACPG systems are illustrated in Figures 1 and 2.



**Figure 1.** Schematic diagram for a solar-aided coal-fired power generation (SACPG) system with parabolic trough collectors.

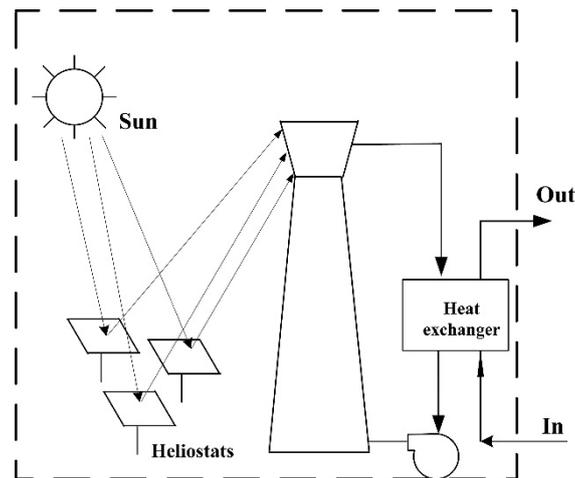


Figure 2. Schematic diagram for solar tower power system.

Figure 1 shows the schematic diagram of a SACPG system with the solar energy integration of the parabolic trough collectors. The coal-fired system in the hybrid system includes a deaerator, three high-pressure (HP) feedwater heaters (H1, H2, H3), four low-pressure (LP) feedwater heaters (H5, H6, H7, H8). The heat from the solar power system is integrated into the coal-fired system through the heat exchanger according to its temperature grade [44]. The solar power system in Figure 1 is integrated to replace part or all extraction steam of heater H1 to heat the feedwater. Figure 2 shows the diagram of a solar tower power system, and it can replace the solar power system with the parabolic trough collectors in Figure 1. The solar heat from the solar tower power system can be integrated to heat feedwater or to vaporize it.

The black dashed-line area in Figure 1 is the solar power system in the SACPG systems. The red dashed-line areas in the SACPG system are the potential areas for solar energy integration. The scheme of solar heat integration to replace the extraction steam of heater H1 in Figure 1 can be regarded as the solar energy integration scheme of heater H1 (SIH1).

## 2.2. Key Factors for a SACPG System

According to the illustrations of solar heat integration in Figures 1 and 2, a SACPG system is composed of a solar power system and a coal-fired power system, and they will have coupling effects during their performance. So the key factors for a SACPG system may fall into three categories. The first category of factors is about the technical characteristics of a solar thermal power system, and the ones of a coal-fired power system which the solar heat is integrated into. The second category of factors is about the solar radiation resources, and about the estimated performance of the hybrid system such as fuel consumption, CO<sub>2</sub> emission reductions. The power output of a SACPG system and its dispatch conditions in the grid, fuel price, and carbon price, the initial cost of the solar power system, belong to the third category.

These factors are shown in Figure 3. They may have an important effect on the design and performance of the SACPG system, and they should have to be integrated to comprehensively evaluate the cost of the solar heat integration in the hybrid system.

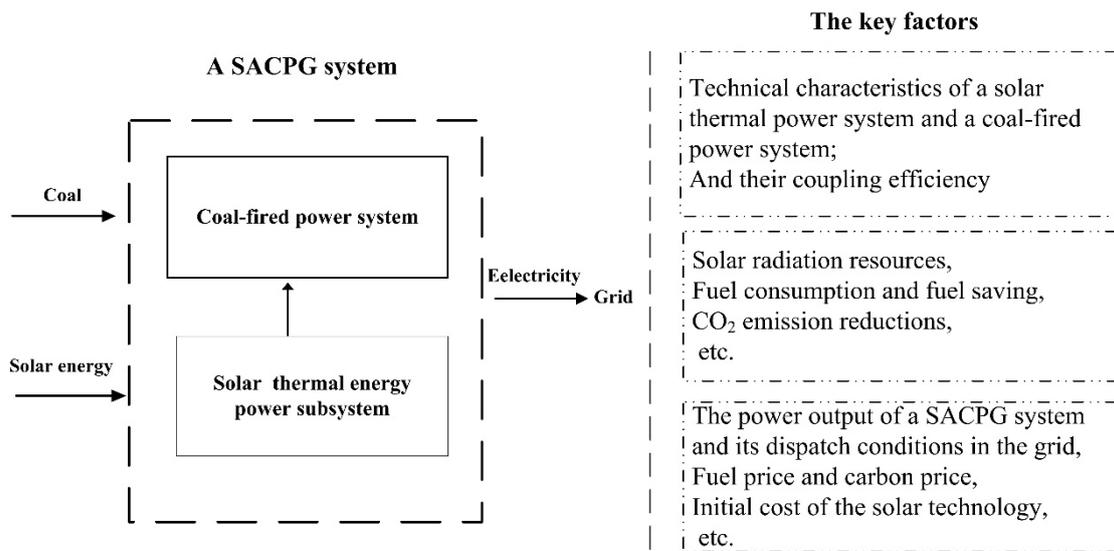


Figure 3. Conceptual diagram and key affecting factors for a SACPG system.

### 3. Methodology of a SACPG System and Qualitative Analysis of Its Key Factors

#### 3.1. Modeling of the Abatement Cost of a SACPG System

##### 3.1.1. Baseline Determination of Energy Saving and CO<sub>2</sub> Emission Reductions

According to energy conservation theory, the total efficiency of a SACPG system and its power output can be defined respectively as in Equation (1) [25] and Equation (2), and the power outputs from its coal-fired power system may be defined as in Equation (3)

$$\eta_{SACPG}(Q_{abs}) = \frac{3600EG_{SACPG}}{M_c H + 1000Q_{abs}} = \frac{3600(EG_{sotoe} + EG_{cotoe})}{M_c H + 1000Q_{abs}} \quad (1)$$

$$EG_{cotoe} = \frac{M_c H \eta_{coe}(Q_{abs})}{3600} \quad (2)$$

$$EG_{sotoe} = \frac{1000Q_{abs} \eta_{so,SACPG}(Q_{abs})}{3600} \quad (3)$$

where  $EG_{SACPG}$  is the output electricity generated by the SACPG system, in kWh;  $M_c$ , is coal consumption of the SACPG system, in kg;  $H$  is the low calorific value of standard coal, in kJ/kg;  $Q_{abs}$  is the solar heat from the solar energy power subsystem, in MJ/h;  $EG_{sotoe}$  is the output electricity generated by the solar power system in the SACPG system, in kWh;  $EG_{cotoe}$  is the output electricity generated by the coal-fired system in the SACPG system, in kWh;  $\eta_{SACPG}(Q_{abs})$  is the total efficiency of the SACPG system;  $\eta_{coe}(Q_{abs})$  is the coal-to-power efficiency in the SACPG system;  $\eta_{so,SACPG}(Q_{abs})$  is the solar-to-power efficiency in the SACPG system.

The solar thermal energy integrated in a SACPG system can make it consume less fossil fuel and reduce the pollutant emissions. When no solar heat is integrated, the solar-coal hybrid system can be taken as a conventional coal-fired power system. Thus, it is assumed that a SACPG system with no solar heat integration is defined as the baseline reference unit for its energy saving and CO<sub>2</sub> emission reductions. As the solar thermal energy is integrated, the coal-fired power system in a SACPG system is regarded to be operated under off-design conditions [16,22,25] and its coal-to-electricity efficiency will be influenced. Meanwhile, the solar energy can replace part of the fossil fuel. According

to the above equations, the energy fuel saving and CO<sub>2</sub> emission reductions can be calculated in Equations (4) and (5)

$$\Delta M_c = \frac{3600EG_{SACPG} - M_c H \eta_{coe}(Q_{abs})}{H \eta_{coe}(Q_{abs})} = \frac{3600EG_{sotoe}}{H \eta_{coe}(Q_{abs})} \quad (4)$$

$$\Delta EM_{CO_2} = \Delta M_c \gamma C_{CO_2} = \Delta b \cdot EG_{o,SACPG} \gamma C_{CO_2} \quad (5)$$

where  $C_{CO_2}$  is the conversion coefficient of carbon to CO<sub>2</sub>, in kg/kg;  $\gamma$  is the carbon proportion of standard coal in kg/kg;  $\Delta EM_{CO_2}$  is CO<sub>2</sub> emission reductions, in kg;  $\Delta b$  is the change of the average fuel consumption rate of the SACPG system, in kg/kWh;  $\Delta M_c$ , is the change of coal consumption of the SACPG system, in kg.

### 3.1.2. Analysis Model of CO<sub>2</sub> Abatement Cost for a SACPG System

According to the baseline assumption for the energy saving and CO<sub>2</sub> emissions reductions of a SACPG system, its cost of CO<sub>2</sub> emission reductions can be defined with Equation (6)

$$EC_{SACPG} = \frac{\Delta CE_{SACPG}}{\Delta EM_{CO_2}} \quad (6)$$

where  $EC_{SACPG}$  is the cost of CO<sub>2</sub> emission reductions in a SACPG system, in RMB/kg;  $\Delta CE_{SACPG}$  is the change of the total costs of solar energy integration, in RMB.

#### (1) The analysis of $\Delta C_{SACPG}$

Compared with the baseline unit of a SACPG system, the investment of the solar thermal power system and its operation and maintenance costs in the hybrid system are its increased costs, and meanwhile, coal consumption can be reduced by solar heat integration. The cost of solar energy integration in a SACPG system can be analyzed based on its levelized electricity generation cost. According to Equation (A2) in Appendix A, the change of  $C_{SACPG}$  (i.e.,  $\Delta C_{SACPG}$ ) can be calculated in Equation (7), and then Equation (6) will turn into Equation (8):

$$\Delta C_{SACPG} = \frac{\alpha \cdot \Delta IC + \Delta OM - \Delta FC - \Delta Cb}{EG_{SACPG}} \quad (7)$$

$$EC_{SACPG} = \frac{\Delta C_{SACPG} \cdot EG_{SACPG}}{\Delta M_c \cdot \gamma \cdot C_{CO_2}} \quad (8)$$

where  $\Delta IC$  is the change of the construction costs of solar energy integration for a SACPG system, in RMB;  $\Delta OM$  is the change of annual operation and maintenance costs of the hybrid system, in RMB;  $\Delta FC$  is the change of annual fuel costs of the hybrid system, in RMB;  $\Delta Cb$  is the change of annual carbon costs of the hybrid system, in RMB.  $\Delta FC$  and  $\Delta Cb$  can be expressed respectively in Equations (9) and (10). According to Equation (3), Equation (8) can turn into Equation (11):

$$\Delta FC = \Delta M_c \cdot p_{coal} / 1000 \quad (9)$$

$$\Delta Cb = \Delta M_c \cdot \gamma \cdot C_{CO_2} \cdot p_{CO_2} / 1000 \quad (10)$$

$$EC_{SACPG} = \frac{\alpha \cdot \Delta IC + \Delta OM}{1000 \gamma \cdot C_{CO_2}} \cdot \frac{H}{Q_{abs}} \cdot \frac{\eta_{coe}(Q_{abs})}{\eta_{so,SACPG}(Q_{abs})} - \frac{p_{coal}}{1000 \gamma \cdot C_{CO_2}} - \frac{p_{CO_2}}{1000} \quad (11)$$

where  $p_{coal}$  is coal price, in RMB/ton;  $p_{CO_2}$  is CO<sub>2</sub> price, in RMB/ton.

#### (2) The analysis of $Q_{abs}$

The solar thermal energy of  $Q_{abs}$  is obtained from the solar energy power system in a SACPG system. Solar energy power systems are usually planned by the designed direct normal irradiation (DNI),

and they are directly related to the initial investment cost of the solar heat integration, the operation and maintenance costs for the SACPG system. However, because the DNI varies during the daytime, the heat from the solar energy power system also varies. The solar energy power system may be bypassed when the DNI is too low to provide enough heat for the hybrid system, so that a threshold value of DNI may exist. A SACPG system will be considered to run as the baseline reference unit does due to the lack of solar thermal energy integration below the threshold value of DNI.

For the comparison of solar energy resources, it can be expressed on the basis of the designed DNI. The solar heat absorbed by the solar energy power system can be calculated in Equation (12) [6,25] and Equation (13), and then Equation (11) can turn into Equation (14):

$$Q_{abs} = A_{Id} \cdot Q_{A_{abs}} = 0.0036 A_{Id} I_d \eta_{Idc} h_{Idx} \quad (12)$$

$$h_{Idx} = \frac{\sum_{I_{tv} \leq I} A_{Id} I \eta_{Ic} h_I}{A_{Id} I_d \eta_{Idc}} \quad (13)$$

$$EC_{SACPG} = \frac{\alpha \cdot \Delta IC + \Delta OM}{3.6\gamma \cdot C_{CO2}} \cdot \frac{H}{A_{Id} I_d \eta_{Idc} h_{Idx}} \cdot \frac{\eta_{coe}(Q_{abs})}{\eta_{so,SACPG}(Q_{abs})} - \frac{p_{coal}}{1000\gamma \cdot C_{CO2}} - \frac{p_{CO2}}{1000} \quad (14)$$

where  $A_{Id}$  is the aperture areas of the solar power system in a SACPG system, in  $m^2$ ;  $Q_{A_{abs}}$  is the thermal energy per unit area from the solar power system,  $MJ/m^2$ ;  $I_d$  is the designed DNI, in  $W/m^2$ ;  $\eta_{Idc}$  is the solar-to-heat efficiency under the designed DNI;  $h_{Idx}$  is the equivalent hours of solar radiation under the designed DNI;  $I$  is the direct solar radiation,  $W/m^2$ ;  $\eta_{Ic}$  is the solar-to-heat efficiency under the DNI of  $I$ ;  $h_I$  is the duration hours of the DNI of  $I$ ;  $I_{tv}$  is the threshold value of DIN below which no solar energy is integrated,  $W/m^2$ .

Based on the investment cost per unit area and the operation and maintenance costs per unit area, which are shown in Equation (15), Equation (14) can be further simplified into Equation (16).

$$\Delta IC = \Delta ic \cdot A_{Id}; \Delta OM = \Delta om \cdot A_{Id} \quad (15)$$

$$EC_{SACPG} = \frac{\alpha \cdot \Delta ic + \Delta om}{3.6\gamma \cdot C_{CO2}} \cdot \frac{H}{I_d \eta_{Idc} h_{Idx}} \cdot \frac{\eta_{coe}(Q_{abs})}{\eta_{so,SACPG}(Q_{abs})} - \frac{p_{coal}}{1000\gamma \cdot C_{CO2}} - \frac{p_{CO2}}{1000} \quad (16)$$

where  $\Delta ic$  is the change per unit area of the construction costs of solar energy integration for a SACPG system, in  $RMB/m^2$ ;  $\Delta om$  is the change per unit area of annual operation and maintenance costs of the hybrid system, in  $RMB/m^2$ .

### 3.2. Qualitative Analysis of the Key Factors on Carbon Abatement Cost of a SACPG System

The  $CO_2$  abatement cost of a SACPG system is influenced by many factors according to Equation (16).  $\eta_{coe}(Q_{abs})$  and  $\eta_{so,SACPG}(Q_{abs})$  are respectively the technical characteristics of the coal-fired power system and the solar thermal power system in a SACPG system.  $I_d \eta_{Idc} h_{Idx}$  is the key factor about the solar radiation resources, and  $\gamma \cdot C_{CO2}$  is the conversion coefficient of the standard coal to  $CO_2$ . The power output of a SACPG system and its dispatch conditions have an effect on  $\eta_{coe}(Q_{abs})$  and  $\eta_{so,SACPG}(Q_{abs})$ .  $p_{coal}$ ,  $p_{CO2}$ ,  $\Delta ic$  and  $\Delta om$  are the key economic factors. The coupling effect of the coal-fired system and the solar field subsystem, the solar energy resource, and the key economic factors play an important role in the  $CO_2$  abatement cost of a SACPG system, and they will be further analyzed.

#### 3.2.1. Coupling Effect Analysis of $\eta_{coe}(Q_{abs})$ and $\eta_{so,SACPG}(Q_{abs})$

The coal-fired power system in a SACPG system may run under off-design conditions due to the solar heat integration. According to the literature [45],  $\eta_{coe}(Q_{abs})$  in a SACPG system will decrease as the solar thermal energy is increasingly integrated. Meanwhile,  $\eta_{so,SACPG}(Q_{abs})$  in the hybrid system may increase.  $\eta_{coe}(Q_{abs})$  and  $\eta_{so,SACPG}(Q_{abs})$  have a coupling effect on their performance. Because the solar thermal energy is regarded as an auxiliary energy for the performance of the coal-fired power

system in a solar-coal hybrid system, and its capacity is regularly smaller,  $\eta_{coe}(Q_{abs})$  may vary slightly despite the solar energy integration. Thus, the coupling effect of  $\eta_{coe}(Q_{abs})$  and  $\eta_{so,SACPG}(Q_{abs})$  can be defined in Equation (17), or be defined in Equation (18) based on the baseline scenario.

$$\eta_{ce,soco} = \frac{\eta_{so,SACPG}(Q_{abs})}{\eta_{coe}(Q_{abs})} \quad (17)$$

$$\eta_{ce,soco} = \frac{\eta_{so,SACPG}(Q_{abs})}{\varphi \cdot \eta_{coe,ref}} \quad (18)$$

where  $\eta_{ce,soco}$  is the coupling coefficient of  $\eta_{coe}(Q_{abs})$  and  $\eta_{so,SACPG}(Q_{abs})$ ;  $\eta_{coe,ref}$  is the baseline coal-to-electricity efficiency of a SACPG system;  $\varphi$  is the off-design coefficient and can be calculated according to the literature [45,46].

According to Equations (16) and (18), the CO<sub>2</sub> abatement cost of a SACPG system may decrease when much higher coupling efficiency of its solar energy power system and coal-fired power system can be achieved in the integration of solar thermal energy, which is conducive to promoting the energy saving and emission reductions for the hybrid system. For further simplification of calculation of  $\eta_{ce,soco}$ ,  $\varphi$  can be set to 1 and the coupling effect can be calculated approximately with Equation (18), for  $\eta_{so,SACPG}(Q_{abs})$  can also implicitly reflect the role of  $\eta_{coe}(Q_{abs})$ . So,  $\eta_{ce,soco}$  may decrease and be less than it is actually.

### 3.2.2. Analysis of Solar Energy Resource

The equivalent number of hours,  $h_{Idx}$ , which is based on the designed DNI, can comprehensively indicate the impact of the solar energy resource on the integration of solar thermal energy. According to Equation (12),  $I_d \eta_{Idc} h_{Idx}$  can also show the extent of the heat from the solar energy resource. Thus, if  $\eta_{ce,soco}$  remains constant or changes slightly,  $I_d \eta_{Idc} h_{Idx}$  can indicate the effect of the solar energy on the performance of a SACPG system. However,  $\eta_{Idc}$  may vary from different solar thermal power generation technologies or different design DNI, and it can be considered to indicate the heat efficiency from the solar energy resource.  $\eta_{ce,soco}$  can show the integration efficiency of the solar heat.  $I_d \eta_{Idc} h_{Idx}$  and  $\eta_{ce,soco}$  are related to the technical integration of solar thermal energy, and they can be used to analyze the solar energy resources and the performance of a SACPG system in different regions.

According to Equation (16), the partial derivatives of  $EC_{SACPG}$  for  $I_d \eta_{Idc} h_{Idx}$  and  $\eta_{ce,soco}$  can be calculated with Equations (19) and (20), respectively.

$$\frac{\partial EC_{SACPG}}{\partial \eta_{ce,soco}} = \frac{(\alpha \cdot \Delta ic + \Delta om)H}{3.6\gamma \cdot C_{CO2} \cdot I_d \eta_{Idc} h_{Idx}} \cdot \frac{1}{\eta_{ce,soco}^2} = \frac{(\alpha \cdot \Delta ic + \Delta om)H}{3.6\gamma \cdot C_{CO2} \cdot I_d \eta_{Idc} h_{Idx} \eta_{ce,soco}} \cdot \frac{1}{\eta_{ce,soco}} \quad (19)$$

$$\frac{\partial EC_{SACPG}}{\partial (I_d \eta_{Idc} h_{Idx})} = \frac{(\alpha \cdot \Delta ic + \Delta om)H}{3.6\gamma \cdot C_{CO2} \cdot \eta_{ce,soco}} \cdot \frac{1}{(I_d \eta_{Idc} h_{Idx})^2} = \frac{(\alpha \cdot \Delta ic + \Delta om)H}{3.6\gamma \cdot C_{CO2} \cdot I_d \eta_{Idc} h_{Idx} \eta_{ce,soco}} \cdot \frac{1}{I_d \eta_{Idc} h_{Idx}} \quad (20)$$

Because  $\eta_{so,SACPG}(Q_{abs})$  is usually less than  $\eta_{coe}(Q_{abs})$ ,  $\eta_{ce,soco}$  is always less than 1.  $I_d \eta_{Idc} h_{Idx}$  is usually greater than 1 in areas with abundant solar radiation resources. Thus, the effect of  $I_d \eta_{Idc} h_{Idx}$  on the abatement cost is lower than that of  $\eta_{ce,soco}$ .

### 3.2.3. Analysis of the Key Economic Factors

According to Equation (16), the key economic factors in a SACPG system include the initial investment cost of the solar energy integration, its operation and maintenance costs, coal price, carbon price. Other parameters, such as  $H$ ,  $\gamma$ ,  $C_{CO2}$ , are constant, except for the technical factors of  $I_d \eta_{Idc} h_{Idx}$  and  $\eta_{ce,soco}$ .

After the determination of  $I_d \eta_{Idc} h_{Idx}$  and  $\eta_{ce,soco}$ , the  $EC_{SACPG}$  of a hybrid system is mainly affected by these key economic factors. When  $EC_{SACPG}$  is less than zero this may indicate that the energy saving and CO<sub>2</sub> emission reductions of the SACPG system is financially attractive. When  $EC_{SACPG}$  is greater

than zero, it means that its energy saving and CO<sub>2</sub> abatement are less financially attractive, but when one of the initial investment cost, the operation and maintenance costs decreases or one of coal price and carbon price increases,  $EC_{SACPG}$  may decrease.

According to Equation (16), the partial derivatives of  $EC_{SACPG}$  for coal price, carbon price, the initial investment costs, and operation and maintenance costs can be calculated in Equations (21)–(23), respectively.

$$\frac{\partial EC_{SACPG}}{\partial p_{coal}} = -\frac{1}{1000\gamma \cdot C_{CO2}} \quad (21)$$

$$\frac{\partial EC_{SACPG}}{\partial p_{CO2}} = -\frac{1}{1000} \quad (22)$$

$$\frac{\partial EC_{SACPG}}{\partial(\alpha \cdot \Delta ic + \Delta om)} = \frac{H}{3.6\gamma \cdot C_{CO2} \cdot I_d \eta_{Idc} h_{Idx} \eta_{ce,soco}} \quad (23)$$

Based on the above analysis,  $\gamma C_{CO2}$  is always greater than 1 ( $\gamma$  is about 0.726 kg/kg, and  $C_{CO2}$  is about 3.667 kg/kg), so that the effect of  $p_{coal}$  on the abatement cost is lower than that of  $p_{CO2}$ . However, the effect of  $\alpha \Delta ic$  and  $\Delta om$  on the abatement cost cannot be determined because of the key factors of  $I_d \eta_{Idc} h_{Idx}$  and  $\eta_{ce,soco}$ .

## 4. Case Study

### 4.1. Description of the Case

In this part, the analysis model of CO<sub>2</sub> abatement cost for a SACPG system will be used to analyze the key factors which affect the design and performance of the hybrid system, and the analyses of these factors may be helpful to make decisions about the project of a SACPG system. It is assumed that a 600 MW coal-fired unit, located in Jinan, Shandong and in Hohhot, Inner Mongolia in China, will be retrofitted to be the SACPG systems, and that they are all connected to the North China regional power grid. Their main parameters are almost the same and shown in Tables 1 and 2.

**Table 1.** Key parameters of feedwater heaters in the SACPG system [47].

Item	Unit	H1	H2	H3	H5	H6	H7	H8
Extraction pressure	MPa	5.89	3.593	1.612	0.305	0.13	0.0697	0.022
Extraction temperature	°C	380.9	316.9	429.1	233.2	137.8	88.5	61
Outlet temperature	°C	274.1	242.3	199.3	129.6	102.9	85.7	58.2
Drain water temperature	°C	247.8	204.8	174.1	108.4	91.2	63.7	38.26
Extraction coefficient	-	0.07289	0.08286	0.03833	0.03497	0.02203	0.03402	0.03058

**Table 2.** Other key parameters of the SACPG system [47].

Item	Unit	Value
Capacity of coal-fired system	MW	600
Main stream of coal-fired system	t/h	1848.84
Designed net coal consumption rate of the baseline unit	g/kWh	322.9
Designed DNI	W/m <sup>2</sup>	800
Solar collector field area	m <sup>2</sup>	148,140

The solar thermal energy can be integrated into the coal-fired unit to build a SACPG system by replacing part or all of the extraction steam, and finally more steam can expand to generate electricity. Under the conditions of solar energy integration for replacing the extraction steam, the replaced steam has higher heat-to-electricity efficiency because of its high parameters (high pressure and high temperature), so the heat-to-electricity efficiency of the solar energy is considered to be increased.

An LS-2 parabolic trough collector will be used in the solar energy power system and its efficiency can be determined according to Equations (24) and (25) [48]. The scheme of the SACPG system with LS-2 parabolic trough collectors is shown in Figure 1, and the solar power system is in the black dashed-line area. The red dashed-line areas in Figure 1 are the potential areas for solar heat integration.

It is assumed that the DIN of 300 W/m<sup>2</sup> is the threshold value below which no solar heat is integrated into the SACPG system. The duration hours under different DIN, respectively in Jinan, Shandong and in Hohhot, Inner Mongolia [49], are shown in Figure 4.

$$\eta_{LS} = K_{ia} \cdot [73.3 - 0.007276 \cdot (\Delta T_{ave})] - 0.496 \cdot \left(\frac{\Delta T_{ave}}{I_{dDNI}}\right) - 0.0691 \cdot \left(\frac{\Delta T_{ave}^2}{I_{dDNI}}\right) \quad (24)$$

$$\Delta T_{ave} = \frac{T_{out} + T_{in}}{2} - T_{am} \quad (25)$$

where  $\eta_{LS}$  is the solar-to-heat efficiency of the LS-2 parabolic trough collector;  $I_{dDNI}$  is the designed DNI, in W/m<sup>2</sup>;  $T_a$  is the ambient temperature of the LS-2 parabolic trough collector, in °C;  $T_{ave}$ ,  $T_{out}$  and  $T_{in}$  are, respectively, the average temperature, outlet temperature, and inlet temperature of the LS-2 parabolic trough collector, in °C;  $K_{ia}$  is the incidence angle coefficient.

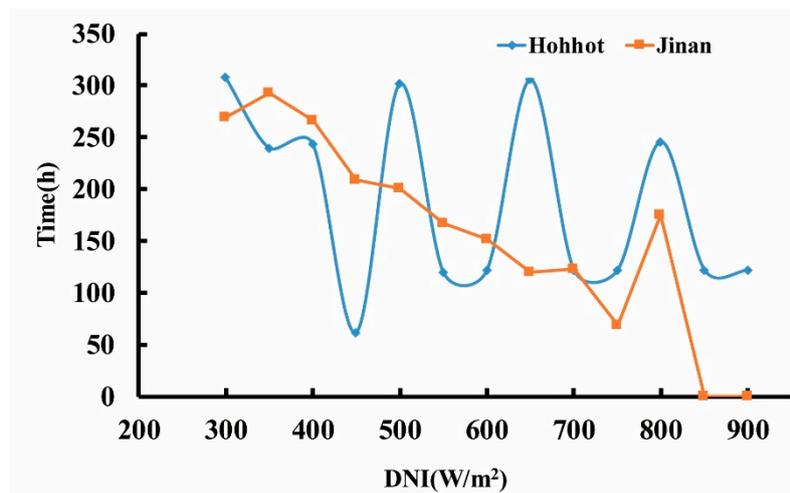


Figure 4. Distribution of direct normal irradiation (DNI).

## 4.2. Results and Discussions

### 4.2.1. Coupling Effect of Solar Integration Schemes on CO<sub>2</sub> Abatement Cost

Based on the parameters of the coal-fired unit and designed DNI of 800 W/m<sup>2</sup> in Hohhot, the coupling effect of solar integration schemes and their CO<sub>2</sub> abatement costs are calculated according to Equation (16). The integration schemes are respectively to replace part or all of the extraction steam from heater H1 to heater H8, except the extraction steam for the deaerator due to its special role in the Rankin cycle, and the results are shown in Figure 5. The horizontal axis in Figure 5 represents the schemes of solar energy integration. SIH1 is the solar energy integration scheme of heater H1 and it means that the solar heat is used to replace the extraction steam of heater H1. The schemes of SIH2, SIH3, along with SIH5 to SIH8, are similar to SIH1, and they also indicate that the solar thermal energy is used to replace the extraction steam of their corresponding heaters.

Based on the parameters of feedwater heaters and their extraction steam (shown in Table 1), the working temperatures of the LS-2 parabolic trough collectors from the schemes of SIH1 to SIH8 decrease successively, so that their solar-to-thermal efficiencies increase correspondingly according to Equation (24). However, the solar heat-to-electricity efficiencies of  $\eta_{so,SACPG}(Q_{abs})$  from the schemes of SIH1 to SIH8 decrease gradually, as do the coupling efficiencies of  $\eta_{ce,soco}$  of the solar energy integration

schemes. The CO<sub>2</sub> abatement costs from the schemes of SIH1 to SIH8 increase successively. In this case,  $\eta_{coe}(Q_{abs})$  can be considered as the efficiency of  $\eta_{coe,ref}$  and  $\varphi$  is the constant value of 1. Then, the coupling efficiency of  $\eta_{ce,soco}$  can be analyzed only according to the efficiency of  $\eta_{so,SACPG}(Q_{abs})$ .

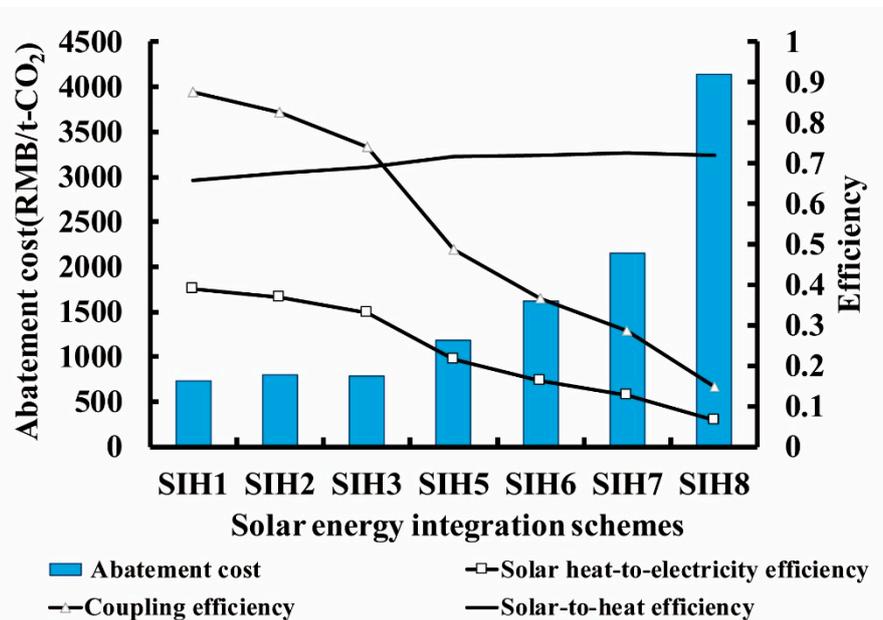


Figure 5. Efficiency analysis and abatement costs of solar integration schemes in a SACPG system.

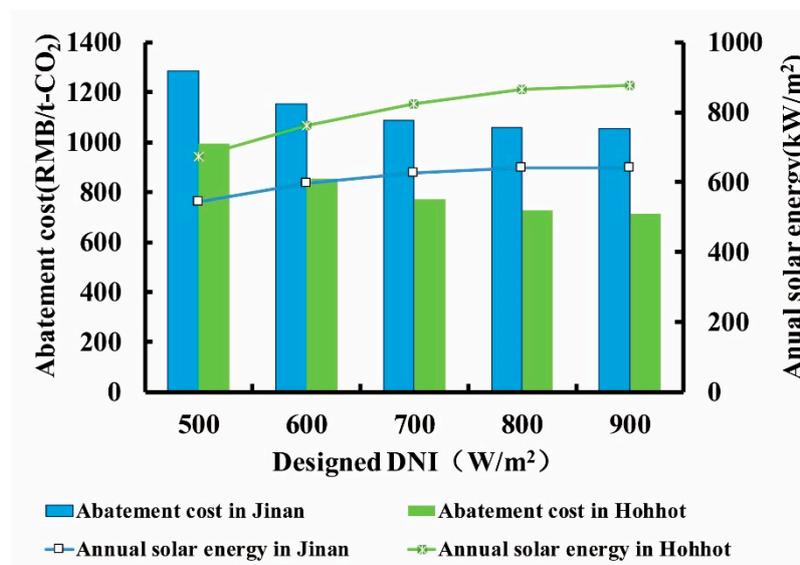
The efficiencies of  $\eta_{ce,soco}$  and  $\eta_{so,SACPG}(Q_{abs})$  in the scheme of SIH1 are 0.877 and 0.391, respectively, which is beyond the efficiencies of the solar-alone power systems [42]. The integration scheme of SIH1 is of the lowest abatement cost due to its highest solar heat-to-electricity efficiency or its efficiency of  $\eta_{ce,soco}$  (or its highest efficiency of  $\eta_{so,SACPG}(Q_{abs})$  when the efficiency of  $\eta_{coe}(Q_{abs})$  in the SACPG system is determined) among these solar heat integration schemes. Therefore, it is indicated that the higher the extraction steam with high parameters replaced by the integrated solar heat in the schemes, the higher its efficiency of  $\eta_{so,SACPG}(Q_{abs})$  and the lower its CO<sub>2</sub> abatement cost.

#### 4.2.2. The Effect of Solar Energy Resource on CO<sub>2</sub> Abatement Cost

For the simplification of comparative calculation, the effect of the solar energy resource on the CO<sub>2</sub> abatement cost of a SACPG system will be analyzed based only on the integration scheme of SIH1. According to the data in Figure 4, annual solar energy per unit area of  $I_d\eta_{Idc}h_{Idx}$  respectively in Jinan, Shandong and in Hohhot, Inner Mongolia, and their relevant abatement costs are shown in Figure 6.

The annual solar energy in Hohhot is higher than that in Jinan under the same designed DNI, and this shows that the solar thermal energy resource in Hohhot is better than that in Jinan. The annual solar energy per unit area in both areas may increase as the designed DNI of a SACPG system increases, and the annual solar energy in Hohhot is higher than that in Jinan under the same designed DNI. If the designed DNI is low, the aperture area of the solar power system may have to be increased. The fluctuations of DNI will increase the probability of curtailing solar thermal energy due to the safety constrains, so that the utilization of the solar energy resources will be reduced, finally resulting in a decrease in the annual solar energy per unit area of  $I_d\eta_{Idc}h_{Idx}$ .

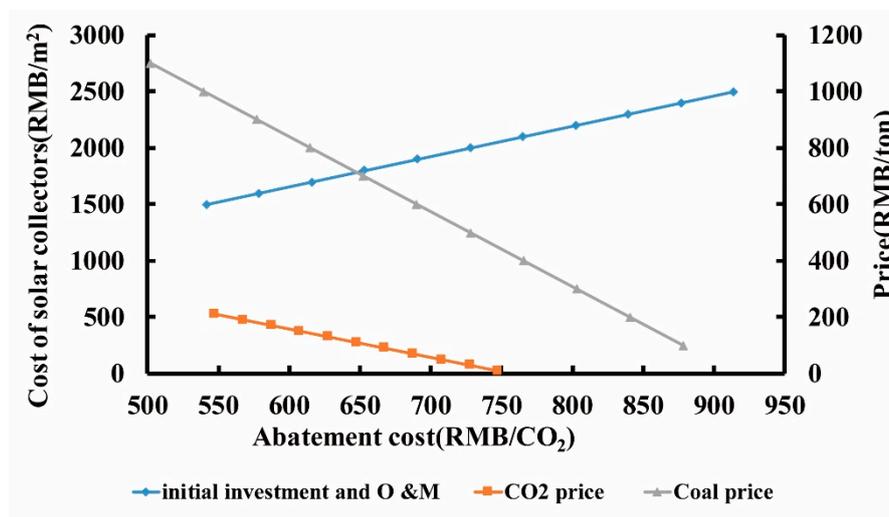
The abatement costs of a SACPG system in both areas may decrease as its designed DNI increases, and the abatement cost of the hybrid system in Hohhot is lower than that in Jinan under the same designed DNI. The selection of designed DNI has to meet the requirements of making full use of solar energy resource while avoiding its underutilization. According to the analysis of  $I_d\eta_{Idc}h_{Idx}$ , the designed DNI should be greater than 800 W/m<sup>2</sup>.



**Figure 6.** Variation in the abatement costs and the annual solar energy with designed DNI for replacing the extraction steam of SIH1.

#### 4.2.3. The Effects of Key Economic Factors on the Abatement Cost

Besides the influences of the solar energy sources, the technical characteristics of the solar power system and coal-fired power system and their coupling effects, the abatement cost of a SACPG system is also affected by the key economic factors such as the costs of solar energy collectors, coal price, and CO<sub>2</sub> price. For the simplification of calculation, the effects of the key economic factors on the CO<sub>2</sub> abatement cost of a SACPG system will be analyzed based on the integration scheme of SIH1 under the designed DNI of 800 W/m<sup>2</sup> in Hohhot, and the results are shown in Figure 7, in which the designed DNI is taken as the horizontal axis in order to include more factors in the figure.



**Figure 7.** Abatement cost variation with coal price, CO<sub>2</sub> price, and the cost of solar collector for replacing the extraction steam of SIH1.

When the efficiency of  $\eta_{ce,soco}$  in a SACPG system is determined, its abatement cost is heavily contingent both on the cost of solar energy collectors and its relevant costs, and on the fuel price or the carbon prices. The abatement cost of a SACPG system may decrease as the coal prices or CO<sub>2</sub> price increase. However, the abatement cost of the hybrid system may increase as the cost of solar energy collectors or their operation and maintenance costs increase. Because of the high cost of the

solar power system, and the low coal price or carbon price, the abatement cost of the SACPG system is greater than zero.

#### 4.2.4. Further Analyses and Discussion

Although the coupling effects of solar heat integration schemes and their CO<sub>2</sub> abatement costs are examined among the integration schemes of the SACPG system in Hohhot, they are similar to those of the hybrid system in Jinan. The CO<sub>2</sub> abatement costs from the schemes of SIH1 to SIH8 of the SACPG system in Jinan also increase successively. However, the CO<sub>2</sub> abatement costs of the corresponding integration schemes in Jinan are greater than those in Hohhot because there are less solar energy resources in Jinan. In addition, the effects of the solar energy resource and key economic factors on the CO<sub>2</sub> abatement cost of a SACPG system are analyzed based on the scheme of SIH1, and they are similar to the effects of these key factors on the carbon abatement cost from the schemes of SIH2 to SIH8. The CO<sub>2</sub> abatement costs of these schemes are higher than those of SIH1 due to their lower efficiencies of  $\eta_{ce,soco}$  and  $\eta_{so,SACPG}(Q_{abs})$ .

The technical characteristics of a SACPG system and its coupling effects, the solar energy resources, and the key economic factors are crucial to the cost of the hybrid system, so that according to these critical factors, the methodology is built on the basis of energy saving and CO<sub>2</sub> emission reductions. However, in the previous studies, there is yet no generally appropriate method to evaluate solar-coal hybridization in a SACPG system [8]. The evaluation models were usually based only on the system thermal efficiency of a SACPG system, its energy efficiency, or its thermal-to-electricity efficiency, and they were taken as the assessment criteria [9,10], and some researches focused only on the energy-saving performance of a SACPG system before and after its solar heat integration [8,28,37,39]. They did not include all of the abovementioned key factors of a solar-coal hybrid system. Because a SACPG system has two types of energy input of solar heat and fossil energy, only its system thermal efficiency or its energy-saving performance may not be suitable to disclose the coupling mechanism of solar-coal hybridization and its performance. Although the system thermal efficiency of a SACPG system or its thermal-to-electricity efficiency may reflect part of the coupling effects of solar-coal hybridization, it cannot fully indicate the performance of the hybrid system. The model of CO<sub>2</sub> abatement cost proposed in the paper includes the crucial information of the costs of the solar energy integration, and solves the problem of incomplete information reflected in the previous models regarding the solar-coal hybridization [7], so it may help in the design and performance evaluation of a SACPG system.

In addition, the abatement cost of a SACPG system is greater than zero, the project of the solar energy integration may be not financially attractive, which means that additional investment may still be needed to achieve the emission reduction target, so the decision about the project should be made deliberately.

## 5. Conclusions

A SACPG system can be built from a coal-fired power unit with solar energy integration, and it can be considered as an energy-saving technology of coal-fired units, along with the CO<sub>2</sub> emission reductions, for the hybrid system can utilize solar heat to replace part of the coal consumption. A general methodology would have to be built to analyze the performance and cost of a SACPG system reasonably and comprehensively among its various solar energy integration schemes. In this paper, a general model of CO<sub>2</sub> abatement cost of a SACPG system is built based on crucial information about the technical characteristics of its solar power system and coal-fired power system and their coupling effects, and also on the key economic factors. The drivers of a SACPG system are both technology- and market-specific. The coupling effects of solar-coal hybridization are its main special technical characteristics and can be reflected finally in reduced coal consumption and CO<sub>2</sub> abatement. The cost of a SACPG system depends significantly both on the investment cost of the solar energy power system, and on the fuel costs and the price of CO<sub>2</sub> emission reductions. These key factors of solar-coal

hybridization are included in the model of CO<sub>2</sub> abatement cost, and it can be used to fully analyze and evaluate the performance of a SACPG system.

According to the model of CO<sub>2</sub> abatement cost of a SACPG system, the mechanism of its solar-coal hybridization can be disclosed from the coupling efficiency of its solar power system and coal-fired power system. A relation expression for the coupling efficiency of a hybrid system is determined and its coupling efficiency can be analyzed from the respective efficiencies of its solar power system and coal-fired power system. The coupling efficiency of solar-coal hybridization should be as high as possible in areas with high DNI, and it can be improved by the coal-fired power system with large capacity in a SACPG system. Besides, the abatement cost of a SACPG system depends significantly both on the cost of the solar power system and its relevant costs, and on the fuel price or the carbon price.

Based on the model of CO<sub>2</sub> abatement cost of a SACPG system, the integration technologies of solar energy and its schemes, the solar energy resources in certain areas, and the key economic factors can be compared reasonably and fully. The comparison analyses can help to optimize the performance of a SACPG system, and to evaluate the hybrid system comprehensively. A case study is carried out to validate the model of CO<sub>2</sub> abatement cost, and the data from the case study are consistent with the results from the theoretical and qualitative analyses. Through the case study of the 600 MW SACPG systems in Jinan and in Hohhot, it is indicated that the efficiencies of  $\eta_{ce,soco}$  and  $\eta_{so,SACPG}(Q_{abs})$  in the scheme of SIH1 are respectively 0.877 and 0.391, and that the designed DNI should be greater than 800 W/m<sup>2</sup> in order to make full use of solar energy resources. In this case, the CO<sub>2</sub> abatement cost of the hybrid system in Hohhot is about 728 RMB/tCO<sub>2</sub> when it is assumed that the coal price is 500 RMB/ton, the CO<sub>2</sub> price is 30 RMB/ton, the initial investment cost of LS-2 is 2000 RMB/m<sup>2</sup>, and the operation and maintenance costs are 55 RMB/m<sup>2</sup>. The carbon abatement cost can be greatly reduced as the coal price or CO<sub>2</sub> price increases, in comparison with the change of initial investment cost of LS-2 and its operation and maintenance costs.

The coupling effects of solar-coal hybridization, the solar energy resources, the benefits of coal-saving and CO<sub>2</sub> abatement, along with the cost of the solar energy system, are critical to the performance and cost of a SACPG system. According to this key information, the model of CO<sub>2</sub> abatement cost can also indicate whether a project of solar energy integration is financially attractive. If a decision about solar energy integration to build a solar-coal hybrid system is made, more other factors, such as electricity prices and subsidies, should be taken into account. In addition, although the model of CO<sub>2</sub> abatement cost is based on the analysis of the solar thermal energy integration in a SACPG system, its related theories and methods can also be applied to the hybrid system in which non-solar heat, such as biomass energy and geothermal energy, is integrated into its coal-fired power system.

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## Appendix A. The Levelized Electricity Generation Cost of a SACPG System

The cost of a SACPG system should include its initiative investment and its operation and maintenance cost, and also include the cost of fuel consumption, the relevant cost of CO<sub>2</sub> emissions,

and other fees. In order to fully indicate the cost of a SACPG system, the levelized electricity generation cost [41] can be calculated with Equation (A1).

$$C_{SACPG} = \frac{\sum_{t=1}^n (IC_t + OM_t + FC_t + Cb_t + DE_t)(1+r)^{-t}}{\sum_{t=1}^n EG_t(1+r)^{-t}} \quad (A1)$$

where  $C_{SACPG}$  is the levelized electricity generation cost, in RMB;  $IC_t$  is the capital construction costs for a SACPG system in year  $t$ , in RMB/kWh;  $OM_t$  is the operation and maintenance costs of the hybrid system in year  $t$ , in RMB;  $FC_t$  is the fuel costs of the hybrid system in year  $t$ , in RMB;  $Cb_t$  is the carbon costs of the hybrid system in year  $t$ , in RMB;  $DE_t$  is the decommissioning costs and other costs of the hybrid system in year  $t$ , in RMB;  $EG_t$  is the quantity of power output of the hybrid system in year  $t$ , in kWh;  $n$  is the number of the years of the lifetime of the hybrid system;  $r$  is the discount rate for year  $t$ .

In order to simplify the analysis of the  $C_{SACPG}$  and highlight the key factors, it is assumed that the annual average operation and maintenance costs for a SACPG system are constant and so are its annual average quantity of power output, the discount rate, the annual fuel costs and carbon costs, and the annual decommissioning costs and other costs. It is also assumed that the total capital construction costs of the hybrid system are regarded as the overnight costs. So, its annual levelized electricity generation cost can be expressed in Equation (A2).

$$C_{SACPG} = \frac{\alpha \cdot IC + OM + FC + Cb + DE}{EG} \quad (A2)$$

$$\alpha = \frac{(1+r)^n r}{(1+r)^n - 1} \quad (A3)$$

where  $IC$  is the capital construction costs for a SACPG system, in RMB;  $OM$  is the annual operation and maintenance costs of the hybrid system, in RMB;  $FC$  is the annual fuel costs of the hybrid system, in RMB;  $Cb$  is the annual carbon costs of the hybrid system, in RMB;  $DE$  is the annual decommissioning costs and other costs of the hybrid system in year  $t$ , in RMB;  $EG$  is the annual power output of the hybrid system, in kWh;  $n$  is the number of the years of the lifetime of the hybrid system;  $\alpha$  is the annual investment rate of return.

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