INTRODUCTION

In the past 30 years, energy consumption and carbon emissions have increased dramatically around the world, resulting in global warming and air pollution problems, so increasing the use of renewable energy has become a trend. Renewables are set to penetrate the global energy system more quickly than any fuel in history.\(^1,2\) As one of the most important renewable energy sources, solar energy has the characteristics of instability and intermittence, and coal-fired units are considered to be able to balance the difference between power supply and power consumption.\(^3\) A solar-aided power generation (SAPG) system is a promising complementary power

Dynamic characteristics of a solar-aided coal-fired power generation system under direct normal irradiance (DNI) feedforward control

Liping Pang | Peixin Lv | Liqiang Duan | Yongping Yang

Key Laboratory of Power Station Energy Transfer Conversion and System (North China Electric Power University), Ministry of Education, School of Energy, Power and Mechanical Engineering, National Thermal Power Engineering & Technology Research Center, North China Electric Power University, Beijing, China

Correspondence
School of Energy, Power and Mechanical Engineering, National Thermal Power Engineering & Technology Research Center, Key Laboratory of Power Station Energy Transfer Conversion and System (North China Electric Power University), Ministry of Education, North China Electric Power University, Beijing, 102206, China.
Emails: liping_pang@163.com; plp@ncepu.edu.cn

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Abstract
A solar-aided coal-fired power generation (SAPG) system is a new type of power generation system in the field of solar thermal power generation. However, the instability of solar radiation will cause fluctuations in steam temperature, which is unfavorable for the operation of boilers and steam turbines. Based on a 600 MW subcritical coal-fired power generation unit, TRNSYS software is applied to establish a transient simulation model of SAPG in this paper. A dynamic feedforward control system for steam temperature is set up. Some essential parameters, such as the fuel consumption rate, solar-heated steam extraction rate, water spraying flow rate, and flue gas damper opening, are under the control of direct normal irradiance (DNI). Then, the dynamic characteristics of SAPG are analyzed using typical weather data. The simulation results show that under the fuel-saving mode, when solar irradiation changes, the SAPG system achieves a coal reduction of 4.9% by using the steam temperature control system with DNI feedforward control, and the main steam temperature fluctuation is less than 5°C with the reheate steam temperature reduced within a reasonable range. The power generation fluctuation is less than 10 MW, and the solar-to-electricity efficiency reaches 22.5%. Some parameters on both the flue gas side and the water/steam side in the utility boiler are simulated to demonstrate the effectiveness of DNI control.

KEYWORDS
dynamic characteristics, feedforward control, solar-aided coal-fired power generation, steam temperature
generation technology that can effectively buffer the instability of solar radiation while avoiding the huge cost of extra heat storage system. It is one of the research hotspots in the power generation industry.4,5

A solar-aided coal-fired power generation system refers to a system that integrates solar thermal energy into a conventional thermal power generation unit, introducing solar energy to replace a portion of fuel energy for power generation. This system is characterized by reducing the use of coal resources by utilizing solar energy. In addition, air pollution emissions from coal are obviously reduced.6,7 SAPG has a high solar-to-electricity efficiency and low coal consumption rate and can relieve the imbalance caused by renewable energy access in the grid by taking advantage of the higher energy density of coal.8 In practical applications, the introduction of solar energy into coal-fired power plants will bring transient heat flow changes, which will bring great challenges for the control and operation of boilers, steam turbines, and thermal systems. Research on the dynamic characteristics of SAPG is of great significance for coupling renewable energy with traditional coal-fired generating units.9

Many researchers have systematically analyzed SAPG system theoretically. A review of hybrid solar-fossil fuel power generation is provided with an emphasis on system integration and evaluation.3 Many researchers around the world have conducted in-depth research on system integration modes, performance analysis, and evaluation methods. In 1975, Zoschak and Wu proposed several coupling models and analyzed the advantages and disadvantages of various solutions.10 Popov compared three types of integration modes: solar-heated low-pressure heaters; solar-heated high-pressure heaters; and solar-heated high-pressure heaters and economizers. The results showed that the higher the steam extraction pressure is the better the integration benefits.11 Hou et al established a model of a 600 MW supercritical solar-aided coal-fired power generation unit. Using solar-heated feedwater and reheat steam, the overall cycle efficiency could be increased by 1.91%, the solar-to-electricity efficiency was increased by 6.01%, and the solar share expanded from 9.53% to 17.26%.12 Hu et al introduced the concept of solar-aided power generation in conventional coal-fired power stations and conducted further research. The results showed that the higher the energy quality replaced by solar energy, the better the overall system performance is.1

Hong et al analyzed the typical thermodynamic performance of a 330 MW solar-hybrid coal-fired power plant under a partial load.13,14 Zhai conducted comprehensive system analysis, including exergetic and parametric studies, evaluation methods, economics, and improved optimization research.9,15-21 At present, many researchers have carried out fruitful work on the characteristics and economics of SAPG. Studying the dynamic characteristics of solar-aided coal-fired systems is very important for the coupling of renewable energy with conventional coal-fired power generation units. Zhang et al established a 330 MW SAPG model and analyzed the dynamic performance of the unit and the dynamic response of the main parameters under typical weather conditions. When the heat output of the solar field reached $2.13 \times 10^8 \text{ kJ/h}$, the coal saving rate increased by 6.4%. Based on TRNSYS software, Duan et al established a tower solar collector-aided coal-fired power generation system model, and the maximum annual solar-to-electricity efficiency was 16.74%, the levelized cost of electricity (LOCE) of the solar-aided coal-fired power plant is reduced from 301.5 g/kWh to 294.5 g/kWh compared with coal-fired power plant.23

However, there are more difficulties in the operation of the hybrid system. Dynamic characteristics of parameters such as steam temperature are closely related to the operators who want to know how to maintain the stability of unit. Time-invariable operation of the power plant is analyzed to maximize the production of the electricity and process steam and the combination of feedforward and three-level cascade control is the best alternative to track the temperature set point. A single three-level cascade control without feedforward had less oscillations and low fuel consumption compared to the others control strategies.24,25

In recent years, research on the dynamic characteristics of SAPG has still been insufficient, especially when solar energy is integrated with a coal-fired power generation unit, and the dynamic process of the unit and the steam temperature control mode have not been fully discussed. Whether the high-temperature components of boilers and steam turbines can work safely is a problem that must be solved before solar energy is coupled with a conventional coal-fired power station. It is essential to improve the configuration of the coal-fired unit control system.

In this paper, on the basis of Transient System Simulation (TRNSYS) developed by Wisconsin University Madison, a comprehensive model of SAPG, including solar-heated steam extraction, flue consumption, flue gas dampers, and water spraying control strategies, is established to solve problems caused by the instability and intermittence of solar energy and explore the control strategy under the condition of DNI fluctuation, and these aspects are very important for SAPG system.

2 | METHODOLOGY

2.1 | Model

2.1.1 | System description

The thermal system flowchart of the SAPG model in this paper is shown in Figure 1. Some of the mentioned structures will correspond to the labels in Figure 1.
The SAPG model includes a solar collection system, boiler, steam turbine, and thermal system, wherein the solar collection system includes a tower solar mirror field (2), a receiver (3), and a molten salt heat exchanger (24). The molten salt heat exchanger (24) heats up a part of the high-temperature superheated steam extracted from the platen superheater (7) outlet header, and then the produced superheated steam mixes with the remaining superheated steam at the high-temperature superheater (8) outlet to enter the steam turbine high-pressure cylinder (13). Additionally, after the superheated steam is extracted, to keep the turbine power output stable, the fuel-saving mode is adopted, and the fuel consumption is reduced according to the DNI input. To ensure the stability of both the main steam mass flow rate and temperature, the desuperheating water is extracted from the feedwater pump (21) outlet and sprayed into the steam pipe between the low-temperature superheater (11) outlet header and the platen superheater (7) inlet header to control the overall superheated steam temperature. To ensure the stability of the reheat steam temperature, the flue gas damper (26) opening is adjusted according to the changes in DNI.

A subcritical coal-fired power generation unit is modeled to simulate the boiler, steam turbine, and thermal system. The power generation unit uses a subcritical natural circulation drum boiler with a single reheat, four-corner tangential combustion, and bituminous coal. The main steam temperature is adjusted by spraying water, and the adjustment of the reheat steam temperature depends on the flue gas damper. The steam turbine is a condensing steam turbine with a single shaft and four-cylinder, four-exhaust. There are eight stages of steam extraction, including three high-pressure feed water heaters, four low-pressure feed water heaters, and a deaerator. The parameters of the prototype of the model are shown in Table 1.

For the solar collection system, a Spanish Abengo solar thermal unit is applied as a prototype to establish a tower solar collection system that is suitable for coupling with the coal-fired power generation unit. The main design parameters of the solar field are shown in Table 2.

The main advantages of establishing SAPG are as follows:

- Compared with a traditional coal-fired power generation system, SAPG improves efficiency and reduces environmental impact.

**FIGURE 1** Schematic diagram of an SAPG system. SAPG, Solar-aided power generation system

**TABLE 1** Main design parameters of the coal-fired power generation unit

| Parameters                      | Value | Unit |
|---------------------------------|-------|------|
| Power output                    | 600   | MW   |
| Main steam flow rate            | 1754.8| t/h  |
| Fuel consumption                | 277.4 | t/h  |
| Boiler efficiency               | 0.9415| –    |
| Rated net heat consumption rate | 7731.5| kJ/(kW·h) |
| Excess air ratio                | 1.21  | –    |
| Feed water temperature          | 271   | °C   |
unit, coupling with solar energy is equivalent to adding a heat source, providing extra energy for power generation according to the solar irradiation, reducing coal consumption, and improving the overall thermal performance of the power station; b) Compared with independent solar thermal power generation, the working parameters of the tower solar collector are at relatively high levels, and the energy utilization efficiency of solar energy is higher. The working medium after heat absorption has a greater ability to conduct work and a higher energy-saving potential.

2.1.2 | Tower solar collector model

**Mirror field model**

The tower of the solar collection system is equipped with a receiver at the top, and many heliostats are arranged around it. In tower solar thermal power generation, heliostats are key components for tracking and reflecting the sunlight onto the receiver at the top of the tower. The heat-exchange medium is piped from the ground to the receiver at the top of the tower to absorb the solar irradiance energy. After that, the medium is sent back to the ground through the pipeline, and then the extracted steam is heated inside a shell-and-tube heat exchanger. The extracted steam is on the tube side, and the molten salt is on the shell side. Higher-temperature molten salt is driven through a molten salt pump. The DNI weather data are provided every 10 minutes. The dynamic response in this model is based on a 10-minute interval.

The heliostat tracking mode applies the altitude-azimuth two-axis tracking method. The altitude axis is parallel to the horizontal plane while performing a pitch motion perpendicular to the azimuth axis, and the azimuth axis is rotated perpendicularly to the ground. The simulation model takes the positive south direction as the x-axis and the positive east direction as the y-axis. The receiving tower establishes the ground coordinate system for the origin. A schematic diagram of the coordinates of the solar mirror field is shown in Figure 2.

![Schematic diagram of the heliostat coordinate system](image)

As shown in Figure 2, the azimuth angle of the heliostat $\theta_{he}$ ($^\circ$) is calculated by the following Equation (1):

$$
\theta_{he} = \begin{cases} 
\arccos \frac{x}{\sqrt{x^2+y^2}}, & y \geq 0 \\
\arctan \frac{y}{x} + \pi, & y < 0
\end{cases}
$$

(1)

The angle between the reflected light at the center of the mirror and the vertical direction $\lambda$ ($^\circ$) is calculated by the following Equation (2):

$$
\tan \lambda = \frac{\sqrt{x^2+y^2}}{H_{re} - H_{he}}
$$

(2)

The Heliostat Field (type 394) model requires a user-supplied field efficiency matrix to evaluate the field efficiency, $\eta_{field}$, as a function of the date and time. The power of the receiver is evaluated by the following Equation (3). In this model, the DNI value is used to evaluate the heat from solar irradiation. In this SAPG system, the solar heat is directly related to DNI. The higher the DNI input is the greater the steam extraction from the platen superheater.

$$
\dot{Q}_{rec} = A_{field} \cdot \rho_{field} \cdot DNI \cdot \eta_{field} \cdot \Gamma
$$

(3)

**Receiver model**

The Tower Receiver (type 395) model in TRNSYS is based on the mirror field efficiency model for the interpolation calculation. By inputting a known meteorological data file, the power absorbed by the receiver can be obtained by matrix interpolation, wherein the conduction power loss is ignored. The net received power of the receiver $\dot{Q}_{net}$ (W) is calculated by the following Equation (4):

$$
\dot{Q}_{net} = a \dot{Q}_{inc} - \dot{Q}_{conv} - \dot{Q}_{rad}
$$

(4)

### Table 2: Main design parameters of the solar field

| Parameters                               | Unit   | Value  |
|------------------------------------------|--------|--------|
| Mirror field reflectivity                | –      | 0.9    |
| Mirror surface area                      | m²     | 185 000|
| Ambient temperature                      | °C     | 20     |
| Molten salt heat exchanger inlet steam temperature | °C     | 421    |
| Receiver efficiency                      | –      | 0.8    |
| Pipe pressure drop of solar collection system | MPa  | 0.4    |
| Maximum solar-heated extraction flow rate | t/h   | 175.4  |
Both \( \dot{Q}_{\text{conv}} \) (W) and \( \dot{Q}_{\text{rad}} \) (W) are calculated by Equation (5) and Equation (6), respectively.

\[
\dot{Q}_{\text{conv}} = C_0 + C_1 V + C_2 V^2 + C_3 V^3 \quad (5)
\]

\[
\dot{Q}_{\text{rad}} = R_0 + R_1 \dot{Q}_{\text{inc}} + R_2 \dot{Q}_{\text{inc}}^2 + R_3 \dot{Q}_{\text{inc}}^3 \quad (6)
\]

The receiver efficiency \( \eta_{\text{rec}} \) is calculated by the following Equation (7):

\[
\eta_{\text{rec}} = \frac{\dot{Q}_{\text{net}}}{\dot{Q}_{\text{inc}}} = \frac{\dot{Q}_{\text{net}}}{\dot{Q}_{\text{rec}}} \quad (7)
\]

### 2.1.3 Boiler model

In TRNSYS, a multistage heat exchanger is applied in series to simulate coal-fired boiler combustion.

The heat exchanger model Eco_SH (type 315) in the STEC library is applied in the simulation of economizers, superheaters, reheaters, and solar heat exchangers. A zero-capacitance sensible heat exchanger is modeled in the counter-flow mode. The cold side input is assumed to be water or steam depending on quality. The respective specific heat of the cold-side fluid is calculated from water/steam property data. The effectiveness of the heat exchanged in the heat exchanger is calculated by the following Equation (9):

\[
\eta_{\text{ECO}} = \frac{1 - \text{Exp} \left[ \frac{U_r}{C_{\text{min}}} \cdot \left(1 - \frac{C_{\text{min}}}{C_{\text{max}}} \right) \right]}{1 - \frac{C_{\text{min}}}{C_{\text{max}}} \cdot \text{Exp} \left[ \frac{U_r}{C_{\text{min}}} \cdot \left(1 - \frac{C_{\text{min}}}{C_{\text{max}}} \right) \right]} \quad (8)
\]

The heat exchanged in the heat exchanger \( \dot{Q}_{\text{ECO}} \) (kJ/h) is calculated by the following Equation (9):

\[
\dot{Q}_{\text{ECO}} = \eta_{\text{ECO}} \cdot C_{\text{min}} \cdot (T_2 - T_1) \quad (9)
\]

The steam, water, and flue gas parameters of the heat exchangers at different parts of the boiler are shown in Table 3.

### 2.1.4 Steam turbine model

The steam turbine model uses the component Stage (type 318). The multistage turbine model is based on a series of single-stage turbine models. There are nine stages, including two HP cylinders, two IP cylinders, and five LP cylinders. During the dynamic change process of DNI, the turbine parameters also change accordingly. The model uses the Stodola equation to describe the relationship between the pressure drop and the mass flow change at a certain stage of a turbine under variable operating conditions, as shown in the following Equation (10):

\[
p_{\text{in}} = \sqrt{\left( \frac{m_{\text{in}}}{m_{\text{in,design}}} \right)^2 \cdot \left( p_{\text{in,design}}^2 - p_{\text{out,design}}^2 \right) + p_{\text{out}}^2} \quad (10)
\]

Some relevant parameters of the steam turbine are shown in Table 4.

### 2.1.5 Model validation

To reduce the complexity of the model and facilitate calculation convergence, the actual power plant structure is simplified in the TRNSYS simulation.

1. The boiler feedwater pump is replaced by an electric pump.
2. Limited by the TRNSYS components, the model simplifies the milling and firing processes of coal. A calculated initial flue gas stream, which has a certain temperature and mass flow rate, replaces the coal-fired heat release process.
3. Both the shaft seal steam leakage and the furnace air leakage have little effect on the dynamic operation of the unit during actual operation, and they are neglected in the modeling.
4. When the solar collection system starts the steam extraction, both the boiler efficiency and the steam turbine efficiency will change accordingly, but the impact on the operation of the unit is much less than the impact of the solar energy access. Therefore, when the solar collection system is in operation, both the boiler efficiency and the steam turbine efficiency remain unchanged.
Comparisons of the key operating parameters between the model and the original power generation unit are shown in Table 5. Compared with the original parameters, the simulation results are basically the same or have slightly deviations, and these deviation values are within an acceptable range. It is considered that the simulation model can carry out further strategy implementation and parameter analysis.

2.2 System evaluation model

2.2.1 Fuel consumption

The boiler fuel consumption $B_{SAPG}(t/h)$ is used to evaluate the performance of the system and represents the amount of coal consumption. The calculation formula and dynamic characteristics of $B_{SAPG}$ are given in section 2.3.3. The coal components and lower heating value ($Q_{net,ar}$) of SAPG are shown in Table 6. The relationship between the fuel consumption rate $B_{SAPG}$ and the flue gas flow rate $\dot{m}_{flue}(t/h)$ is given by the following Equation (11):

$$\dot{m}_{flue} = B_{SAPG} \left\{ (1 - \beta) + \alpha \left[ 0.115 (C_{ar} + 0.375S_{ar}) + 0.342H_{ar} - 0.0431O_{ar} \right] \right\}$$  (11)

2.2.2 Solar-to-electricity efficiency

The solar-to-electricity efficiency ($\eta_{ste}$) is one of the most important indicators for evaluating any solar power generation system and can be calculated by the following Equation (12):

$$\eta_{ste} = \frac{P_{solar}}{Q_{solar}} \times 100\% = \frac{10^6 P_{solar}}{A_{field} \cdot \rho_{field} \cdot DNI} \times 100\%$$  (12)

2.2.3 Solar share

In the process of coupling coal-fired units with solar thermal energy, the share of solar power generation in the total power generation is an important indicator for evaluating an SAPG system. In this paper, the solar power share $x$ is used to evaluate the share of the output power from solar heat and is calculated by the following Equation (13):

$$x = \frac{P_{solar}}{P_{SAPG}} \times 100\%$$  (13)

2.3 Steam temperature control strategy

In a typical solar thermal power generation system, DNI cannot be used as a control variable for the system. In the established SAPG system, the solar energy access to coal-fired power generation units is affected by the DNI, and the solar energy input is used to heat up the superheated steam. In the actual operation of the SAPG system, it is necessary to adjust the amount of steam extracted, the coal consumption of the boiler, the amount of water spraying, and the flue gas damper opening according to the changes in DNI. As a result, the SAPG system applies feedforward control from the DNI signal to maintain the stability of the steam temperature and the system heat balance.

The heat transfer process of coal-fired units has time lag. If the input of the DNI disturbance is known, it is theoretically possible to reduce the effects of disturbance by extra-added input before it affects the output value. The so-called feedforward control is to correct the disturbance before the coal-fired unit is affected by

| TABLE 5 | Model validation between the design and simulation values |
| Parameters/unit | Working condition: 100% THA |
| | Design | Simulation | Error/% |
| Main steam pressure/MPa | 17.28 | 17.40 | 0.69 |
| Main steam temperature/℃ | 541 | 541 | 0 |
| Main steam flow rate/t·h$^{-1}$ | 1754.8 | 1755.2 | 0.02 |
| Reheat steam flow rate/t·h$^{-1}$ | 1466.7 | 1444.6 | −1.50 |
| Reheat steam inlet pressure/MPa | 3.35 | 3.39 | 1.19 |
| Reheat steam outlet pressure/MPa | 3.20 | 3.28 | 2.50 |
| Reheat steam inlet temperature/℃ | 310 | 306 | −1.29 |
| Reheat steam outlet temperature/℃ | 541 | 541 | 0 |
| Feedwater temperature/℃ | 270 | 265.8 | −1.56 |
| Back pressure/kPa | 4.5 | 4.5 | 0 |
| Power output/MW | 600.36 | 595.40 | −0.83 |

| TABLE 6 | Ultimate analysis of coal |
| Parameters | Value | Unit |
| $M_{ar}$ | 13.25% | – |
| $A_{ar}$ | 26% | – |
| $C_{ar}$ | 47.62% | – |
| $H_{ar}$ | 3.01% | – |
| $O_{ar}$ | 8.77% | – |
| $N_{ar}$ | 0.88% | – |
| $S_{ar}$ | 0.47% | – |
| $Q_{net,ar}$ | 17 981 kJ/kg | |
DNI fluctuations. In the SAPG system of this paper, the change of DNI is in real-time monitoring and transmitted to the control center through the measuring device of the mirror field. When DNI rises instantaneously, the collected solar energy will increase, and the solar steam parameters will increase, thereby generating an impact on the boiler steam turbine. Under the feedforward control, when DNI rises instantaneously, the control system will weaken the impact of the DNI increase in advance by adjusting the fuel consumption rate, solar-heated steam extraction rate, water spraying flow rate, and flue gas damper opening. When the disturbance arrives the output side, the correction orders arrive, and the output remains stable in the DNI fluctuation process.

2.3.1 Initial conditions and control methods

The meteorological data (ambient temperature, wind speed, and DNI) for January 3 in Dunhuang, northwestern China, are selected as input parameters for the model. The steam temperature control strategy is further explored. The initial conditions of SAPG, including a series of dynamic parameters such as ambient temperature, wind speed, and DNI, are shown in Figure 3.

By importing external meteorological data files, the tower solar collector model generates corresponding dynamic heat collection data and dynamically calculates various important parameters of actual operation. The model uses the measuring devices of the overall solar mirror field to generate a real-time corresponding DNI control signal.

The DNI control signal produces the effects of feedforward control on the SAPG system in the following ways: The signal is transmitted to the boiler coal-fired control system to control and modify the coal consumption and is also transmitted to the steam extraction valve opening control system to control the steam extraction flow rate from the platen superheater. At the same time, the signal is transmitted to the flue gas damper opening control system and the spray desuperheating control system to keep the steam temperature at a constant value. Under the coordination of the feedforward control system in this paper, the steam temperature can be kept nearly stable. As DNI rises, the SAPG system undergoes a series of changes: The amount of steam extracted to the solar collection system increases; the coal consumption rate of the boiler decreases; the flue gas damper openings on the lower temperature reheater increase, and the reheat steam temperature remains relatively stable; and the spray desuperheating flow rate increases, the main steam temperature remains substantially stable, and vice versa. The DNI control flowchart of this SAPG system is shown in Figure 4.

2.3.2 Steam extraction strategy

In the model, the amount of steam extracted to the solar collection system is affected by the feedforward control of the DNI signal. The installation of the tower solar collection system introduces the additional heat $\dot{Q}_{\text{net}}$ in addition to the boiler’s coal heat release, which is used to heat up approximately 10% of the main steam mass flow.

According to the heat exchange equilibrium condition of the solar heat exchanger combined with Equations (3), (4), (5), and (6), the steam extraction flow rate $\dot{m}_{\text{ex}}$ (t/h) of the solar collection system can be calculated by the following Equation (14):

$$\dot{m}_{\text{ex}} = 3.6 \times 10^{-3} \times \frac{\dot{Q}_{\text{net}}}{\Delta h_{\text{sol}}},$$

$$= 3.6 \times 10^{-3} \times \frac{1}{h_{\text{sol,out}} - h_{\text{sol,in}}} \times (\alpha A_{\text{field}} \cdot \rho_{\text{field}} \cdot DNI \cdot h_{\text{field}} \times \Gamma - C_0 - CV - C_2 V^2 - C_3 V^3 - R_0 - R_1 \dot{Q}_{\text{inc}} - R_2 \dot{Q}_{\text{inc}}^2 - R_3 \dot{Q}_{\text{inc}}^3).$$
Under the assumptions of the model and the determined rated conditions, the steam extraction flow rate $\dot{m}_{ex}$ is a function of both DNI and wind speed $V$, that is, $\dot{m}_{ex} = f(DNI, V)$. When the wind speed $V$ is 0, $\dot{m}_{ex}$ changes linearly with $I$, that is, $\dot{m}_{ex} = f_{V=0}(DNI)$. The change in the extraction steam flow rate under the control of DNI is shown by the black line in Figure 5.

### 2.3.3 Coal consumption control strategy

In the model, the change in fuel consumption is the same as that of the steam extraction and is also subject to the feedforward control of DNI. The solar collection system produces the additional heat $\dot{Q}_{net}$ in addition to the boiler’s coal-fired heat release. In the fuel-saving mode, this additional solar energy is balanced in the form of a reduction in the coal consumption in the boiler. According to the heat balance conditions of both the boiler heat exchangers and the solar heat exchangers, the boiler-side fuel consumption $B_{SAPG}$ ($\mathrm{t/h}$) can be calculated using the following Equation (15):

$$
B_{SAPG} = \frac{\dot{m}_{SAPG} - \dot{m}_{SP} - \dot{m}_{ex}}{(h_{L,b} - h_{ECP}) + \dot{m}_{ex} (h_{solar,out} - h_{solar,in})}
$$

(15)

Under the assumptions of the model and the determined rated conditions, the fuel consumption $B_{SAPG}$ is obtained by the following Equation (16):

$$
B_{SAPG} = f(\eta_{boil}, DNI)
$$

(16)

In this model, the boiler efficiency has a relatively small impact on the power generation unit. After ignoring its influence, the fuel consumption is linearly related to DNI. When the DNI is 0, the steam extraction amount is 0, and the fuel consumption of the SAPG system is equivalent to that of the coal-fired unit. When DNI increases, $B_{SAPG}$ decreases accordingly. The change in fuel consumption under the same control strategy as in Figure 4 is shown by the red line in Figure 5.

### 2.3.4 Dynamic flue gas damper control and spray desuperheating control

Similar to the steam extraction control system and the boiler coal-fired control system, the flue gas damper is also affected by the DNI signal, resulting in corresponding dynamic control to regulate the reheat steam temperature. During the nighttime, the reheater flue gas damper opening is set to 64.5%, and during the daytime, the flue gas damper opening is increased to reduce the impact of the coal reduction effect on the reheat steam temperature; the maximum opening is 74.4%. The change in the flue gas damper opening under the control of DNI is calculated by Equation (17) and is shown in Figure 6.

$$
k = \frac{m_{flue,LRH} + \frac{DNI}{800} \times k_0}{m_{flue}} \times 100\%
$$

(17)

With the dynamic changes in the extraction control system, the coal-fired control system, and the flue gas damper control system, different degrees of steam temperature disturbance occur on the main steam side. To maintain the stability of the main steam temperature, the spray desuperheating system corresponding to the DNI works dynamically to weaken or eliminate the influence.

![Extraction steam and fuel consumption](image1.png)

**Figure 5** Change in the extraction steam flow rate and fuel consumption under the control of DNI. DNI, Direct normal irradiance

![Flue gas damper opening](image2.png)

**Figure 6** Changes in the damper opening under the control of DNI. DNI, Direct normal irradiance
of changes in steam extraction, coal consumption, and flue gas on the main steam temperature. The logic control flowchart of the spray desuperheating control system is shown in Figure 7.

In Figure 7, \( f(x) \) is a function describing the Equation (16), and the other functions and parameters are the same as the control logic of the coal-fired unit.

3 | DYNAMIC PROCESS SIMULATION

The parameters such as the mass flow rate, temperature, and pressure of both the steam and the flue gas are the core parameters of the operation process of a traditional coal-fired power generation system. Studying the dynamic changes in these parameters is of great significance to the actual operation of SAPG. In section 2, the responses of DNI feedforward control, such as the steam extraction flow rate, the fuel consumption, the flue gas flow rate, and the spray desuperheating flow rate, are introduced. This section focuses on changes in the key operating parameters of SAPG during dynamic operating processes.

3.1 | Steam flow rate

The dynamic responses of the flow rate parameters under the actual operating conditions of SAPG are obtained by the dynamic simulation model. Figure 8 shows the mass flow rate responses of both the PSH steam and the HSH steam under the control of DNI.

As shown in Figure 8, after 8:00 AM, the sun rises, the DNI increases, and the extraction steam amount on the solar energy side gradually increases, which is separated from the PSH outlet and does not enter the HSH. Therefore, the HSH steam flow rate is reduced, and the mass flow rate difference between the PSH steam and the HSH steam is the amount of steam extracted by the solar collection system. When the solar irradiance is unstable, such as around 10:00 AM, due to the application of the DNI control strategy, the SAPG system has self-adjusting capacity. The mass flow rates of steam undergo a limited fluctuation process; however, the deviation values are not too large. When the solar irradiance is rich, such as from 12:00 PM to 16:00 PM, the extraction steam flow rate on the solar energy side reaches the highest value. At this time, the maximum steam extraction mass flow rate accounts for 10% of the total steam mass flow rate, approximately 175.5 t/h, and the SAPG system tends to be stable overall.

3.2 | Temperature response

The dynamic responses of the temperature parameters of each part of the boiler under the actual operating conditions of SAPG are obtained by the dynamic simulation model. The daily variation curves of the steam temperatures of some heat exchangers on January 3 are shown in Figure 9.

For the LSH, the effects of changes in DNI on the main steam temperature and LSH outlet steam temperature are in the allowed temperature ranges, and because of the dynamic adjustment of the flue gas damper opening, the steam temperature before and after the LSH is slightly affected. For the PSH, due to the introduction of spray desuperheating at the entrance of the PSH, both the boiler fuel consumption and the steam temperature before and after
the PSH are lowered. For the main steam, both the HSH steam and the solar heat exchanger extraction steam mix, and the main steam temperature is affected by both the solar-side steam temperature and the HSH steam temperature. There is a certain degree of temperature fluctuation during the unstable period of solar energy; however, the temperature can be maintained at approximately the rated value of 541°C. The main steam temperature fluctuation range is approximately 5°C. When the solar irradiance is sufficient, the main steam temperature rises slightly, which helps to balance the effect of the reheat steam temperature reduction on the unit’s power generation and has less effect on the stable operation of the steam turbine.

During the operation of the actual SAPG system, the heat inertia of heat exchangers is large, and the changes in the extraction steam mass flow rate, the flue gas mass flow rate, the fuel consumption, and the spray desuperheating mass flow rate are smoother than those of the simulated parameters.

Therefore, the rates of change in the steam temperatures with time are smaller, so it is considered that the main steam temperature of the boiler outlet can be maintained as stable, and the steam temperature dynamic process of heat exchangers is smoother.

### 3.3 Pressure response

The daily variation curves of the main steam and reheat steam pressure and mass flow rate on January 3 are shown in Figure 10 and Figure 11, respectively.

As shown in Figure 10 and Figure 11, the responses of the main steam and reheat steam pressure are consistent with the changes in the corresponding steam mass flow rates, which are in accordance with the change relationship between the steam flow rate and the steam pressure. The night pressure of the main steam is approximately 17.05 MPa, the maximum pressure is approximately 17.3 MPa during the fluctuation process, and the fluctuation range is 0.25 MPa. The change in the reheat steam pressure is similar to that of the main steam. The maximum reheat steam pressure fluctuation range is approximately 0.06 MPa, which has little impact on the operation of the unit. The inlet steam pressures of the HP turbine and IP cylinder during the operation of SAPG are in the controllable range.

### 3.4 Power response

The SAPG system is affected to some extent by a reduction in the reheat steam temperature. Figure 12 shows the dynamic change in the reheat steam temperature with the change in the amount of coal burned. Figure 13 shows the response of the total power output of the SAPG system.
Figure 14 shows the power dynamic processes of each cylinder of the turbine.

As shown in Figure 12, the reheat steam temperature is approximately 539°C at night. During the period of abundant solar irradiance, as the flue consumption decreases, the temperature of reheat steam slightly decreases, and the temperature drop is approximately 7°C. The main reasons can be explained from the following aspects.

As DNI increases, the amount of steam extracted from the boiler side increases, the mass flow rate of the HSH steam decreases, and the main steam temperature rises; however, these changes can be adjusted by mixing with the solar-side steam or the spray desuperheating method before entering the HP cylinder. This process stabilizes the main steam temperature. However, for the reheat steam after the HP cylinder, the temperature is only affected by the coal reduction on the boiler side and can only be adjusted slightly through the flue gas damper. Therefore, in the SAPG system of this paper, the reduction in the reheat steam temperature cannot be avoided, and the power generation of the IP cylinder is affected.

Due to the dynamic fluctuation of coal reduction, steam extraction variation, flue gas damper opening, and spraying water flow rate, the change in the output power has a similar trend with that of the mass flow rate or pressure of the steam, and the output power fluctuation range is approximately 10 MW, which is within the acceptable range of the unit.

As shown in Figure 14, to balance the power losses of the IP and LP cylinders, the HP cylinder power increases. Because the power of the HP, IP, and LP cylinders is dynamically controlled by the changes in DNI, the power generation of the steam turbine is relatively maintained within a limited range of 10 MW. Under stable sunlight conditions, the SAPG system can maintain sufficient power, as shown in Figure 13.

### 3.5 Simulation results of consecutive days

This section selects the continuous meteorological data from January 1 to January 10 in Dunhuang. The changes in the extraction steam mass flow rate, flue consumption, and flue gas damper opening with changes in DNI are shown in Figure 15. The changes in both the main steam temperature and power generation of the SAPG system within the ten days are shown in Figure 16.

In the simulation of meteorological data for ten consecutive days, the main steam temperature of the SAPG system increases slightly in the fuel-saving operation mode of the SAPG system; however, within a reasonable fluctuation range, the power generation of the SAPG system remains stable. After applying the control strategy, the expected operational data are achieved. SAPG can achieve a coal reduction
of 4.9% by using the steam temperature control strategy, the main steam temperature fluctuation is less than 5°C, and the power generation fluctuation is less than 10 MW.

3.6 Solar-to-electricity efficiency

The changes in both the solar share and the solar-to-electricity efficiency following the DNI for ten consecutive days are shown in Figure 17. At the peak DNI, the solar share reaches a maximum of 5.27%, and the solar-to-electricity efficiency of the SAPG system reaches a maximum of 22.5%. During unstable periods of DNI, the solar-to-electricity efficiency fluctuates slightly.

4 CONCLUSIONS

This paper establishes a TRNSYS model of a SAPG system and selects the meteorological data for a certain year in Dunhuang city, Northwest China, to simulate the dynamic characteristics of the SAPG system. A steam temperature control strategy is applied, and the responses of key parameters of the SAPG system under different conditions in a period of time are investigated. The main conclusions are as follows:

1. By inputting specific meteorological data, the SAPG system is subjected to the feedforward control of DNI in the case of large changes in solar radiation, such as sunrise and sunset. The main steam temperature fluctuation range is approximately 5°C, and other parameters are within reasonable fluctuation ranges.

2. When implementing the control strategy in consecutive days, the SAPG system is well controlled by the feedforward control of DNI. The spray desuperheating mass flow rate, fuel consumption, extraction steam flow rate, and flue gas damper opening are all constantly changing processes. In the selected ten days, the SAPG system can operate stably and efficiently, and the highest solar-to-electricity efficiency reaches 22.5%.

3. Because of the dynamic coal reduction, the reheat steam temperature decreases in the daytime, and the IP cylinder power generation decreases. These changes result in a reduced performance of the SAPG system to some extent; however, the control strategy limits the fluctuation range within 10 MW.

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NOMENCLATURE

Afield Mirror surface area(m²)
B_sapg The fuel consumption of SAPG(t/h)
Abbreviations

SAPG, Solar-aided power generation system; TRNSYS, Transient system simulation program; DNI, Direct normal irradiance; STEC, Solar thermal electric components; LSH, Low-temperature superheater; LRH, Low-temperature reheater; PSH, Platen superheater; HSH, High-temperature superheater; HRH, High-temperature reheater; HP, High pressure; IP, Intermediate pressure; LP, Low pressure; STE, Solar-to-electricity.

ORCID

Liping Pang https://orcid.org/0000-0002-3661-2477

REFERENCES

1. Hu E, Yang Y, Nishimura A, Yilmaz F, Kouzani A. Solar thermal aided power generation. *Appl Energy*. 2010;87(9):2881-2885.
2. Energy B. *BP Energy Outlook-2019 edition*. England: BP Energy; 2019:73.
3. Yang YP, Cui YH, Hou HJ, Guo XY, Yang ZP, Wang NL. Research on solar aided coal-fired power generation system and performance analysis. *Sci China*. 2008;51(8):1211-1221.
4. Sheu EJ, Mitsos A, Eter AA, Mokheimer EMA, Habib MA, Al-Qutub A. A Review of hybrid solar-fossil fuel power generation systems and performance metrics. *J SolEnergyEng*. 2012;14(04):041006-1-041006-17.
5. Sheu EJ, Mitsos A. Optimization of a hybrid solar-fossil fuel plant: Solar steam reforming of methane in a combined cycle. *Energy*. 2013;51:193-202.
6. Vakilabadi MA, Bidi M, Najafi AF, Ahmadi MH. Exergy analysis of a hybrid solar-fossil fuel power plant. *Energy Sci Eng*. 2019;7(1):146-161.
7. Akbari Vakilabadi M, Bidi M, Najafi AF, Energy. Exergy analysis and optimization of solar thermal power plant with adding heat and water recovery system. *Energy Convers Manage*. 2018;171:1639-1650.
8. Pierce W, Gauché P, Backström TV, Brent AC, Tadros A. A comparison of solar aided power generation (SAPG) and stand-alone concentrating solar power (CSP): A South African case study. *Appl Therm Eng*. 2013;51:657-662.
9. Zhu Y, Zhai R, Peng H, Yang Y. Exergy destruction analysis of solar tower aided coal-fired power generation system using exergy and advanced exergetic methods. *Appl Therm Eng*. 2016;108:339-346.
10. Zoschak RJ, Wu SF. Studies of the direct input of solar energy to a fossil-fueled central station steam power plant. *Sol Energy*. 1975;17(5):297-305.
11. Popov D. An option for solar thermal repowering of fossil fuel fired power plants. *Sol Energy*. 2011;85(2):344-349.
12. Wu J, Hou H, Hu E, Yang Y. Performance improvement of coal-fired power generation system integrating solar to preheat feedwater and reheated steam. *Sol Energy*. 2018;163:461-470.
13. Peng S, Hui H, Wang Y, Wang Z, Jin H. Off-design thermodynamic performances on typical days of a 330 MW solar aided coal-fired power plant in China. *Appl Energy*. 2014;130(5):500-509.
14. Peng S, Wang Z, Hong H, Da XU, Jin H. Exergy evaluation of a typical 330 MW solar-hybrid coal-fired power plant in China. *Energy Convers Manage*. 2014;85(9):848-855.
15. Zhai R, Zhu Y, Yang Y, Tan K, Hu E. Exergetic and parametric study of a solar aided coal-fired power plant. *Entropy*. 2013;15:1014-1034.
16. Zhai R, Peng P, Yang Y, Zhao M. Optimization study of integration strategies in solar aided coal-fired power generation system. *Renew Energy*. 2014;68:80-86.
17. Zhai R, Zhao M, Tan K, Yang Y. Optimizing operation of a solar-aided coal-fired power system based on the solar contribution evaluation method. *Appl Energy*. 2015;146:328-334.
18. Zhai R, Zhao M, Chao L, Pan P, Yang Y. Improved optimization study of integration strategies in solar aided coal-fired power generation system. *Renew Energy*. 2015;68(3):80-86.
19. Zhai R, Liu H, Li C, Zhao M, Yang Y. Analysis of a solar-aided coal-fired power generation system based on thermo-economic structural theory. *Energy*. 2016;102:375-387.
20. Zhai R, Qi J, Zhu Y, Zhao M, Yang Y. Novel system integrations of 1000MW coal-fired power plant retrofitted with solar energy and CO2 capture system. *Appl Therm Eng*. 1000MW:125:1133-1145.
21. Zhu Y, Zhai R, Qi J, et al. Annual performance of solar tower aided coal-fired power generation system. *Energy*. 2017;119:662-674.
22. Zhang N, Hou H, Yu G, Hu E, Duan L, Zhao J. Simulated performance analysis of a solar aided power generation plant in fuel saving operation mode. *Energy*. 2019;166:918–928.
23. Duan L, Yu X, Jia S, Wang B, Zhang J. Performance analysis of a tower solar collector-aided coal-fired power generation system. *Energy Sci Eng*. 2017;5(1):38-50.
24. Ghobeity A, Noone CJ, Papanicolas CN, Mitsos A. Optimal time-invariant operation of a power and water cogeneration solar-thermal plant. *Sol Energy*. 2011;85(9):2295-2320.
25. Fontalvo A, Garcia J, Sanjuan M, Padilla RV. Automatic control strategies for hybrid solar-fossil fuel power plants. *Renew Energy*. 2014;62:424-431.

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