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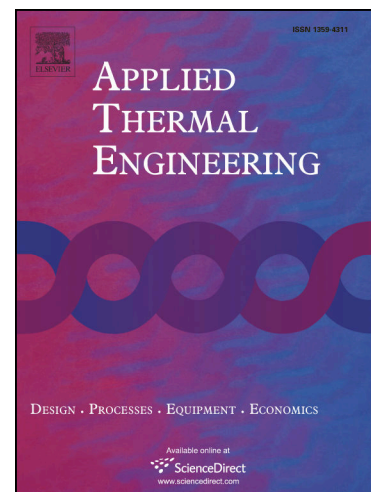
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## **Model predictive control of a combined solar tower and parabolic trough aided coal-fired power plant**

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**Abstract:** Investigating the potential to add solar tower and parabolic trough technology to aid coal-fired power generation could be a valuable intermediate step along the route to decarbonisation while making use of an existing assets, that would have a high efficiency and percentage contribution to utilise solar energy to reduce coal consumption. Based on the plant model of a typical 600MW coal-fired plant with the addition of tower and trough solar heat sources developed in Ebsilon Professional platform, the model predictive controller is developed in this study, incorporating the information of predictive weather data and real power load, to minimise accumulative coal consumption in a specific time horizon. Simulations on a typical day and a 10-day consecutive period are performed to observe the benefits and operation processes with a model predictive controller. Compared with a standard controller that doesn't make use of

future solar and load predictions, the typical day simulation shows, that the coal consumption reduction using a predictive control approach is increased by 21.3-tonne (13.6%), and 320.0-tonne (20.3%) in the 10 consecutive day simulation. The absolute difference of reduction tends to be most significant in high radiation conditions (day 2), which gave a 61.7-tonne (34.3%) saving. The improvement appears to be achieved by dispatching the thermal energy storage ability to store more energy and discharging thermal energy optimally. The benefits from this approach is insensitive to forecast error and shows sensitivity to system configurations, which tends to be greater with sufficient solar energy input but inadequate thermal storage capacity. While the general area of solar aided coal-fired plants have been investigated in various configurations by others, this paper is novel in that it examines the benefit of using future weather forecast data within a model predictive controller to significantly improve the potential solar contribution such a plant can use. As such it quantifies the potential improvements such an approach may achieve. In summary, the application in the solar tower and parabolic trough aided coal-fired power generation system improved the understanding of the benefits and the limitations in using the model predictive control in the operation process.

**Keywords:** Solar tower; Parabolic trough; Coal-fired power generation; Model predictive control; Power load; Sensitivity studies;

## 1. Introduction

In recent decades, the contradiction between the growth of energy demand for social activities and the negative impacts of fossil fuels is becoming increasingly prominent [1]. An important trend and practical choice is to restructure the energy source [2]; generating power from renewable energy is attracting more attention [3]. Concentrated Solar Power (CSP) is deemed as a promising renewable technology due to its ability to store energy efficiently and fairly cheaply, in large scale to provide stable and dispatchable electricity compared with other renewable energy, such as wind power and photovoltaic energy [4]. Different CSP technologies are explored, such as CSP based on supercritical carbon dioxide Brayton cycle [5, 6] and organic Rankine cycle [7, 8]. On the other hand, the development of standalone CSP technology is compromised by high investment costs and often relatively low thermal efficiency [9]. Solar-aided coal-fired power generation, in which solar energy is integrated into the boiler or regenerative components, while the condenser and turbines are shared to produce power [10, 11], has been demonstrated as having the benefit of improving solar-to-electricity efficiency [12, 13], reducing coal consumption and sharing investment [14]. The integrated system is first explored in 1975 [15], then was further studied after identifying the benefits and conceptualised by Hu et al. in 2010 [16]. Studies in this field fall into three main categories according to the integrated solar energy technology: solar parabolic trough aided coal-fired power generation (SPCG), solar tower-aided coal-fired power generation (STCG) and the combined solar tower and parabolic trough aided coal-fired power generation

(STPG).

Within the three categories, the most efforts have been focused on SPCG, and its integration schemes, performance analysis on thermodynamic, economic and specific components, and development of different evaluation methods. To identify the optimum integration scheme, Rech et al. examined 22 alternatives integrated with parabolic trough collectors, linear Fresnel collectors or solar towers. High-pressure preheater/s was proved to be the optimum integration point with the hybrid thermal efficiency of 42.67% at a solar share of 7.63% [17]. Wang et al. performed a general optimisation method using eight virtual molten salt heat exchangers and different heat distribution proportions to simulate all schemes integrated with preheaters. Results show that the highest-pressure feedwater heater is the best integration point when solar energy is sufficiently available [18]. Qin et al. investigated 4 connection styles between solar energy and feedwater preheater and 3 operation modes to adjust extraction feed-water [19]. Based on the normal high-pressure preheater scheme, Wu et al. added a second parabolic trough field to preheat the cold reheat steam before entering the boiler [20]. The new configuration showed that the enhanced system efficiency increased by 1.93%. Liu et al. developed a generalised multi-heat-source system model as the common integration method for different energy sources [21]. To identify the benefits and limits of SPCG, system performances are investigated from several aspects. Bakos et al. showed the system efficiency is increased from 33% to 37.64% after integration in power-boosting mode while a 38,081-tonne annual reduction of coal consumption can be achieved in fuel-saving mode [22]. Shagdar et

al. investigated the techno-economic performance and ecological advantages of a 330 MW<sub>e</sub> SPCG, in which the coal consumption rate is reduced by 14.92 g/kWh and the levelised cost of electricity (LOCE) is estimated as 0.13 USD/kWh [23]. Adibhatla et al. also investigated the exergy and thermo-economic performances of a 500MW<sub>e</sub> subcritical power plant with solar aided feed water heating [24]. Similar studies are also performed by Hou et al. [25] and Wu et al. [26, 27]. Zhao et al. for different sizes of solar field in a 200 MW<sub>e</sub>, 330 MW<sub>e</sub> and 600 MW<sub>e</sub> SPCG to find a minimum LCOE, which is 0.56, 0.53 and 0.49 CNY/kWh in the three systems, respectively [28]. Li et al. investigated a 600 MW<sub>e</sub> solar preheating SPCG from the viewpoint of boiler safety and found the maximum solar energy input is 66.5 MW<sub>th</sub> [29]. Recently, the dynamic performances of a SPCG during a specific period are observed to further understand the operation process [30, 31]. To promote the practical application of the system, the behaviour of crucial components have been focused on in recent years, including the direct air-cooled condenser [32], the boiler [33] and the thermal energy storage system (TES) [34]. Different analysis methods have also been applied to evaluate SPCG from a comprehensive set of perspectives. Reddy et al. [35] and Peng et al. [36] performed the exergy evaluation on these systems. The integrated system characteristics are also analysed utilising thermo-economic structural theory [37] and life cycle assessment method [38]. Wang et al. proposed a comprehensive evaluation factor to calculate the “coal-savability” and “efficiency-promotability” in a SPCG [39]. To accurately distinguish the contribution of solar energy in the integrated system, a thermo-economic cost method is developed for solar contribution and

applied in a 600 MW<sub>e</sub> system, the percentage of solar power in the case is found to be 4.84% (29.04 MW<sub>e</sub>) [40]. Then the method was utilised to optimise the flow rate of heat transfer fluid under five load conditions (100%, 85%, 75%, 50%, and 40%) [41]. Hou et al. also established a solar contribution evaluation method based on exergy analysis and applied in a 600 MW<sub>e</sub> system [42].

In the category of STCG, due to the higher concentration factor, the heat transfer fluid can be heated to a higher temperature by the solar tower compared to parabolic troughs and can be utilised in the boiler for a higher efficiency. Considering the complexity of the boiler, researchers developed integration structures based on detailed boiler model in studies of STCG instead of a "black box model" used in most studies of SPCG. Zhang et al. compared two schemes that use solar energy to heat superheated steam or subcooled feed-water [43]. Results show the reduction in coal consumption rate of more than 17 g/kWh can be obtained in both schemes, and the maximum solar contribution is 6.11% and 4.90% respectively considering the safety constraints of the boiler. Li et al. compared three integration schemes considering water-wall, superheaters and reheaters [44]. The situation using solar tower energy to reheat exhaust steam from the immediate turbine has also been proposed recently [45]. Then the off-design and annual performance of STCG are separately studied by Zhang et al. [46] and Li et al. [47, 48].

In the category of STPG, the combined solar tower and parabolic troughs lead to an improved solar contribution and flexibility in operation, which is proposed in our previous study [49]. The comparison results show improved cost-effectiveness with

7.83%–11.88% more solar exergy provided under the same solar field investment compared to the other two categories. Besides, the maximum solar energy introduced into the reheat steam extraction is proved to be enhanced by the integration of parabolic troughs in preheaters, which is improved by 24.2 MW<sub>th</sub>, 11.5 MW<sub>th</sub>, and 5.6 MW<sub>th</sub> considering boiler safety constraints under 100%, 75% and 50% loads [50]. These studies have identified the benefits of STPG in efficiency and in the proportion of solar energy able to be contributed within the operational boundary taking into consideration safety concerns to maintain a stable steam temperature. However, to promote the actual application of the system, the continuous operational process of a STPG system over a specific time horizon considering the actual load requirement, weather conditions and implementation of a controller is required, which hasn't been studied either in STPG but also in the other two categories.

To improve this limited knowledge about the consecutive operation of STPG systems under actual external conditions and addresses the gap in utilisation of operational controller in STPG systems, this paper aims to develop a Model Predictive Control (MPC) approach for the system utilising solar energy from parabolic troughs and solar tower to reduce as much coal consumption as possible, and to identify its advantages and limitations by comparing it with a standard control approach, which is the typical solution due to the simplicity. MPC is an advanced control approach that combines the detailed system model and the future operational conditions over a specific time horizon to achieve the global optimisation of energy systems. MPC has been adapted in processes related to renewable energy utilisation in

recent years, including wind power [51] and PV-battery microgrid system [52], and showed potential to achieve better global performance by considering variable input information. The main research contributions and scientific value of this study are: (1) Model predictive control method is developed, incorporating the operating characteristic of STPG, safety constraints of inputs and information of predictive weather data and power load. (2) The behaviour and operational results of a STPG system with two control approaches are investigated and compared for the first time over a specific time horizon. (3) A comprehensive understanding of advantages, limitations and applicability of the model predictive controller in a STPG system is gained, and provides reference for the application.

## **2. System description**

The composition of the integrated STPG system and the operational control strategies are introduced in this section.

### **2.1 Solar tower and parabolic trough aided coal-fired power system**

This solar tower and tower aided coal-fired power system is developed on the foundation of a conventional coal-fired power generation plant (CFPG), integrated with a solar tower system, parabolic troughs and thermal energy storage system, as shown in Figure 1. A typical 600 MWe supercritical coal-fired power plant is configured as the fundamental plant in this study, composed of a boiler, condensing steam turbine, feedwater heaters, deaerator, condenser and generator. The feed-water from the condenser is preheated by turbine steam extraction in high-pressure preheaters (PH1, PH2, and PH3), low-pressure preheaters (PH5, PH6, PH7, and PH8)

and the deaerator. Then the feed-water enters the boiler to absorb the thermal energy from coal combustion in heat transfer surfaces including the economizer, water wall heat exchanger, steam separator, platen superheater, rear plate superheater, final superheater, low-temperature reheater and final reheater, as presented in the previous study [48]. Then the superheated enters the high-pressure cylinder (HP) of the steam turbine and the reheat steam goes into the intermediate-pressure turbine (IP) to produce power.

The solar tower system consists of a heliostat field staggered along the radial direction, a tower located in the centre of heliostat field with the receiver on the top, and the high-temperature molten salt-steam heat exchanger (HMSE). Solar energy is reflected to the receiver by heliostats and heats the molten salt (wt. 60%  $\text{NaNO}_3$ +40%  $\text{KNO}_3$ ) pumped from the cold tank to approaching 600 °C. The hot molten salt is stored in hot tank 1 before used to heat cold reheat steam extraction in HMSE. For the parabolic troughs, solar energy is reflected to the vacuum encased heat absorber tubes and heat the molten salt from the cold tank to approximately 395 °C. The medium-temperature molten salt is stored in hot tank 2 before used to preheat feed-water extraction in the medium -temperature molten salt-steam heat exchanger (MMSE).

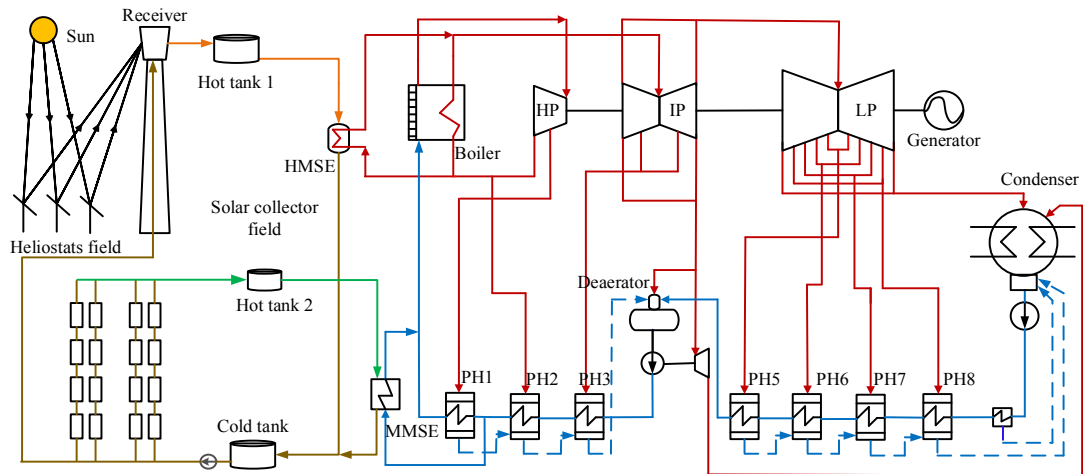


Figure 1. The diagram of the solar tower and parabolic trough aided coal-fired power system

## 2.2 Standard control of STPG

The logic flow chart of the standard control approach is illustrated in Figure 2. The performance of parabolic troughs and the thermal energy that can be collected ( $Q_{col,eff}$ ) are calculated according to the weather data and solar time. Considering the thermal energy stored in medium-temperature molten salt ( $Q_{ms}$ ) and the maximum TES capacity ( $Q_{ms,max}$ ), if  $Q_{ms} + Q_{col,eff}$  is greater than  $Q_{ms,max}$ , the troughs will be defocused. If the molten salt in the cold tank ( $m_{cs}$ ) is insufficient to provide the salt required by parabolic troughs and the tower receiver, the focus state of troughs and heliostats will both be adjusted considering the three-tank TES structure with a shared cold tank. Then, combined with the specific power load requirement, the maximum solar power that can be absorbed by feed-water ( $Q_{fw,max}$ ) and introduced as solar energy ( $Q_{fw}$ ) are determined. Simultaneously, the heliostat field tracking system is activated and the heliostat field and the receiver are calculated when the solar altitude angle is larger than  $15^\circ$  and the DNI reaches  $150 \text{ W/m}^2$ . The solar energy collected by

the receiver ( $Q_{rec}$ ) and thermal energy medium-temperature molten salt can provide ( $Q_{ms}$ ) can be identified and controlled combining the condition of hot tank 1, the cold tank and the focus state of mirrors. Then, based on the power load requirement and the effects of introduced solar energy from troughs presented in our previous study [48], the maximum solar power reheat steam can absorb ( $Q_{rs,max}$ ) under the boiler safety constraints and the introduced solar energy ( $Q_{rs}$ ) are determined. This standard control system represents the most common solution to integrate solar energy in a STPG system, in which the absorbed and utilised solar energy are maximised at each time point without using any information about likely future solar radiation and plant generated output.

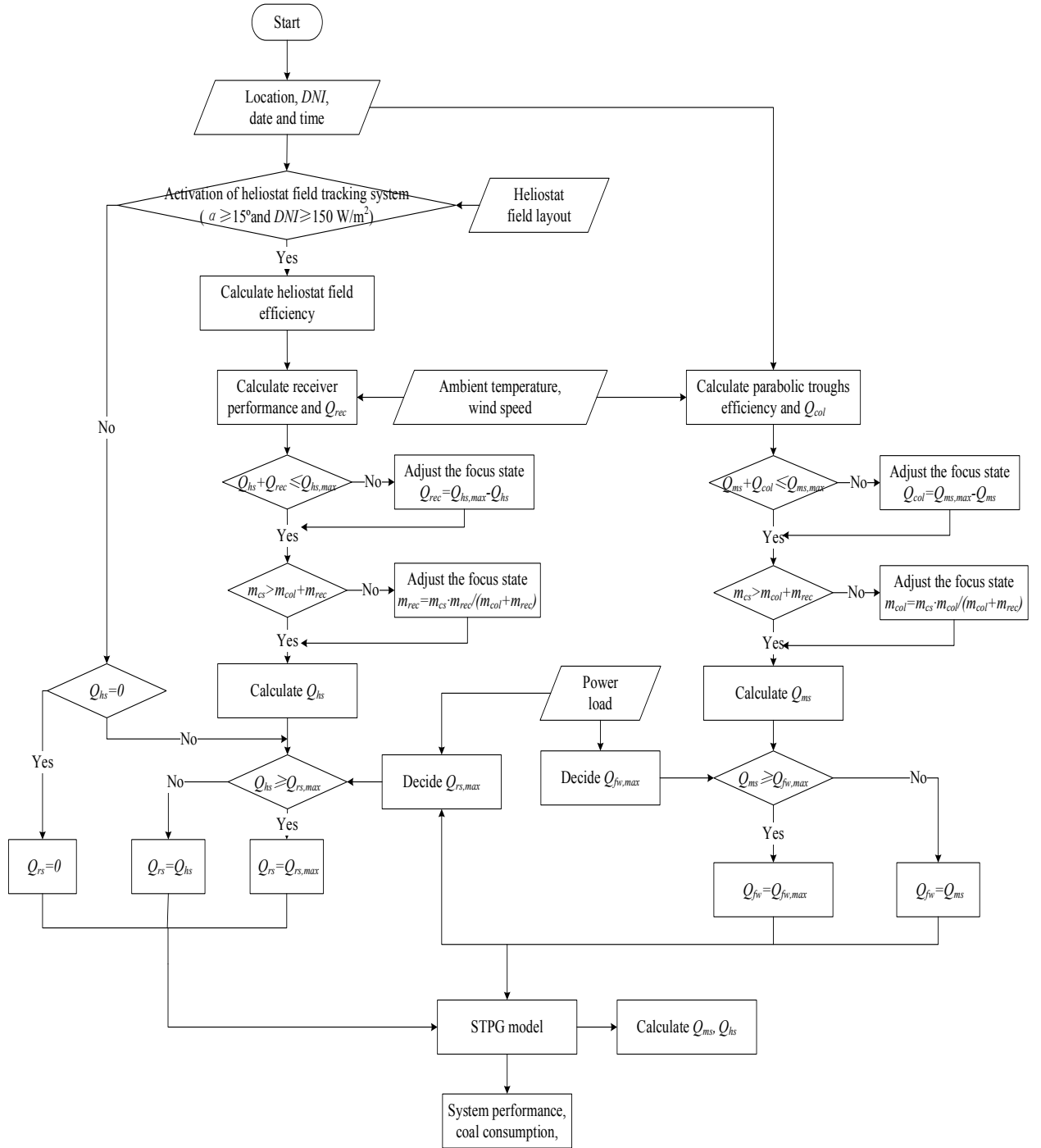


Figure 2. Logical flow chart of the standard control approach.

### 2.3 MPC control of STPG

The logic flow chart of Model Predictive Control approach is presented in Figure 3. In each time step, the combined genetic algorithm-particle swarm optimisation (GA-PSO) algorithm is employed to determine the optimal series control inputs

considering the changing conditions in future time steps. In the calculation of each input sequence and each time step, the STPG model and inputs of the last step are invoked to determine the bound and validity of control inputs in the current time step. The performance of parabolic troughs, heliostat field and the states of the three TES tanks depend on the control inputs of last time step are involved to decide the boundary of absorbed solar energy ( $Q_{col,eff}$  and  $Q_{rec}$ ). The power load demand and the available medium-temperature salt resulting from the TES state and absorbed solar energy are considered to identify the boundary of  $Q_{fw}$ , which is then used to decide the bound of  $Q_{rs}$ . Then the control inputs from GA-PSO are then delivered to the STPG model to calculate the performance in the time step and the initial state of the next time step. The MPC uses a 12 hr forward looking and, time-horizon within which it is assumed that forecasting predictions will be accurate: perfect forecasting over this 12hr period is assumed in this study. The temporal resolution and each time step of simulation are considered as 1hr. Then total coal consumption ( $\min \sum_{i=0}^{N-1} B_{st,i}$ ) is obtained as the objective function to evaluate the potential benefits from the inputs sequence, where the  $B_{st,i}$  is the coal consumption and  $N$  is the total number of steps of the control horizon. To speed up the calculation process, the optimal results of each time step are used as the initial inputs sequence for the optimisation of the next time step.

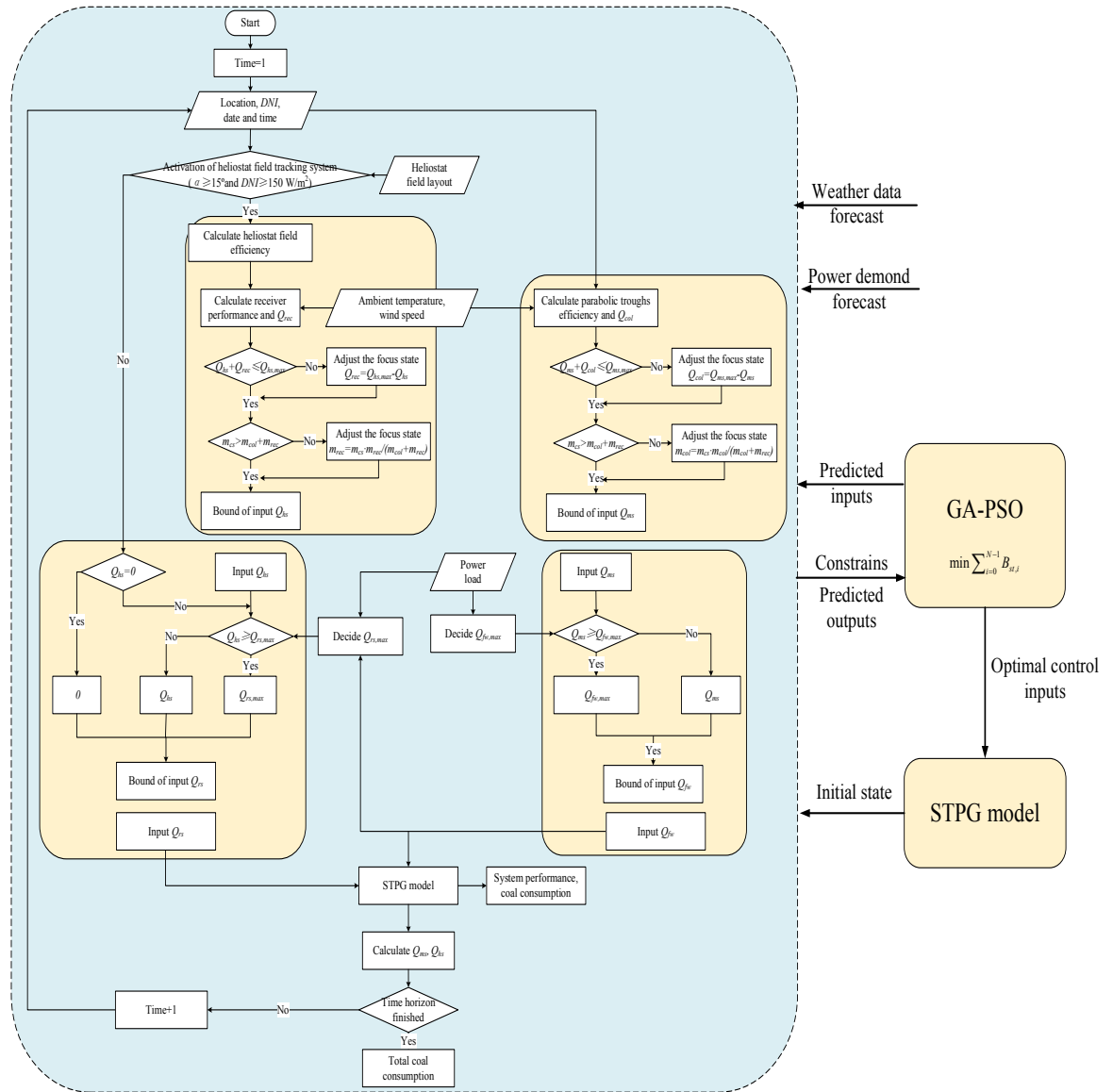


Figure 3. Logic flow chart of the Model Predictive Control approach.

### 3. STPG Model and GA-PSO Algorithm

The model of STPG system and GA-PSO algorithm are introduced in this section.

### 3.1 Heliostats and receiver

For the solar tower system, the incident solar energy is first collected by the heliostat field and reflected to the receiver on the top of the tower, calculated as:

$$\dot{Q}_{receiver} = A_f \cdot DNI \cdot \eta_{field} \quad (1)$$

where  $A_f$  is the effective area of heliostats,  $m^2$ ;  $DNI$  is the direct normal irradiance,  $W/m^2$ ;  $\eta_{field}$  is the efficiency of the heliostat field, calculated from the efficiency of each heliostat:

$$\eta_{field} = \frac{\sum_1^n \eta_{hel_i}}{n} = \frac{\sum_1^n \rho_i \cdot \cos \theta_i \cdot f_{sb_i} \cdot f_{at_i} \cdot f_{int_i}}{n} \quad (2)$$

where  $n$  is the number of heliostats;  $\rho_i$  represents the effective reflectivity of heliostat with soiling included;  $\cos \theta_i$  is the cosine factor, calculated as the cosine of the angle between the incident beam and the normal direction of the receiving plane;  $f_{sb_i}$  represents the shading and blocking factor, reflecting the shadowing and blocking over the heliostat surface caused by surrounding heliostats;  $f_{at_i}$  is the atmospheric attenuation factor, reflecting the influence of atmospheric on the transmission of the beam from the heliostat to the receiver;  $f_{int_i}$  is the interception factor, with the sun shape error ( $\sigma_{sun}$ ), the beam quality error ( $\sigma_{bq}$ ), the astigmatic error ( $\sigma_{ast}$ ) and the tracking error ( $\sigma_t$ ) considered. The detailed mathematical model is developed in MATLAB and has been validated and employed in previous studies [53, 54].

This is used to calculate the reflected solar energy absorbed by molten salt and, converted to thermal energy. The energy balance in the receiver is calculated as:

$$\dot{Q}_{rec} = \dot{Q}_{receiver} - \dot{Q}_{loss,opt} - \dot{Q}_{loss,rad} - \dot{Q}_{loss,cov} \quad (3)$$

where  $\dot{Q}_{rec}$  is the thermal power absorbed by molten salt;  $\dot{Q}_{loss,opt}$  is the optical loss;  $\dot{Q}_{loss,cov}$  is convective heat loss and  $\dot{Q}_{loss,rad}$  is the radiation heat loss.

### 3.2 Parabolic trough collectors

For parabolic troughs, the solar power input is calculated as follows:

$$\dot{Q}_{col} = DNI \cdot A_{net} \cdot \eta_{col,opt} \cdot K \cdot e_{shad} \cdot e_{end} \cdot e_{spill} \cdot e_{clean} \cdot e_{avail} \quad (7)$$

$$A_{net} = N_{coll} \cdot L \cdot W \cdot N_{opt} \quad (8)$$

where  $A_{net}$  is the net aperture area of parabolic troughs,  $m^2$ ;  $N_{coll}$  is the number of parabolic trough collectors;  $L$  is the collector length and  $W$  is the aperture width of the troughs;  $N_{opt}$  is the optically active portion of aperture;  $\eta_{col,opt}$  represents the peak optical efficiency;  $e_{shad}$  represents the factor considering shading losses caused by parallel trough rows when the sun is near the horizon;  $e_{end}$  is the factor to correct optical end gain and end loss;  $e_{spill}$  is the factor to consider the optical losses when the trough structure is deformed by the wind;  $e_{clean}$  is the ratio of actual cleanliness of the mirrors relative to the ideally clean state, and  $e_{avail}$  is field availability.  $K$  represents the deviation of the collector performance response to incident angle, calculated using the common formulations:

$$K = (1 - a_c + a_c \cdot \cos\theta)(b_c \cos\theta + b_0 + b_1\theta + b_2\theta^2 + b_3\theta^3 + b_4\theta^4 + b_5\theta^5) \quad (9)$$

where the  $\theta$  is the incident angle. The coefficients are determined by the collector properties. In this model,  $b_0 = 1$ ,  $b_1 = 0.00010596$ ,  $b_2 = -0.00017091$  and other coefficients are set as 0.

Then the effective thermal energy absorbed by working fluid can be obtained:

$$\dot{Q}_{col,eff} = \dot{Q}_{col} \cdot R_{focus} - q_{col,loss} \cdot L \cdot N_{coll} - \dot{Q}_{pipe,loss} \quad (9)$$

where  $R_{focus}$  represents the actual focus state of the field;  $q_{col,loss}$  is the length-specific heat loss to the surrounding in the collectors and  $\dot{Q}_{pipe,loss}$  is the heat loss in pipes.

### 3.3 Thermal energy storage

The TES system is a three-tank molten salt type in this study, comprised of two tanks to store hot salt and a shared cold tank. The TES process in each tank is calculated through mass and energy balance:

$$m_{new} = m_{act} + (\dot{m}_{load} - \dot{m}_{unload}) \cdot t_{int} \quad (10)$$

$$H_{mid1} = \frac{m_{act} \cdot h_{act} + \dot{m}_{load} \cdot h_{load} \cdot t_{int}}{m_{act} + \dot{m}_{load} \cdot t_{int}} \cdot m_{new} \quad (11)$$

$$H_{mid2} = H_{mid1} - k_{loss} \left( \frac{T_{act} + T_{new}}{2} - T_{amb} \right) \cdot t_{int} \quad (12)$$

$$H_{new} = H_{mid2} - 0.5 \left( h_{act} + \frac{H_{mid2}}{m_{new}} \right) \cdot \dot{m}_{unload} \cdot t_{int} \quad (13)$$

where  $m_{act}$  and  $m_{new}$  are the initial mass and the mass at the end of time interval in the tank, respectively;  $\dot{m}_{load}$  and  $\dot{m}_{unload}$  are the loading mass flow and unloading mass flows of the tank;  $t_{int}$  is the time interval of the calculation;  $h_{act}$  and  $h_{load}$  are the specific enthalpy of the stored fluid in the tank and incoming flow, respectively;  $k_{loss}$  is the coefficient of heat loss to the surrounding;  $T_{act}$  and  $T_{new}$  are the temperatures of fluid in the tank at the beginning and the ending of the time interval, respectively;  $H_{mid1}$  and  $H_{mid2}$  is the intermediate step enthalpy in the tank considering the load process and heat loss.  $H_{new}$  is the final enthalpy after unload process.

### 3.4 Thermodynamic index

The solar thermal-to-electricity efficiency is calculated as:

$$\eta_{solar} = \frac{P_{sp} + P_{st}}{e_{sp} + e_{st}} \quad (14)$$

where  $P_{sp}$  and  $P_{st}$  are the power output from parabolic troughs and solar tower, respectively, MW<sub>e</sub>.

The system power generation efficiency is calculated as:

$$\eta_{STPG} = \frac{P_{STPG}}{e_{sp} + e_{st} + Q_{coal}} \quad (15)$$

where  $P_{STPG}$  is the power output from the integrated system, MW<sub>e</sub>;  $e_{st}$  is the solar energy input from solar tower, MW<sub>th</sub>;  $Q_{coal}$  is the energy input from coal fuel, MW<sub>th</sub>.

The overall exergy efficiency of the system is calculated as:

$$\eta_{ex} = \frac{P_{STPG}}{Ex_{coal} + Ex_{st} + Ex_{sp}} \quad (16)$$

where  $Ex_{st}$  and  $Ex_{sp}$  are the solar exergy input from parabolic troughs and solar tower, MW<sub>th</sub>, respectively.  $Ex_{coal}$  is the exergy provided by coal fuel, MW<sub>th</sub>.

### 3.5 Genetic algorithm-particle swarm optimisation

To ensure the calculation accuracy and speed of calculation, the GA-PSO algorithm is employed to optimise the control inputs, which is a compound optimisation algorithm combining the global optimisation ability of genetic algorithm [55] and the fast convergence of particle swarm optimisation in the calculation process [56], with the detailed optimisation process illustrated in Figure 4. The GA is an evolutionary programming inspired by natural processes including mutation, crossover and selection. The calculation starts from several individuals generated randomly as the initial population. Then the individuals are evaluated based on the objective function and selected to generate the new population through the genetic operators including crossover and mutation. The processes are iterated to generate individuals with better fitness until the end of the calculation. The GA has the advantages in global optimisation ability due to the diversity of solutions, although this does generate superfluous computations. PSO is a swarm-based heuristic search

method describing the candidate solutions as moving particles with a position and velocity in the search-space. Then the particles update their position and velocity according to the shared information of local best position and the global best position as follows:

$$v_i(t+1) = \omega \cdot v_i(t) + c_1 r_1 (pbest_i(t) - x_i(t)) + c_2 r_2 (gbest_i(t) - x_i(t)) \quad (17)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (18)$$

where  $x_i(t)$  and  $x_i(t+1)$  is the position of particle  $i$  at the moment  $t$  and  $t+1$ , respectively;  $v_i(t)$  and  $v_i(t+1)$  are the corresponding velocities;  $pbest_i(t)$  is the historical optimal solution of the particle and  $gbest_i(t)$  is the global optimal solution;  $\omega$  is the adaptive weight coefficient used to avoid the local optimum, defined as:

$$\omega = \begin{cases} \omega_{min} + \frac{(\omega_{max} - \omega_{min})(fit - fit_{min})}{fit_{ave} - fit_{min}} & fit \leq fit_{ave} \\ \omega_{max} & fit > fit_{ave} \end{cases} \quad (19)$$

where  $\omega_{min}$  and  $\omega_{max}$  are the maximum weight coefficient and minimum weight coefficient, respectively;  $fit_{min}$  is the minimum fitness of present swam and  $fit_{ave}$  is the average value;  $fit$  is the fitness of the particle, which is the average coal consumption rate in the time horizon in this study and calculated through the invoked predictive model (dashed box of Figure 3). The total coal consumption over the control horizon is minimised as the objective function ( $\min \sum_{i=0}^{N-1} B_{st,i}$ ). In addition, to improve the optimisation process and reduce the computational burden, the optimal result of each time step is used to generate the initial population for the optimisation of next time step instead of randomly generating.

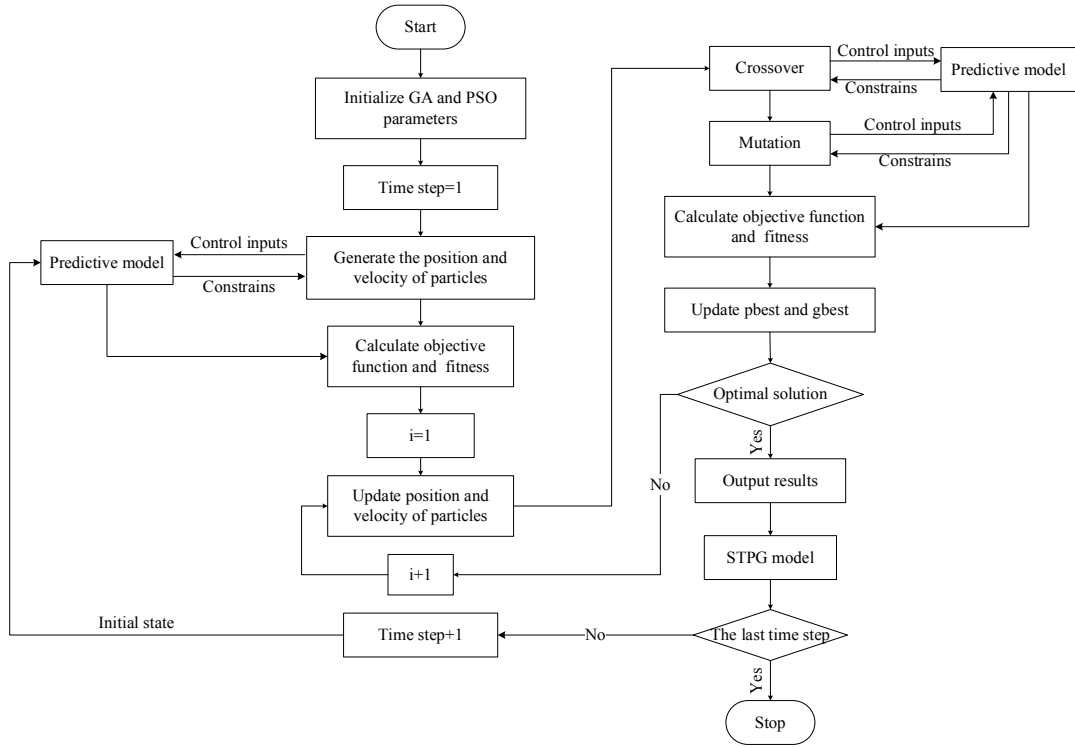


Figure 4. The flow chart of GA-PSO hybrid algorithm.

#### 4. Case studies

This section provides the input data including configuration data, weather information and power load. System performance with two controllers are observed in a typical day and for a cumulative ten-day periods. A sensitivity analysis on the potential benefits of the MPC approach is then performed.

##### 4.1 Basic data

In this study, Delingha (97.37°E, 37.37°N) is selected as the location and the typical meteorological year (TMY) weather data obtained from the System Advisor Model (SAM) software is considered as the operating environment of the STPG system. The parameters of the heliostat field, parabolic troughs and TES are shown in Table 1. The total mass of molten salt in TES is 14,166-tonne, which can be used for 5 hr at maximum feed-water extraction and maximum reheat steam extraction

conditions under 100% power load. A practical 600 MW<sub>e</sub> supercritical coal-fired power plant configured with a N600-24.2/566/566 type steam turbine is investigated as the basic plant. Bituminous coal with a low heat value (LHV) of 21,981 kJ/kg is considered as the fuel. The main parameters of the power block and the properties of the coal fuel are shown in Table 2. The detailed power block model is developed in Ebsilon Professional software and has been validated under different power load conditions [50]. The simulation of STPG is on the bases of the operation performance and coupling mechanism of the system under design and off-design conditions, including the variation in thermodynamic performance of the plant, the efficiency of boiler and the system, the safety constraints and maximum introduced solar energy in feed-water preheater and the reheater, which are explored and identified in the previous study [50].

The weather data and the real-time power load for the 23<sup>rd</sup> March, is shown in Figure 5, and is considered for the daily system operation because the daily DNI 4.1 kWh/m<sup>2</sup>/day is close to the annual average of yearly DNI 1543.6 kWh/m<sup>2</sup>/year (4.2 kWh/m<sup>2</sup>/day), and the date is close to the vernal equinox, which make the daily operation more widely representative. The weather data and the real-time power load from 16<sup>th</sup> to 25<sup>th</sup> October are selected for the cumulative simulation because it contains comprehensive weather conditions, composed of five days of high irradiance, four days of medium irradiance and one day of low irradiance, as shown in Figure 6, so that different operation performance can be observed.

Table 1. Main input parameters of the heliostat field and parabolic troughs

| Parameter                          | Value        | Unit                     |
|------------------------------------|--------------|--------------------------|
| Latitude                           | 37.37 N      | °                        |
| Longitude                          | 97.37 E      | °                        |
| Annual DNI                         | 1543.64      | kWh/m <sup>2</sup> /year |
| Tower optical height               | 140          | m                        |
| Receiver radius                    | 4            | m                        |
| Receiver height                    | 9            | m                        |
| Heliostat number                   | 5520         | -                        |
| Heliostat size                     | 12.305×9.752 | m <sup>2</sup>           |
| Standard deviation surface error   | 0.94         | mrاد                     |
| Standard deviation tracking error  | 0.63         | mrاد                     |
| Standard deviation of sun shape    | 2.51         | mrاد                     |
| Effective reflectivity             | 0.88 × 0.95  | -                        |
| Receiver optical efficiency        | 0.93         | -                        |
| Receiver surface emissivity        | 0.88         | -                        |
| Convective heat loss coefficient   | 7            | W/m <sup>2</sup> ·K      |
| Design wall temperature difference | 20           | °C                       |
| Aperture width of trough           | 5.77         | m                        |
| Gross length of one trough unit    | 576          | m                        |
| Total net aperture area            | 345882       | m <sup>2</sup>           |
| Number of parabolic troughs        | 110          | -                        |
| Optical active portion of aperture | 0.9461       | -                        |
| Peak optical efficiency            | 0.734        | -                        |
| Row spacing                        | 17.3         | m                        |
| Molten salt hot tank 1 temperature | 580          | °C                       |
| Molten salt hot tank 2 temperature | 390          | °C                       |
| Cold tank temperature              | 320          | °C                       |
| TES capacity                       | 14166        | tonne                    |

Table 2. Main input parameters of the power block

| Parameters                  |          |      | 100%            | 75%   | 50%   | Unit           |
|-----------------------------|----------|------|-----------------|-------|-------|----------------|
| Power output                |          |      | 600             | 450   | 300   | MWe            |
| Feed-water temperature      |          |      | 276.3           | 257.7 | 235.3 | °C             |
| Main steam temperature      |          |      | 566.0           | 561.0 | 545.0 | °C             |
| Main steam mass flow rate   |          |      | 467.5           | 342.2 | 227.3 | kg/s           |
| Reheat steam temperature    |          |      | 566.0           | 555.0 | 555.0 | °C             |
| Reheat steam mass flow rate |          |      | 399.6           | 297.6 | 201.6 | kg/s           |
| Condenser pressure          |          |      | 4.9             | 4.9   | 4.9   | kPa            |
| Material                    | Fraction | Unit | Heating surface |       | Area  | Unit           |
| $C_{ar}$                    | 57.5     | %    | FSH-2           |       | 2549  | m <sup>2</sup> |
| $H_{ar}$                    | 3.11     | %    | FSH-1           |       | 1882  | m <sup>2</sup> |
| $O_{ar}$                    | 2.78     | %    | RSH             |       | 1425  | m <sup>2</sup> |

|           |       |       |       |       |       |
|-----------|-------|-------|-------|-------|-------|
| $N_{ar}$  | 0.99  | %     | PSH   | 1386  | $m^2$ |
| $St_{ar}$ | 2.0   | %     | FRH   | 2443  | $m^2$ |
| $A_{ar}$  | 23.72 | %     | LRH-V | 1518  | $m^2$ |
| $M_{ar}$  | 9.9   | %     | LRH-H | 10683 | $m^2$ |
| LHV       | 21981 | kJ/kg | ECON  | 17590 | $m^2$ |

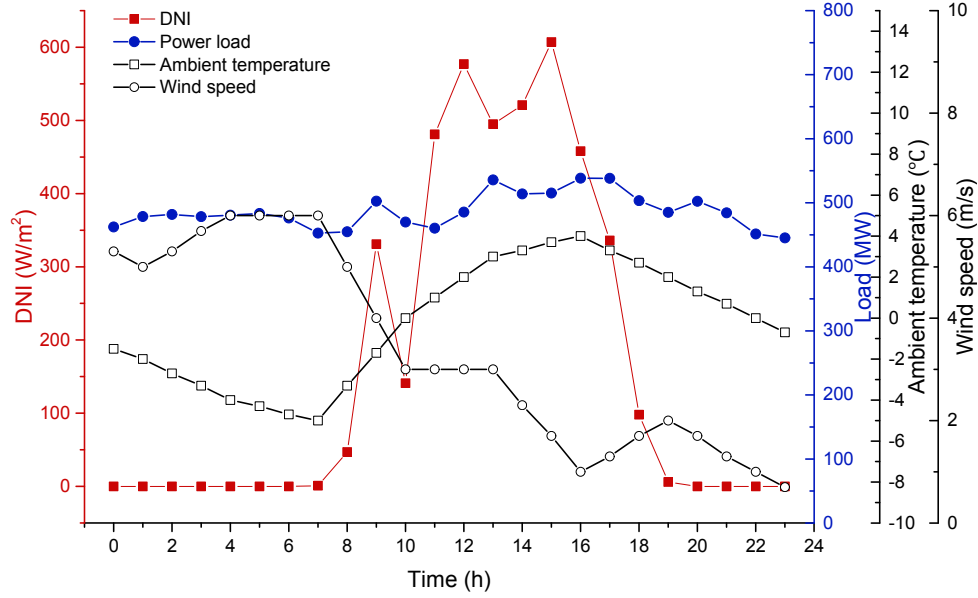


Figure 5. Hourly weather data in 23<sup>rd</sup> March of TMY and the corresponding power load.

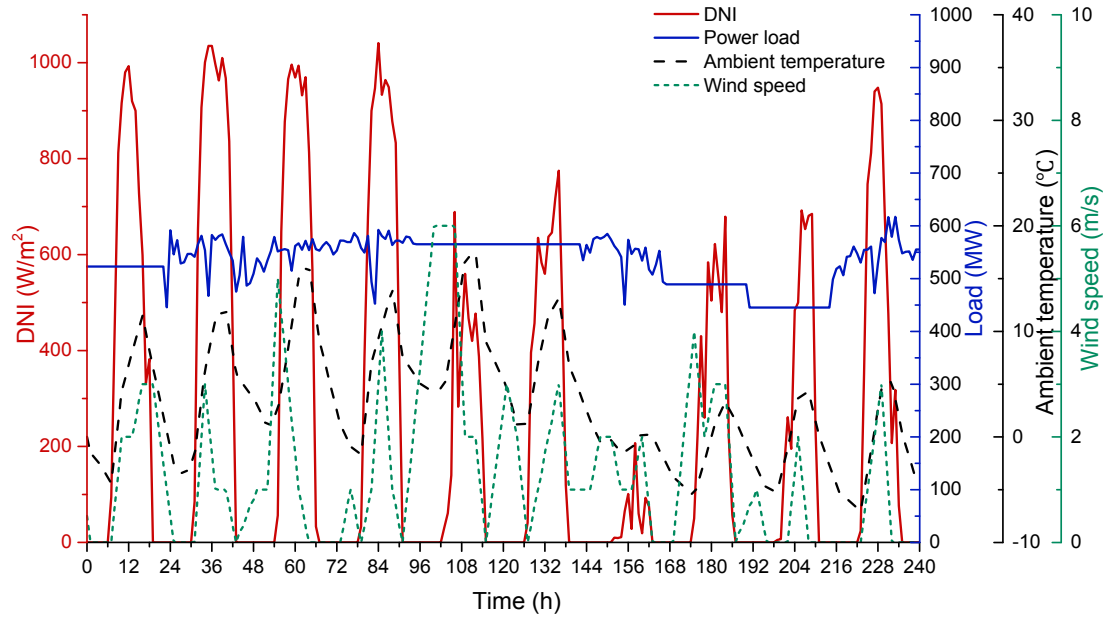


Figure 6. Weather data from 16<sup>th</sup> to 25<sup>th</sup> October and the corresponding power load.

## 4.2 Results and discussion

The MPC approach is performed to reduce coal consumption of the STPG system through the optimised TES capacity assignment and improved solar energy utilisation. A typical day simulation has been presented to illustrate the behaviour differences between a standard controller and the MPC approach in the input and utilisation processes of solar energy from parabolic troughs and heliostats. Then the results of ten consecutive days are provided to avoid the influences of the remaining energy in hot tanks.

### 4.2.1 Daily system operation

The simulation results of STPG system in two control approaches and the basic coal-fired power plant are summarised in Table 3. Compared with the CFPG, 13.4 g/kWh average coal consumption rate is reduced in a standard controlled STPG due to the solar energy contribution, leading to 156.6-tonne coal consumption saving and 440.2-tonne CO<sub>2</sub> emission reduction. In the MPC controlled STPG system, the solar energy input and utilisation processes are improved by considering the future operational information, leading to 159.3 MWh increase of solar tower energy input and enhanced exergy performance. As the result, the reduced average coal consumption rate is improved by 13.6% (1.8 g/kWh) and 21.3-tonne coal fuel is further saved than standard controller.

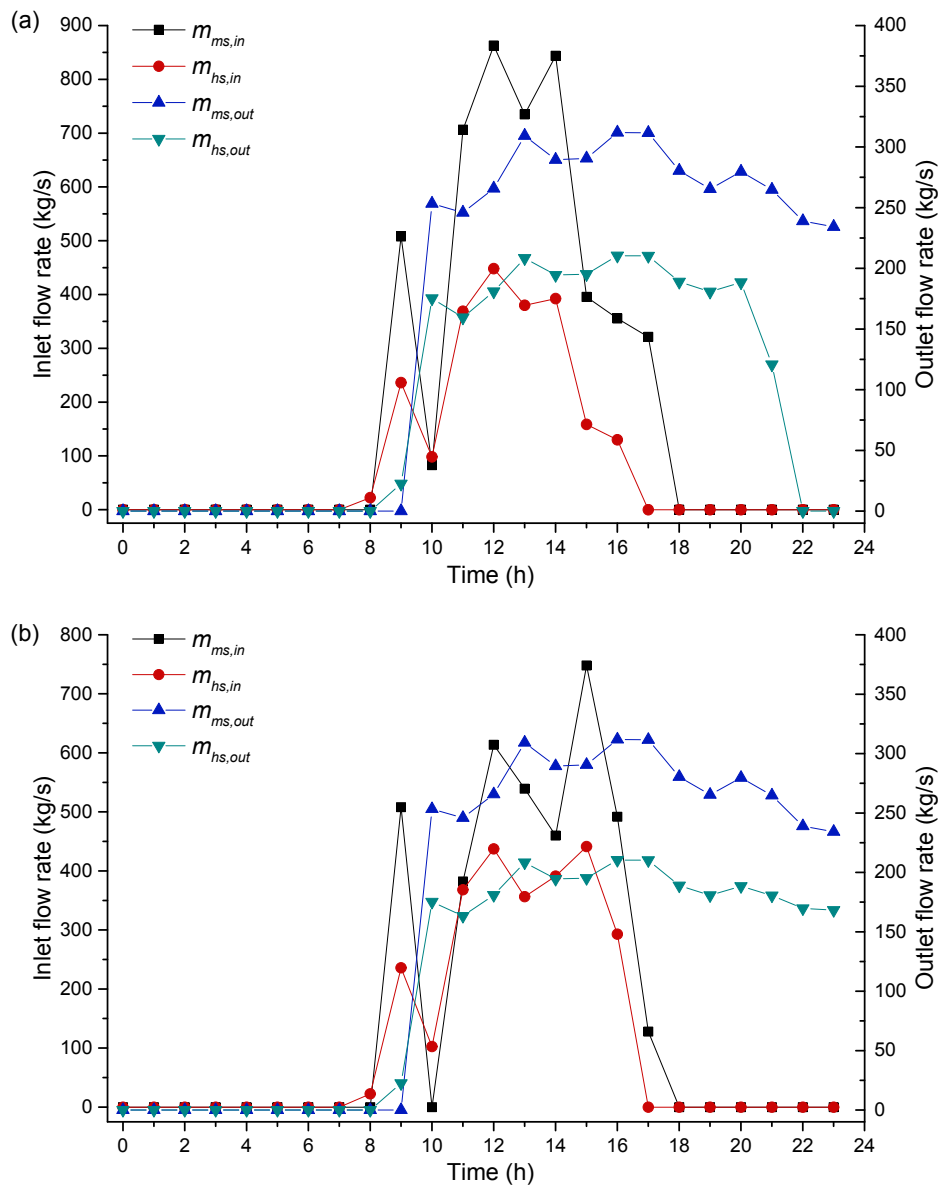
Table 3. Results comparison of two control approaches in the daily operation

| Parameters               | CFPG    | STPG                |                       |
|--------------------------|---------|---------------------|-----------------------|
|                          |         | Standard controller | Predictive controller |
| Daily power output (MWh) | 11679.7 | 11679.7             | 11679.7               |

|                                                   |        |        |        |
|---------------------------------------------------|--------|--------|--------|
| Average standard coal consumption rate (g/kWh)    | 280.4  | 267.0  | 265.1  |
| System energy efficiency (%)                      | 43.8   | 43.8   | 43.8   |
| System exergy efficiency (%)                      | 41.9   | 42.9   | 43.0   |
| Daily standard coal consumption (tonne)           | 3274.7 | 3118.1 | 3096.8 |
| Incident solar energy to parabolic troughs (MWh)  | -      | 1365.2 | 1365.2 |
| Average efficiency of parabolic troughs (%)       | -      | 36.9   | 29.7   |
| Parabolic trough energy input (MWh)               | -      | 402.4  | 402.4  |
| Power output from parabolic troughs (MWh)         | -      | 156.5  | 156.4  |
| Incident solar energy to heliostats (MWh)         | -      | 2423.0 | 2423.0 |
| Average efficiency of solar tower system (%)      | -      | 36.6   | 43.3   |
| Solar tower energy input (MWh)                    | -      | 885.9  | 1045.2 |
| Power output from solar tower (MWh)               | -      | 407.7  | 480.2  |
| Daily solar thermal-to-electricity efficiency (%) | -      | 43.8   | 44.0   |
| Daily CO <sub>2</sub> emission reduction (tonne)  | -      | 440.2  | 500.1  |

The control inputs in the case of standard control and MPC, including the mass flow rates of charged medium-temperature salt ( $m_{ms,in}$ ) and high-temperature salt ( $m_{hs,in}$ ), the discharged medium-temperature salt ( $m_{ms,out}$ ) and high-temperature salt ( $m_{hs,out}$ ) to heat feed-water and reheat steam extraction for daily period simulation are shown in Figure 7. The observed system dynamic in the two different control approaches, including standard coal consumption rate ( $b_{st}$ ), solar energy input from parabolic troughs ( $e_{sp}$ ) and solar tower ( $e_{st}$ ), and the solar energy percentage ( $\lambda_{solar}$ ) are shown in Figure 8. From the comparison of control inputs, the standard controller transfers maximum molten salt to the hot tanks at each time step, depending on the solar irradiation and the remaining salt, while MPC tends to allocate the TES capacity optimally considering the knowledge in a time horizon. For instance, the  $m_{ms,in}$  in the MPC is obviously constrained from 11:00 to 14:00 and more cold salt is then heated in the receiver, as shown in Figure 7. This enables high-temperature salt to be provided to heat the reheat steam extraction until the end of the day.  $e_{st}$  in the MPC

remains at approximately 67 MW at the end of the day with a stable solar energy percentage, leading to 72.5 MWh increased energy output from the solar tower and improved the solar thermal-to-electricity efficiency compared to the standard controller. As the result, the coal consumption rate, shown in Figure 8, is 255.3 g/kWh, 257.2 g/kWh and 257.5 g/kWh in the hours after 21:00 in the MPC while it increases to 277.6 g/kWh in the standard controller.



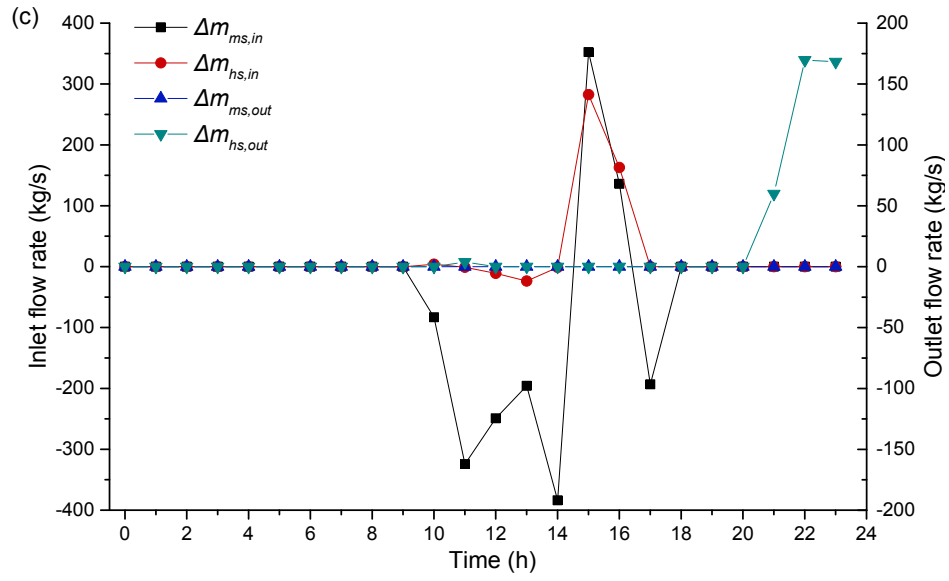
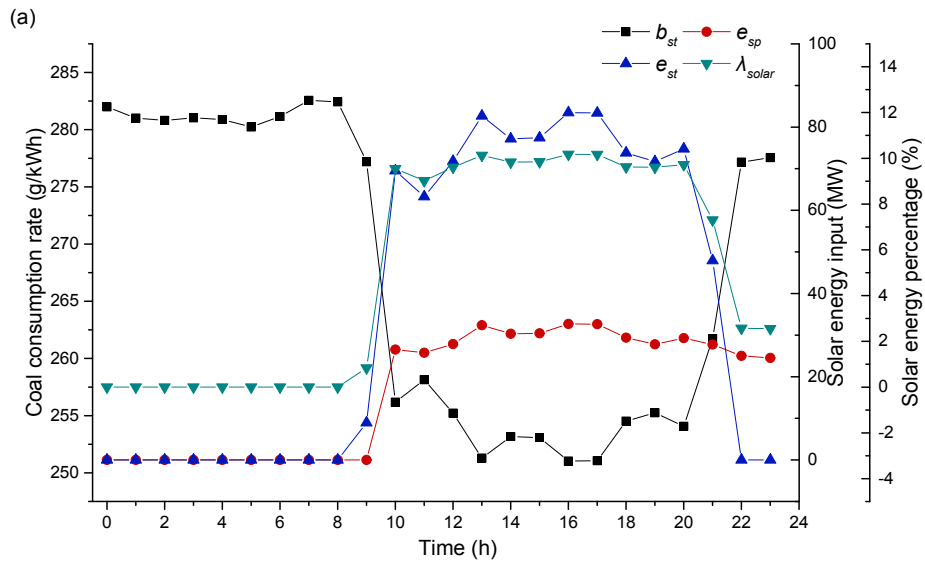


Figure 7. Typical day operation of STPG plant: (a) standard control (b) MPC approach (c) the differences.



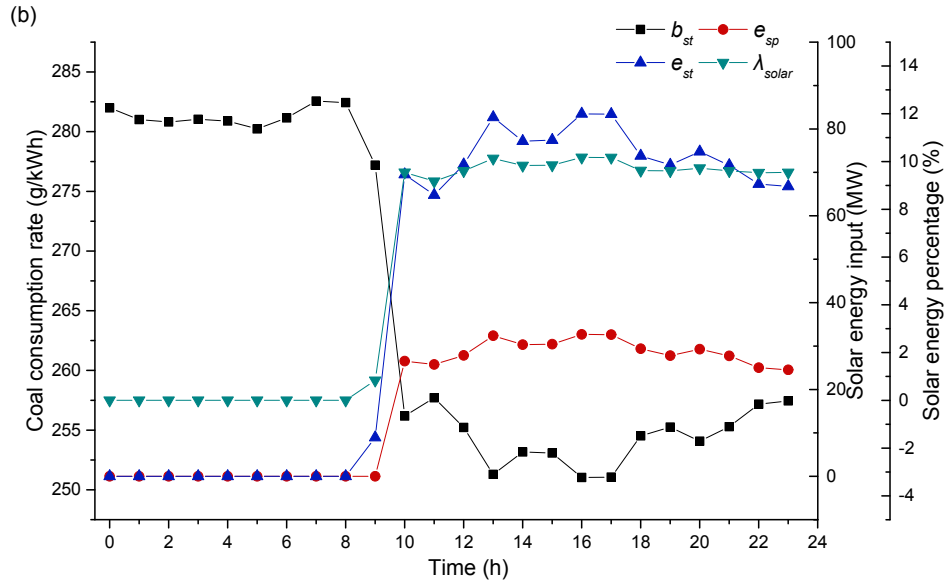


Figure 8. Typical day performance of STPG plant using (a) standard control (b) MPC approach.

#### 4.2.2 Consecutive system operation

To eliminate the effects of initial and ending states of the tanks, the consecutive operation in 10 days period is observed. The annual simulation isn't performed due to the heavy computation demand that might take near one month. Table 4 shows the operation results using two control approaches in a 10 days period, of which day 2 has high irradiation (average value  $\geq 800 \text{ W/m}^2$ ), day 6 and day 8 are medium irradiation ( $400 \text{ W/m}^2 < \text{average value} < 800 \text{ W/m}^2$ ) and day 7 is a typical rainy day characterised by low radiation (average value  $\leq 400 \text{ W/m}^2$ ). The control inputs in 10 days of operation using the standard control and MPC are shown in Figure 9. The system performance including solar energy input from parabolic troughs ( $e_{sp}$ ) and sola tower ( $e_{st}$ ), and the comparison of coal consumption are shown in Figure 10. From the Table, 1893.9 MWh and 3920.7 MWh power output can be provided by solar energy collected by parabolic troughs and heliostats during the 10-day operation using a

standard controller. As the result, a reduction in average coal consumption rate of 12.3 g/kWh and a 1578.4-tonne reduction in standard coal consumption are achieved. When using the MPC controller, the system exergy efficiency is improved by 0.4%. A 14.8 g/kWh reduction in average coal consumption rate and 1898.4-tonne coal consumption is reduced compared with CFPG, a 20.3% improvement over that achieved using the standard controller.

Table 4. Results comparison of two control approaches in ten days

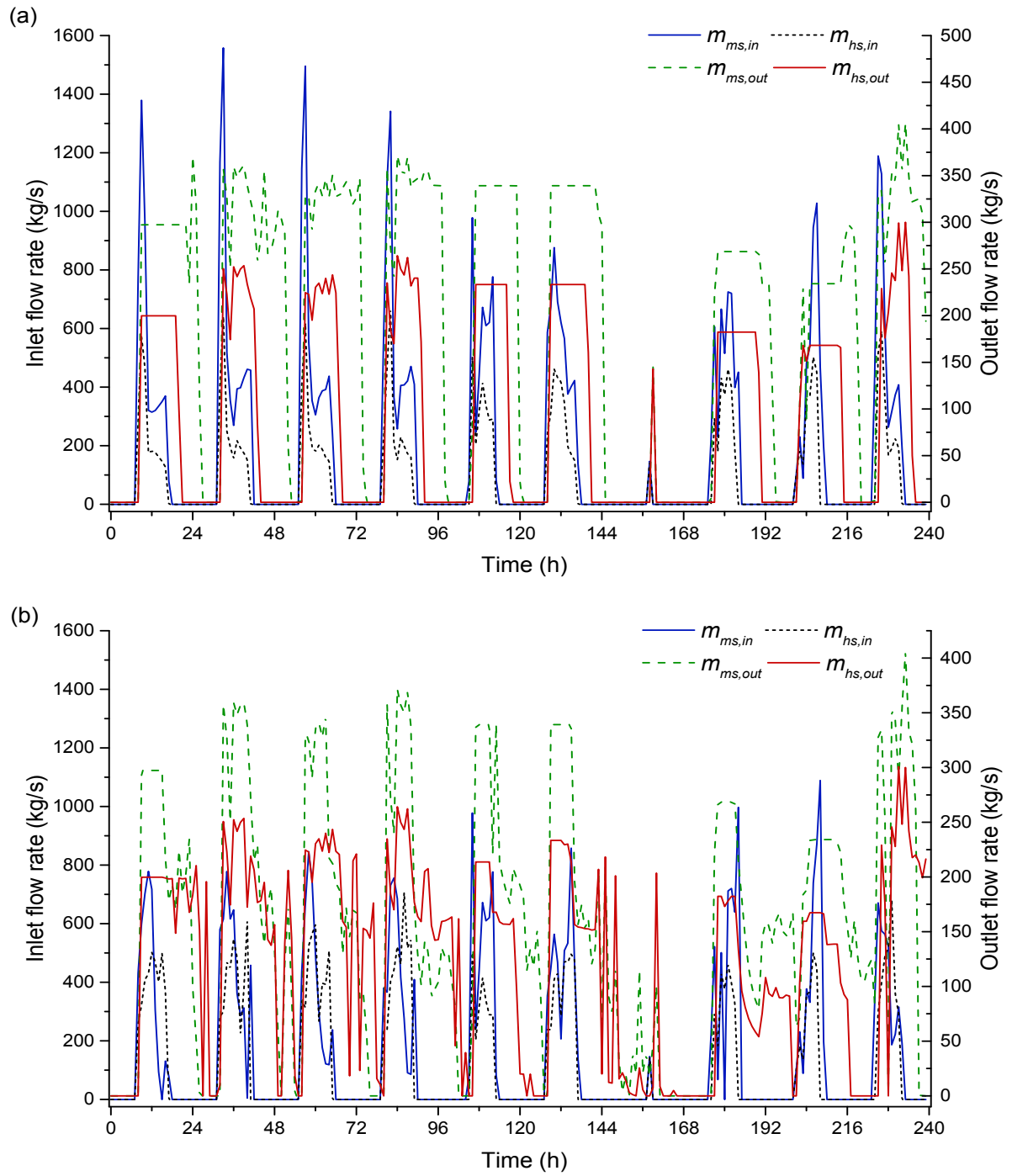
| Parameters                                       | Day 2  | Day 6  | Day 7  | Day 8  | Total   |
|--------------------------------------------------|--------|--------|--------|--------|---------|
| Power output (MWh)                               | 13080  | 13534  | 13100  | 11691  | 128142  |
| Solar irradiation (W/m <sup>2</sup> • day)       | 9915   | 6061   | 678    | 4660   | 62378   |
| CFPG                                             |        |        |        |        |         |
| Average coal consumption rate (g/kWh)            | 276.6  | 275.6  | 276.6  | 280.4  | 277.3   |
| Standard coal consumption (tonne)                | 3618.3 | 3729.9 | 3623.4 | 3278.6 | 35529.3 |
| System energy efficiency (%)                     | 44.4   | 44.6   | 44.4   | 43.8   | 44.3    |
| System exergy efficiency (%)                     | 42.5   | 42.7   | 42.5   | 41.9   | 42.4    |
| Standard control                                 |        |        |        |        |         |
| Average coal consumption rate (g/kWh)            | 262.9  | 261.5  | 275.7  | 266.5  | 264.9   |
| Standard coal consumption reduction (tonne)      | 180.0  | 191.4  | 11.8   | 163.5  | 1578.4  |
| System energy efficiency (%)                     | 44.3   | 44.5   | 44.4   | 43.8   | 44.2    |
| System exergy efficiency (%)                     | 43.4   | 43.6   | 42.6   | 42.9   | 43.2    |
| Incident solar energy to parabolic troughs (MWh) | 2483.1 | 2040.7 | 71.6   | 1324.7 | 19833.9 |
| Average efficiency of parabolic troughs (%)      | 25.6   | 27.8   | 21.7   | 36.2   | 24.6    |
| Parabolic trough energy input (MWh)              | 582.9  | 531.7  | 46.4   | 413.5  | 4839.4  |
| Power output from parabolic troughs (MWh)        | 230.2  | 209.3  | 18.2   | 160.4  | 1893.9  |
| Incident solar energy to heliostats (MWh)        | 5674.7 | 3580.9 | 137.1  | 2274.0 | 34800.7 |
| Average efficiency of solar tower system (%)     | 16.7   | 30.2   | 41.3   | 40.6   | 24.5    |
| Solar tower energy input (MWh)                   | 947.4  | 1082.2 | 56.7   | 923.3  | 8505.7  |
| Power output from solar tower (MWh)              | 441.0  | 498.0  | 25.9   | 424.0  | 3920.7  |
| Solar thermal-to-electricity efficiency (%)      | 43.9   | 43.8   | 42.8   | 43.7   | 43.6    |
| CO <sub>2</sub> emission reduction (tonne)       | 505.9  | 538.2  | 33.2   | 459.6  | 4437.4  |
| MPC                                              |        |        |        |        |         |
| Average coal consumption rate (g/kWh)            | 258.2  | 260.9  | 272.8  | 270.1  | 262.4   |
| Standard coal consumption reduction (tonne)      | 241.6  | 199.1  | 50.5   | 120.6  | 1898.4  |
| System energy efficiency (%)                     | 44.4   | 44.5   | 44.4   | 43.8   | 44.3    |
| System exergy efficiency (%)                     | 43.9   | 43.7   | 42.8   | 42.7   | 43.6    |

|                                                  |        |        |       |        |         |
|--------------------------------------------------|--------|--------|-------|--------|---------|
| Incident solar energy to parabolic troughs (MWh) | 2483.1 | 2040.7 | 71.6  | 1324.7 | 19833.9 |
| Average efficiency of parabolic troughs (%)      | 19.9   | 23.5   | 21.7  | 35.0   | 20.3    |
| Parabolic trough energy input (MWh)              | 443.4  | 488.3  | 105.8 | 303.8  | 3988.4  |
| Power output from parabolic troughs (MWh)        | 178.0  | 191.6  | 41.2  | 117.6  | 1559.9  |
| Incident solar energy to heliostats (MWh)        | 5674.7 | 3580.9 | 137.1 | 2274.0 | 34800.7 |
| Average efficiency of solar tower system (%)     | 26.1   | 39.0   | 41.3  | 43.0   | 33.0    |
| Solar tower energy input (MWh)                   | 1517.3 | 1169.2 | 306.7 | 679.0  | 11495.1 |
| Power output from solar tower (MWh)              | 693.8  | 536.9  | 140.5 | 311.2  | 5273.1  |
| Solar thermal -to-electricity efficiency (%)     | 44.5   | 44.0   | 44.1  | 43.6   | 44.1    |
| CO <sub>2</sub> emission reduction (tonne)       | 679.3  | 559.8  | 141.9 | 339.0  | 5337.0  |

In the literature [43], the saved coal consumption in a 660 MWe solar aided coal-fired power generation system reaches 17 g/kWh. In the literature [47], the daily coal consumption rate is 3856.0-3917.3tonne, 2978.3-3041.5 tonne and 2089.3-2115.9 tonne in the vernal equinox day under different power load, configured with 5-8 hr TES capacity. Therefore, the results in this paper are consistent with those in literature.

The comparison of control inputs over the 10-day period illustrates the different behaviour of the two control approaches, and the comparison of coal consumption shows the profit advantage from using an MPC approach. From the figures, the operation in MPC is improved mainly by, (i) dispatching the TES capacity optimally by reserving part of salt for the high-temperature cycle instead of using it to extract the maximum solar energy in each instant, (ii) discharging thermal energy gradually instead of releasing maximum energy at each instant to reduce the influence on the efficiency of the original plant. For daily operation, the most significant relative difference in performance occurs in day 7 (low radiation), which shows a 0.9 g/kWh reduction in average coal consumption rate for the standard controller and a 3.9 g/kWh reduction for MPC. The reason for this is that in the standard controller

scenario, the available solar energy is very limited because the stored energy is already released and the only effective solar input is at 14:00 (207 W/m<sup>2</sup>). Instead of discharging the maximum thermal energy at each instant in the standard controller, MPC decides to utilise the stored energy in high-efficiency operational states by considering the future information on operational conditions, including TES state, power load and weather forecast. Therefore, part of the stored energy from the previous day is retained in the TES and is gradually released in day 7, as shown in Figure 8. The most significant absolute difference in performance occurs in day 2 (high radiation), in which shows a 13.8 g/kWh coal consumption rate reduction for the standard controller and an 18.5 g/kWh reduction for MPC. This is because in conditions where there is excess solar input, more cold salt can be dispatched to the receiver-reheat steam cycle with higher solar thermal-to-electricity efficiency, leading to more energy sales than when there is insufficient solar input. It is worth noting that in day 8, the coal consumption in MPC is 42.9-tonne more than that in standard controller. That is because the stored solar energy is not fully released on day 8. This energy is retained to be discharged in day 9 to achieve a higher efficiency and an improved coal consumption reduction (43.9-tonne), as shown in Figure 9 and Figure 10. The behaviours of the controller under these different weather conditions with typical high irradiation, medium irradiation and low radiation provides reference for the real applications.



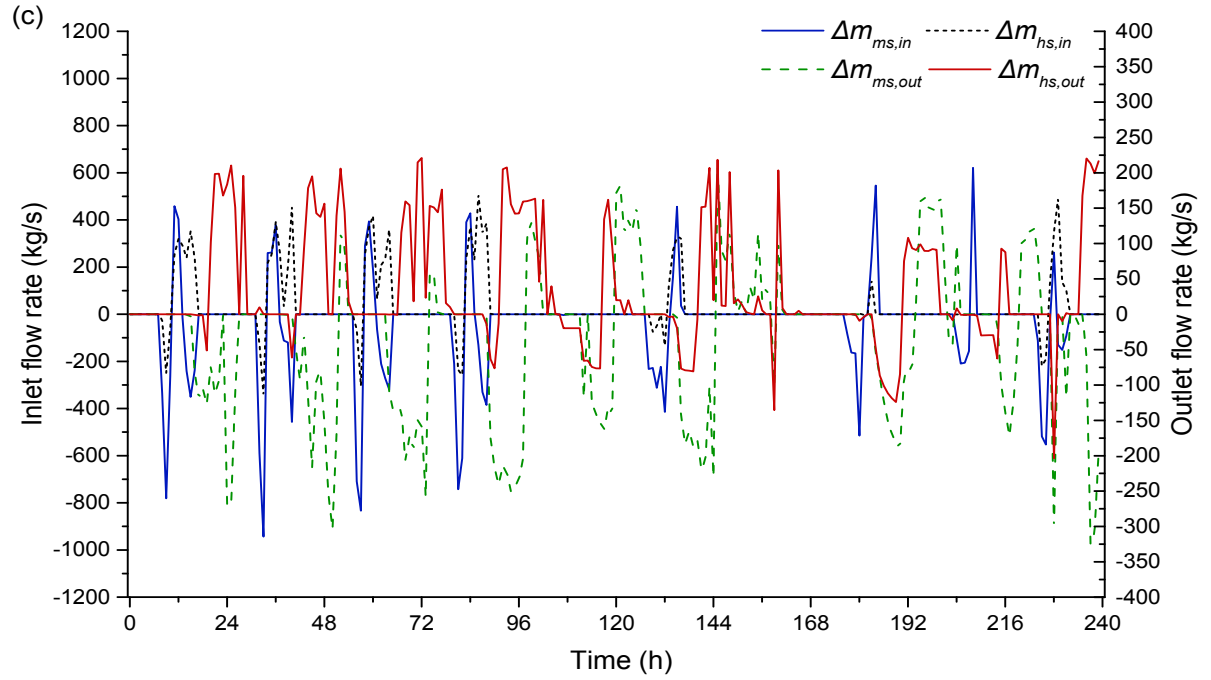
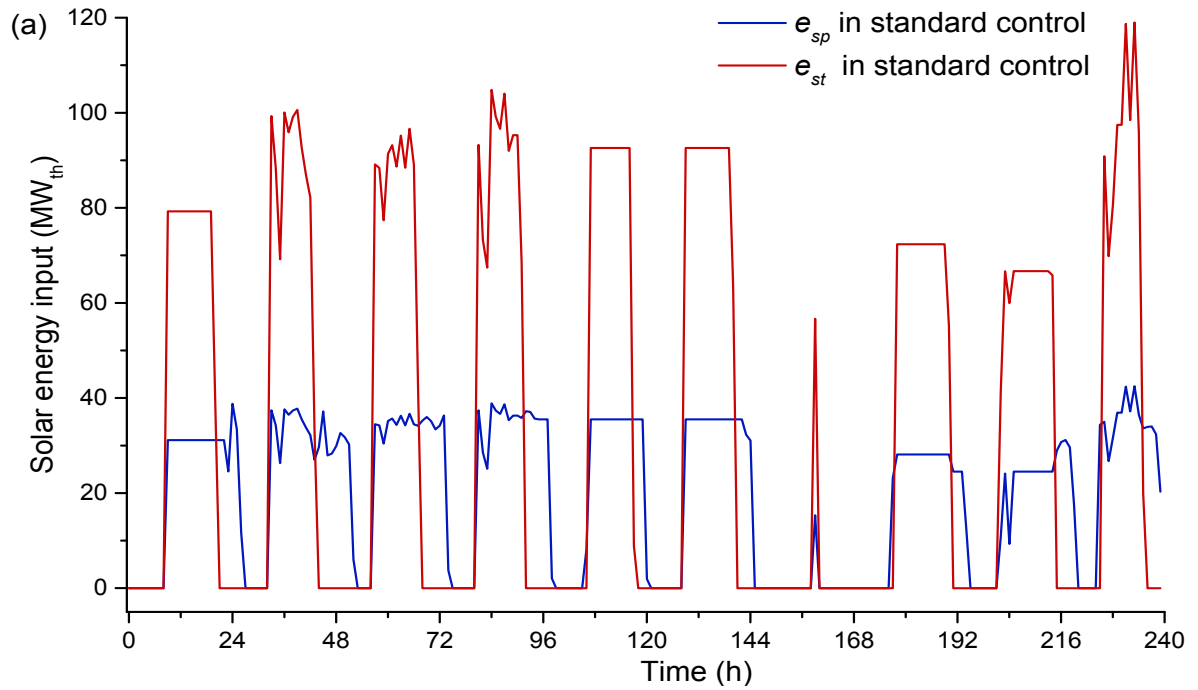


Figure 9. 10 days operation of STPG plant using (a) standard control (b) MPC approaches (c) the differences.



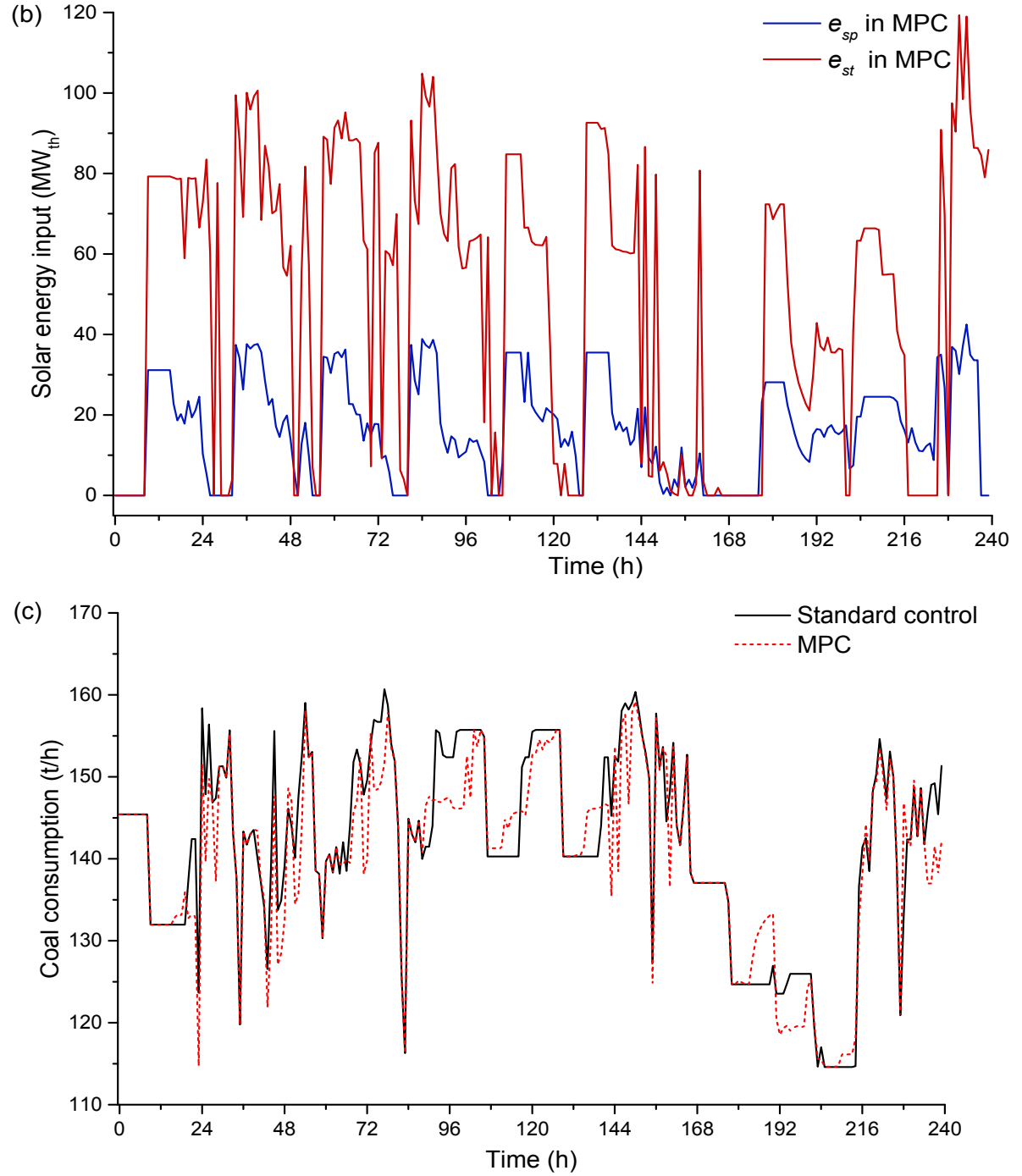


Figure 10. 10 days performances of STPG plant using (a) standard control (b) MPC approaches (c) differences in coal consumption.

Figure 11 shows the variation of saved cost due to the coal consumption reduction with standard controller and MPC approach in 10-day period. Considering the cost of bituminous coal as 58.93 \$/tonne, according to the average annual sale

prices of coal at mines by main rank of coal in 2019 [54], 251,000 \$ can be further saved in 10-day period with MPC, which could provide promising economic benefits in the life cycle of the power plant.

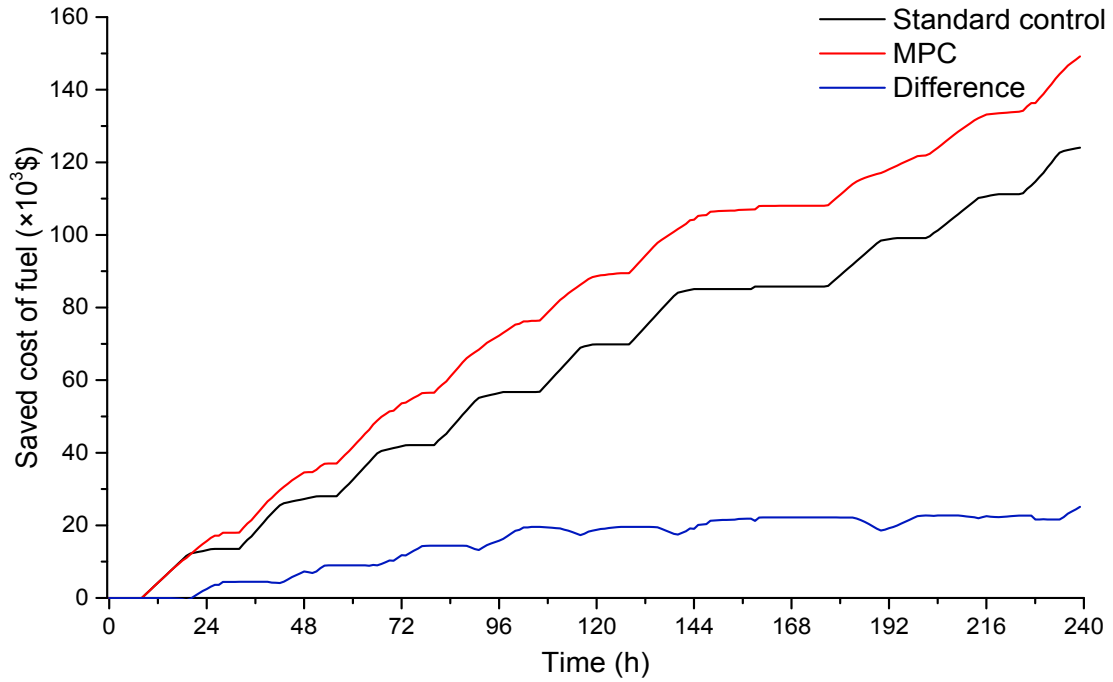


Figure 11. Saved cost due to the coal consumption reduction in 10-day period

#### 4.2.3 Effects of forecast error

To consider the effects of forecast error, a random error in the range of  $\pm 5\%$ ,  $\pm 10\%$ ,  $\pm 15\%$  and  $\pm 20\%$  are added on the basis of perfect forecast. The random errors are shown in Figure 11 and the non-perfect forecast DNI in 10 days are shown in Figure 12. The operation results in non-perfect prediction based MPC are shown in Table 6. From the table, the average coal consumption rate increases from 262.6 g/kWh to 262.7 g/kWh as the forecast error increases to 20%. Compared to the coal consumption reduction of 1898.4 tonne in perfect prediction-based MPC, the coal consumption reduction decreases by 20.4–36.8 tonne (1.08%-1.94%), considering the

forecast error of 5%-20%, which is still 17.9%-19.0% higher than 1578.4 tonne in standard controller. Therefore, the forecast error has an insignificant influence on the operation of MPC and considerable benefits still presents in non-perfect prediction-based controller. The difference of coal consumption in each operation are shown in Figure 13. As the forecast error increases from 5% to 20%, the power output from solar tower decreases from 5277.5 MWh to 5205.6MWh. The difference of operation results mainly occurs in the periods after sunset, which is caused by different charging and discharging processes in the operation.

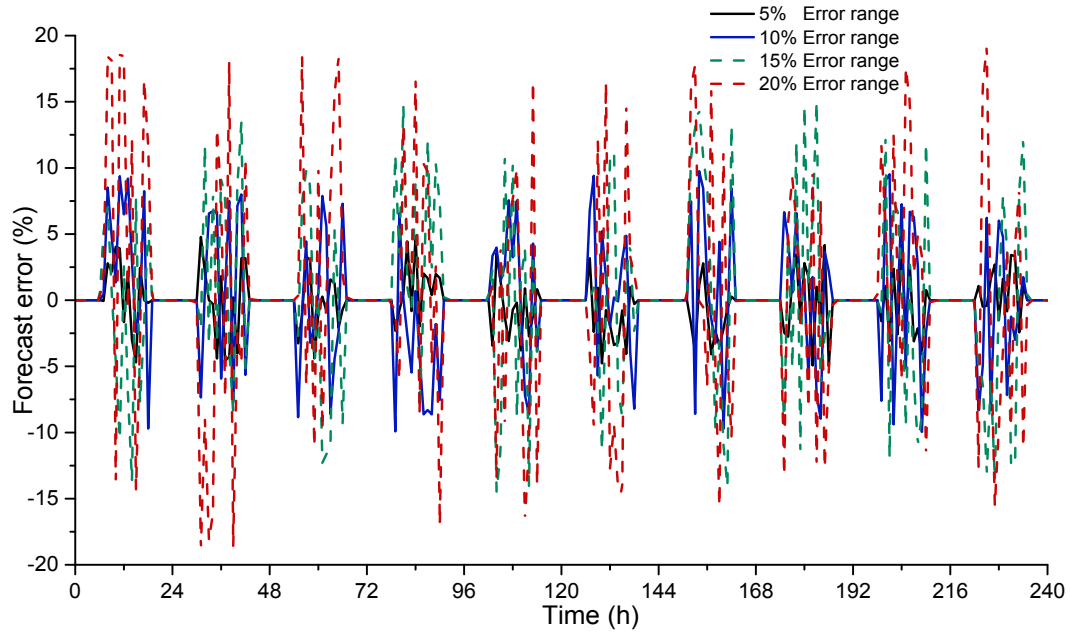


Figure 11. The distribution of random errors for DNI forecasting in the range of  $\pm 5\%$ ,  $\pm 10\%$ ,  $\pm 15\%$  and  $\pm 20\%$ .

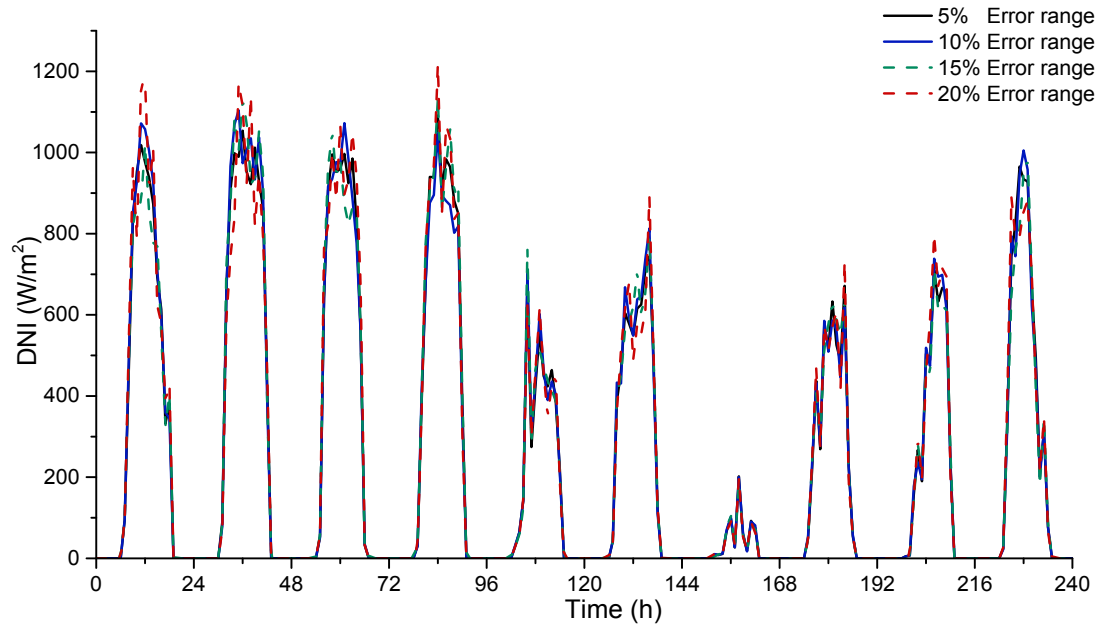


Figure 12. Non-perfect forecasted DNI from 16<sup>th</sup> to 25<sup>th</sup> October.

Table 5. Comparison of 10-day MPC operation considering different ranges of forecast error

| Range of forecast error                     | 5%      | 10%     | 15%     | 20%     |
|---------------------------------------------|---------|---------|---------|---------|
| Average coal consumption rate (g/kWh)       | 262.6   | 262.6   | 262.7   | 262.7   |
| Standard coal consumption reduction (tonne) | 1878.0  | 1877.7  | 1871.8  | 1861.6  |
| Parabolic trough energy input (MWh)         | 3958.3  | 3950.5  | 3930.3  | 3953.1  |
| Power output from parabolic troughs (MWh)   | 1546.3  | 1546.5  | 1534.4  | 1545.0  |
| Solar tower energy input (MWh)              | 11498.5 | 11463.2 | 11415.6 | 11331.1 |
| Power output from solar tower (MWh)         | 5277.5  | 5265.0  | 5250.5  | 5205.6  |
| Solar thermal-to-electricity efficiency (%) | 44.1    | 44.2    | 44.2    | 44.2    |
| CO <sub>2</sub> emission reduction (tonne)  | 5279.6  | 5278.9  | 5262.3  | 5233.6  |

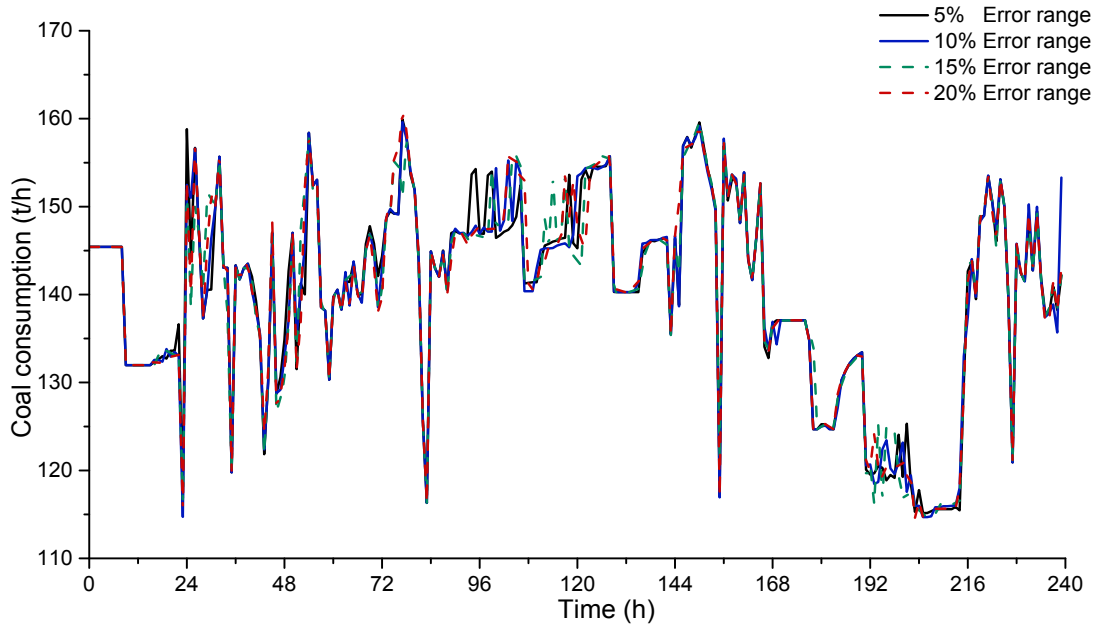


Figure 13. 10 days performances of STPG plant using non-perfect prediction-based MPC.

#### 4.2.4 Effects of TES capacity

Simulations with different TES capacities are performed to evaluate the effects of TES capacity on plant operation and the improvement benefits from using MPC, that can be used for 3h and 7h in maximum feed-water extraction and maximum reheat steam extraction conditions respectively under 100% power load. The comparison of results is summarised in Table 6. From the table, the operational improvement by using MPC becomes more significant as the TES capacity becomes more restricted and imposes more constraints on the acceptance of solar energy. The input solar energy from parabolic troughs is adjusted in the MPC scenario to ensure that storage capacity for input of solar energy from the solar tower is prioritised, enabling this energy component to be increased by 67.4% and 17.5% in the 7h-TES and 3h-TES cases, respectively. Consequently, a 1.5 g/kWh, 2.5 g/kWh and 3.6 g/kWh reduction in average coal consumption rate is achieved by MPC compared to

the standard control, leading to 10.5%, 20.3%, 37.3% coal consumption reduction in the 7h-TES, 5h-TES and 3h-TES cases, respectively. This is because in the large capacity TES scenario, molten salt is capable of fully absorbing solar energy delivered from parabolic troughs and heliostats with the standard control approach, leading to little space for optimising the allocation of TES capacity. In a small capacity TES scenario, the opposite is the case and there is great potential to optimally dispatch the charging and discharging of molten salt in this three-tank TES system by MPC.

Table 6. Results comparison in ten days considering effects of TES capacity

| Parameters                                  | 3h Capacity         |         | 7h Capacity         |         |
|---------------------------------------------|---------------------|---------|---------------------|---------|
|                                             | Standard controller | MPC     | Standard controller | MPC     |
| Average coal consumption rate (g/kWh)       | 267.7               | 264.2   | 263.0               | 261.5   |
| Standard coal consumption reduction (tonne) | 1221.1              | 1676.8  | 1831.4              | 2024.2  |
| Parabolic trough energy input (MWh)         | 3835.2              | 2617.0  | 5591.7              | 4807.7  |
| Power output from parabolic troughs (MWh)   | 1503.4              | 1025.0  | 2191.6              | 1878.0  |
| Solar tower energy input (MWh)              | 6557.5              | 10977.1 | 9890.3              | 11617.0 |
| Power output from solar tower (MWh)         | 3015.2              | 5028.9  | 4548.8              | 5334.1  |
| Solar thermal-to-electricity efficiency (%) | 43.5                | 44.5    | 43.5                | 43.9    |
| CO <sub>2</sub> emission reduction (tonne)  | 3433.0              | 4714.0  | 5148.6              | 5690.7  |

#### 4.2.5 Effects of parabolic troughs scale

The effects of parabolic trough scale on the potential to utilising energy have been examined by simulations configured with different numbers of parabolic troughs, as shown in Table 7. From the table, MPC shows more potential to improve the utilisation of energy and presents more benefit compared to standard controller in  $N_{coll} = 90$  scenario. It is worth noting that in the standard controller approach, the

enlargement of parabolic troughs leads to further restrictions to the solar tower energy input, which is decreased by 10.7% in  $N_{coll} = 90$  case than that in  $N_{coll} = 70$  case. As the result, the solar thermal-to-electricity efficiency declines by 0.6% and the average coal consumption rate increases by 1.4 g/kWh. By contrast, in the MPC approach, by adjusting the solar energy inputs and utilisation, the average coal consumption rate is decreased by 0.7 g/kWh and 2.5 g/kWh in  $N_{coll} = 70$  and  $N_{coll} = 90$  cases, respectively. As the result, the accumulated coal consumption reduction is enhanced by 5.3% and 12.0% compared to a standard approach in two cases and leads to superior performance in the large parabolic trough scale scenario than small-scale scenario. Therefore, the behaviour of the system in solar energy collection and utilisation process is more necessary to be adjusted with large scale parabolic troughs.

Table 7. Results comparison in ten days considering effects of parabolic troughs scale

| Parameters                                  | $N_{coll} = 70$     |         | $N_{coll} = 90$     |         |
|---------------------------------------------|---------------------|---------|---------------------|---------|
|                                             | Standard controller | MPC     | Standard controller | MPC     |
| Average coal consumption rate (g/kWh)       | 263.5               | 262.8   | 264.9               | 262.4   |
| Standard coal consumption reduction (tonne) | 1764.0              | 1857.7  | 1679.3              | 1880.0  |
| Parabolic trough energy input (MWh)         | 3880.7              | 3448.9  | 4469.2              | 3786.3  |
| Power output from parabolic troughs (MWh)   | 1520.5              | 1348.5  | 1752.1              | 1471.1  |
| Solar tower energy input (MWh)              | 10629.7             | 11691.5 | 9488.4              | 11578.5 |
| Power output from solar tower (MWh)         | 4889.9              | 5358.1  | 4368.7              | 5286.4  |
| Solar thermal-to-electricity efficiency (%) | 44.2                | 44.3    | 43.6                | 44.1    |
| CO <sub>2</sub> emission reduction (tonne)  | 4959.1              | 5222.5  | 4721.0              | 5285.4  |

#### 4.2.6 Limitations and other scenarios

The inherent limitation also presents in the application process of the control approach. Due to the complex structures and coupling mechanism of STPG, the safety constraints of each variate need to be recalculated when the particles are generated in the optimisation process, leading to large computational quantity. Considering the calculation process that optimal series control inputs are determined in each time step, disadvantage of long computation time might be more significant in annual operation. The optimisation of the algorithm for better computational speed is an important direction for the implementation of the MPC approach.

Traditionally all parabolic trough plants use thermal oil as heat transfer fluid (HTF) and molten salts for the storage. In the system configuration aspect, the use of molten salt as HTF has the advantages of low cost, large specific heat capacity and stable chemical properties. In addition the benefit of using molten salts as main HTF there is no temperature difference between the HTF and the salt charging and it is possible to run the heat absorber tubes and the steam cycle at higher temperatures. However, the higher freezing point also leads to higher requirements for system operation. At present, the main solution is the use of electric heat tracing system, in addition, the research and development of low melting point molten salt is also actively advanced. Besides, molten salt for parabolic trough applications has been assessed [58, 59] and tested in demo plants [60, 61, 62], which have been successfully operated and shows a good application potential. And some projects using molten salt as HTF are also under development [63, 64].

The linear Fresnel reflector is a promising option to replace the parabolic troughs. At present, the utilisation of parabolic trough collectors is relatively mature and extensive with better annual efficiency of 14%–22% compared to 13%–18% in the linear Fresnel reflector [65]. However, the linear Fresnel technology has many advantages, including the utilisation of striped flat mirrors, uncomplicated supporting structure and tracking system, leading to lower investment and less cost for operation and maintenance [66, 67]. Therefore, in the scenario of using linear Fresnel reflector and not parabolic troughs, the thermodynamic performance of the system might be deteriorated while there is great potential to reduce the initial and operation cost.

## 5. Conclusions

This study developed the MPC approach based on the GA-PSO algorithm to find optimum control inputs to reduce accumulative coal consumption in a practical 600 MW<sub>e</sub> STPG system, considering constraints of integrated solar energy and real power load. Daily simulation on a typical day and consecutive simulation over a 10-day period are performed to illustrate the operation with a standard controller and a MPC approach.

Results of the typical day show the advantages of MPC in reducing average coal consumption rate and accumulative coal consumption compared with using a standard controller that attempts to maximise solar energy input and output at each instant. The integrated solar tower energy is increased by 159.3 MWh, leading to a 21.3-tonne (13.6%) improvement in coal consumption reduction. In the consecutive 10 days simulation, a 14.8 g/kWh reduction in average coal consumption rate and

1898.4-tonne reduction in coal consumption is achieved in a STPG controlled with MPC, which is an improvement of 20.3% compared with using a standard controller. The substantial absolute difference between performances with two different control approaches tends to occur in the high radiation conditions (day 2), which shows a 61.7-tonne (34.3%) change in the daily coal consumption reduction. The relative improvement also tends to be significant in the low radiation scenario (day 7), which shows a three times improvement by the MPC approach compared with a standard controller.

The MPC approach is observed to generate these improvements compared with standard controller by, (i) dispatching the TES energy optimally by reserving part of molten salt capacity for the high-temperature cycle instead of attempting to maximise the absorbed solar energy at each instant, (ii) discharging thermal energy gradually instead of releasing maximum energy at each instant to reduce the influence of adverse efficiency changes in the plant. This observation shows potential to develop advanced operational strategies that molten salt is preferred for high-temperature circulation under sufficient solar irradiation condition and discharging the storage thermal energy gradually under insufficient solar irradiation condition. The sensitivity analysis shows that the quantity of benefits from MPC is insensitive to forecast error. With the forecast error increase from 5%-20%, the coal consumption reduction decreases by 1.08%-1.94% than the perfect forecast scenario. Besides, the system with larger solar energy collection ability but less TES capacity allow more potential to the improve overall energy utilisation through MPC approach.

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## Nomenclature

### Abbreviations

|        |                                                                             |
|--------|-----------------------------------------------------------------------------|
| CFPG   | conventional coal-fired power generation plant                              |
| CSP    | concentrated solar power                                                    |
| GA     | genetic algorithm                                                           |
| GA-PSO | combined genetic algorithm-particle swarm optimisation                      |
| HMSE   | high-temperature molten salt-steam heat exchanger                           |
| HTF    | heat transfer fluid                                                         |
| LOCE   | levelised cost of electricity                                               |
| MMSE   | medium -temperature molten salt-steam heat exchanger                        |
| PSO    | particle swarm optimisation                                                 |
| SPCG   | solar parabolic trough aided coal-fired power generation                    |
| STCG   | solar tower-aided coal-fired power generation                               |
| STPG   | combined solar tower and parabolic trough aided coal-fired power generation |
| TES    | thermal energy storage                                                      |

### Mathematical symbols

|           |                                                        |
|-----------|--------------------------------------------------------|
| $A_f$     | effective area of heliostats, m <sup>2</sup>           |
| $A_{net}$ | net aperture area of parabolic troughs, m <sup>2</sup> |
| $b_{st}$  | standard coal consumption rate, g/kWh                  |

|                 |                                                                     |
|-----------------|---------------------------------------------------------------------|
| $\cos \theta_i$ | cosine factor of heliostat                                          |
| $DNI$           | direct normal irradiance, W/m <sup>2</sup>                          |
| $e_{sp}$        | solar energy input from parabolic troughs, MWh                      |
| $e_{st}$        | solar energy input from solar tower, MWh                            |
| $e_{shad}$      | shading losses factor of parabolic troughs                          |
| $e_{end}$       | optical end gain and end loss factor of parabolic troughs           |
| $e_{spill}$     | optical losses factor of parabolic troughs                          |
| $e_{clean}$     | cleanliness factor of the mirrors                                   |
| $e_{avail}$     | field availability                                                  |
| $fit$           | fitness of the particle                                             |
| $f_{at_i}$      | atmospheric attenuation factor of heliostat                         |
| $f_{inti}$      | interception factor of heliostat                                    |
| $f_{sbi}$       | shading and blocking factor of heliostat                            |
| $gbest_i(t)$    | the global optimal solution                                         |
| $m_{ms,in}$     | mass flow rates of charged medium-temperature salt, kg/s            |
| $m_{ms,out}$    | mass flow rates of discharged medium-temperature salt, kg/s         |
| $m_{hs,in}$     | mass flow rates of charged high-temperature salt, kg/s              |
| $m_{hs,out}$    | mass flow rates of discharged high-temperature salt, kg/s           |
| $N_{coll}$      | number of parabolic trough collectors                               |
| $N_{opt}$       | optical active portion of aperture                                  |
| $pbest_i(t)$    | historical optimal solution of the particle                         |
| $Q_{col}$       | input solar energy in parabolic trough collectors, W                |
| $Q_{col,eff}$   | effective thermal energy absorbed in parabolic trough collectors, W |
| $Q_{loss,cov}$  | convective heat loss of receiver, W                                 |
| $Q_{loss,opt}$  | optical loss of receiver, W                                         |
| $Q_{loss,rad}$  | radiation heat loss of receiver, W                                  |
| $Q_{pipe,loss}$ | heat loss in pipes, W                                               |
| $Q_{rec}$       | thermal power absorbed by molten salt in receiver, W                |
| $q_{col,loss}$  | length-specific heat loss to the surrounding in the collectors, W/m |
| $R_{focus}$     | actual focus state of the parabolic troughs field                   |

$v_i(t)$  velocity of particle  $i$  at the moment  $t$

$x_i(t)$  position of particle  $i$  at the moment  $t$

#### Greek symbols

$\sigma_{ast}$  astigmatic error

$\sigma_{bq}$  beam quality error

$\sigma_{sun}$  sun shape error

$\sigma_t$  tracking error

$\lambda_{solar}$  solar energy percentage

$\rho_i$  effective reflectivity of heliostat

$\eta_{field}$  efficiency of the heliostat field

$\eta_{col,opt}$  peak optical efficiency of parabolic troughs

$\omega$  adaptive weight coefficient

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#### **Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

[68]

1. Model predictive control is developed with predictive weather data and power load.
2. The typical daily and consecutive operation of the integrated system is observed.
3. The average coal consumption rate is further reduced by 20.3% in 10-day operation.
4. The controller tends to dispatching more TES energy for high-temperature cycle.
5. The benefits decrease by up to 1.94% considering the forecast error range of  $\pm 20\%$ .

[69]



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## **Model predictive control of a combined solar tower and parabolic trough aided coal-fired power plant**

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