Energy and Built Environment 1 (2020) 11–26

Contents lists available at ScienceDirect

Energy and Built Environment

journal homepage: www.elsevier.com/locate/enbenv

Solar aided power generation: A review

Jiyun Qin[a], Eric Hu[b,*], Xiaohua Li[c]

[a] China Institute of FTZ Supply Chain, Shanghai Maritime University, Shanghai 201306 China
[b] School of Mechanical Engineering, the University of Adelaide, SA 5005 Australia
[c] Department of Building Engineering, Hunan Institute of Engineering, 411104 Hunan, China

ARTICLE INFO

Keywords:
Solar thermal power system
Hybrid power system
Solar preheating
Solar Aided Power Generation

ABSTRACT

Solar Aided Power Generation (SAPG) is the most efficient and economic ways to hybridise solar thermal energy and a fossil fuel fired regenerative Rankine cycle (RRC) power plant for power generation purpose. In such an SAPG plant, the solar thermal energy is used to displace the extraction steam by preheating the feedwater to the boiler. The displaced/saved extraction steam can, therefore, expand further in the steam turbine to generate power. The research and development of the SAPG technology started in the 1990s. This paper is trying to reviews and summarises the progress of research and development of the SAPG plant technology in last almost 30 or so years, including the technical and economic advantages of SAPG over other solar thermal power generation technologies (e.g. solar alone power generation), various modelling techniques used to simulate SAPG perforamnce, impacts of SAPG plant's configuration, size of solar field and strategies to adjust mass flow rate of extraction steam on the plant perforamnce, exergy analysis of SAPG plant and operation strategies to maximise plant's economic returns etc. In addition, the directions for future R& D about SAPG technology have been pointed/proposed in this paper.

1. Introduction

With the development and improvement of living standards of the world, the need for energy grows rapidly [1]. Meanwhile, the increase in electricity demand grows more rapidly than the demand for the liquid fuels, natural gas and coal [2]. In 2014, about 40% of electricity in the world was produced by coal fired power plant, while 26% of electricity came from oil and gas fired power plant [3]. It was reported that fossil fired power plant will increase by 27% in the next 20 years [4]. The increase in fossil fuel combustion leads to a global temperature rise [5]. In order to reduce or prevent the negative environmental impact from fuel combustion, the used to other kinds of energy resources to generate electricity is attracting more attention [6]. It has been reported that the percentage of electricity generated from renewable sources will increase from 6% in 2015 to 38% in 2040 [6]. The solar thermal power generation is attracting more and more attention as a cleaner way for power generation purpose [7].

However, at present stage, the solar thermal power generation has two major shortcomings: high capital costs and relative low thermal efficiency. On the other hand, fossil fuel fired Rankine cycle power plants which are currently still the backbone of electricity production in the world, have a better thermal efficiency and relatively low capital costs to build. Therefore, hybridising solar thermal energy with a fossil fuel fired Rankine cycle power plant is an efficient and economical way to utilise solar thermal energy for power generation and to reduce emission from fossil fire power production [8–11]. This hybrid power system can both reduce the carbon dioxide emissions and promote the output of a power plant [12]. Among various options to hybrid solar thermal energy and the fossil fired Rankine cycle power plants, Solar Aided Power Generation (SAPG) has been proved to be the most efficient one for low to medium temperature (100 °C to 300 °C) solar thermal resources [13], which is the specific review object of this paper.

A typical Rankine cycle power plant consists of the boiler, steam turbine, condenser and a feedwater heater (FWH) system. In order to increase its thermal efficiency, the Rankine cycle has been modified into Regenerative Rankine Cycle (RRC) in which a part of steam is extracted half way from the turbine to preheat the feedwater [14]. Almost all power plants nowadays have multi-stage regenerations/extractions (up to 8 stages) in the world, therefore, solar thermal energy can be used to displace energy of extraction steam to multi-stage.

Generally speaking, there are two potions for the solar thermal energy to be integrated into Rankine power plants as shown in Fig. 1. These two options could also be employed together in the same power plant.

Table 1 summarises the advantages and disadvantages of two options of introducing solar thermal energy into the RRC power plant. SAPG reviewed in this paper refers to the option 2, which solar thermal

* Corresponding author.
E-mail address: eric.hu@adelaide.edu.au (E. Hu).

https://doi.org/10.1016/j.enbenv.2019.09.003
Received 24 June 2019; Received in revised form 22 August 2019; Accepted 3 September 2019
Available online 29 September 2019

Nomenclature

CT	constant temperature strategy
CM	constant mass flow rate strategy
ET	evacuated tube
FS	fuel saving
FWH	feedwater heater
HTF	heat transfer fluid
LCOE	levelized Cost of Electricity
PB	power boosting
PT	parabolic trough
RRC	regenerative Rankine cycle
SAPG	solar aided power Generation
SP	solar preheater
VT-HL	high to low varying temperature
VT-LH	low to high varying temperature

energy is used to preheat the feedwater to the boiler. This option is suitable for low to medium temperature solar thermal energy (i.e. less than 300 °C). The technical performance of this option is better than that of a stand-alone solar thermal power plant with the same solar thermal temperature [16–18]. Also, this option has economic advantages due to low capital costs [19–21]. And, it is flexible in its implement [22]. Comparing with the option 1, this option has advantage of lower capital cost when both options have same capacity [23–26]. However, this option suffers from disadvantages of lower solar share and solar thermal to power efficiency [27–33].

2. Solar Aided Power Generation

The term of Solar Aided Power Generation (SAPG) was firstly used by Hu [22], although it had been informally used since 1997 [34]. The SPAG technology is a solar hybrid power system in which low grade solar thermal energy is used to displace the high grade heat of the extraction steam in an RRC power plant for feedwater preheating purpose [35]. The key feature of SAPG is that the solar heat carried by heat transfer fluid (HTF) or steam does not enter the turbine directly to generate power, instead is to be used only to displace the extraction steam by preheating feedwater entering the boiler. The saved/displaced extraction steam therefore could continue to expend in the turbine to generate power. The power generated by the saved/displaced steam is counted as the power generated by the solar thermal input.

The SAPG concept sounds simple but it has great thermodynamic advantages over other solar thermal power generation systems. For any solar thermal power system, its thermal efficiency is limited/capped by

Table 1
Comparison of the advantages and disadvantages of two options of introducing solar thermal energy into a regenerative Rankine cycle power plant.

	Advantages	Disadvantages
Option 1: High temperature solar heat (higher than 300 °C)	• High solar share • High efficiency	• High cost • Not easy for building
Option 2: Low temperature solar heat (less than 300 °C)	• Low cost • Flexible in its implement	• Low solar share • Low efficiency

the highest temperature of the solar thermal source when the thermal sink temperature is fixed. Namely, the maximum efficiency of a conventional solar thermal power system is limited by the highest temperature of solar thermal input. However, for the SAPG system, the solar to power efficiency is no longer limited/capped by the temperature of solar thermal input but the highest temperature of the whole plant i.e. the combustion temperature, which is normally much higher than solar heat input temperature [14].

A typical SAPG plant was given by Yang et al. as shown in Fig. 2. At the concept level, the advantages of SAPG are summarised as below [22]:

(1) The SAPG technology has higher thermodynamic 1st law and 2nd law i.e., exergy efficiencies over the solar thermal alone power station.
(2) A relatively low implementation cost, and high social, environmental and economic benefits become a reality as SAPG technology could utilise the existing infrastructure of fossil fuel fired power stations.
(3) The SAPG plant can be applied to not only new built power station but also to modify the existing power station with less or no risk to the operation of the existing power stations.
(4) The thermal storage system that at present is still technically immature is not necessary. The simplicity is another beauty of the SAPG technology. The pattern of electricity demand shows that nowadays air conditioning demand has a great impact on the electricity load [37]. Afternoon replaces the evening to be the peak loading period in summer. This means that the additional power generated by the SAPG plant is just at the right time. Namely, the solar contribution and power demand are peak at the same time i.e., during summer day time.
(5) The SAPG plant is flexible in its implement. Depending on the capital a power station has, the SAPG plant can be applied to the power station in stages.

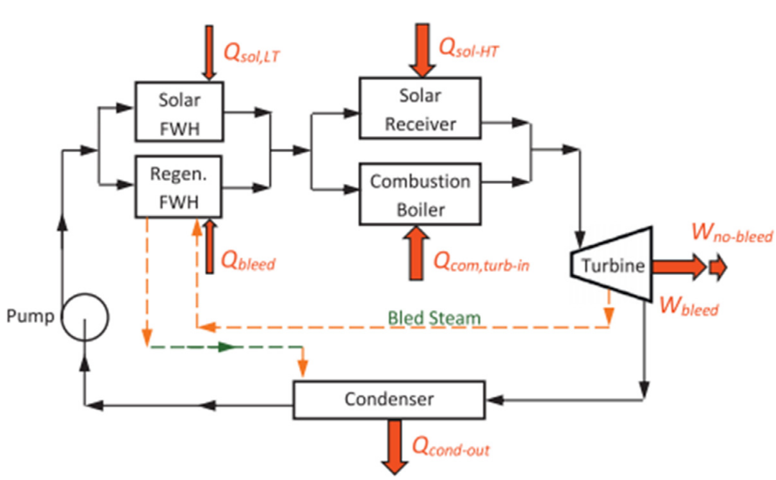

Fig. 1. Basic options for integrating solar thermal energy into a regenerative Rankine cycle power plant, option 1 is integrating high temperature solar thermal energy into the boiler, and option 2 is uing low to medium temperature solar thermal energy to preheat feedwater of power plant. [15].

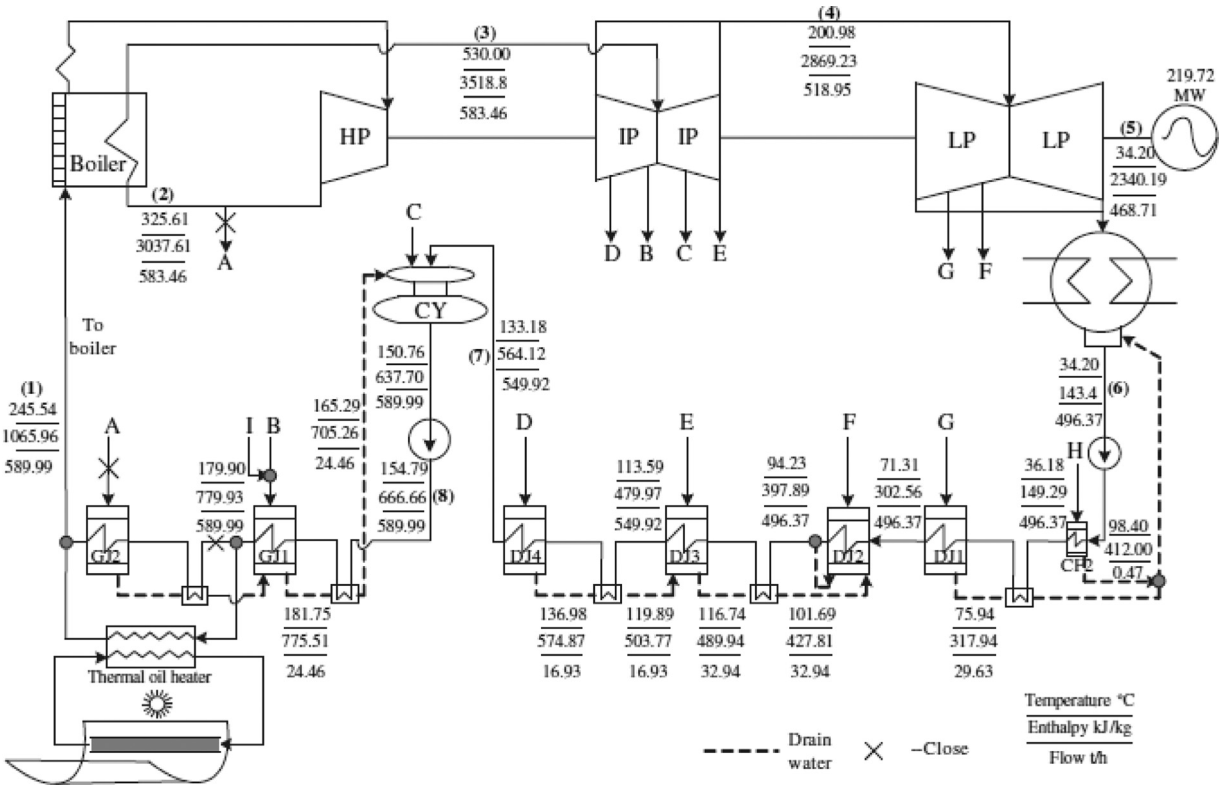

Fig. 2. A schematic diagram of a typical Solar Aided Power Generation (SAPG) plant [36].

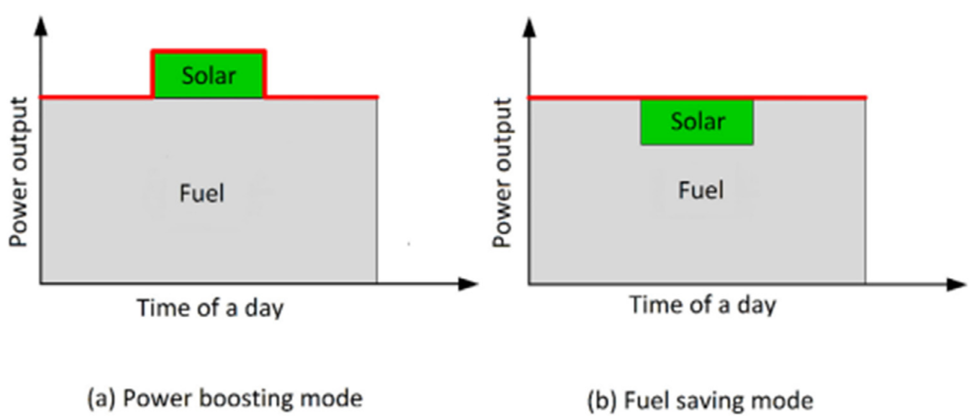

Fig. 3. The alternative daily "power boosting" and "fuel saving" modes for an SAPG plant [36].

(6) Low temperature range solar collectors e.g. evacuated tubes and flat-plate collectors, can be used in the SAPG plant. It is a great new market for the solar (collectors) industry. There is research shows using non-concentrating collectors in SAPG plants has technical advantages over concentrating collectors [38].

(7) The SAPG plant can be operated in either Power Boosting (PB) or Fuel Saving (FS) modes. These two modes are illustrated in Fig. 3 [36]. The PB mode is defined as when the solar thermal energy is being used to increase the power output of the power plant without the increase of fuel consumption in the boiler. On the other hand, the FS mode is defined as when the solar thermal energy is being used to reduce the boiler fuel consumption of the power plant. Under this condition, the power output from the plant remains unchanged.

In addition, with the SAPG principle, other renewable thermal energy, e.g. geothermal energy, can also be used together or independently with solar thermal heat for the same purpose [39–45]. It was found that geothermal hybrid power systems has higher geothermal to power efficiency than a stand-alone geothermal power plant has [39,40].

"Solar (or geothermal) to power efficiency" and "instantaneous solar share" are two often used criteria to compare the perforamnce among plants. The solar thermal to power efficiency is defined as power generated by solar energy (indirectly) on the sum of total solar thermal energy input plus the boiler load changed if any, which is given as:

$$\eta_{solar} = \frac{\Delta W_e}{Q_{Solar} + \Delta Q_{boiler}}, \tag{1}$$

where ΔW_e is the increased power output by saved extraction steam; Q_{Solar} is the solar thermal input; and ΔQ_{boiler} is the changed boiler reheating load, accounting for increases in reheat steam flows. The instantaneous solar share is defined as instantaneous solar thermal input on the (instantaneous) boiler thermal load [13]. The other way to define the solar share is the solar thermal input on the total plant thermal loads including boiler load and solar thermal input [13]. Two different

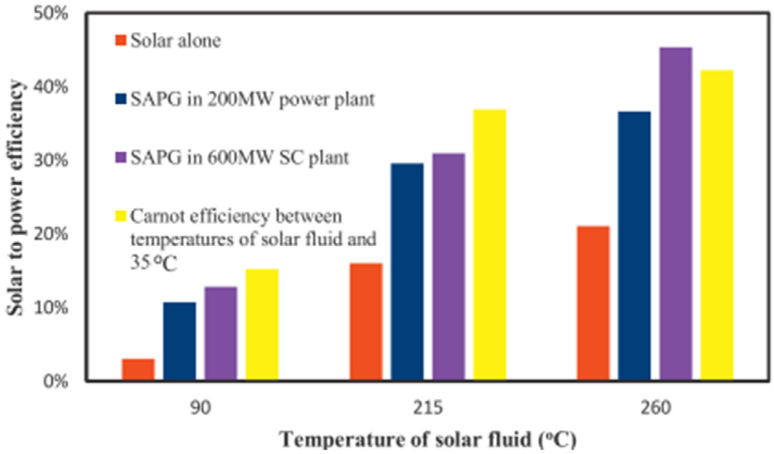

Fig. 4. Solar thermal to power efficiency of an SAPG plant at the temperature of 90 °C, 215 °C and 260 °C [13].

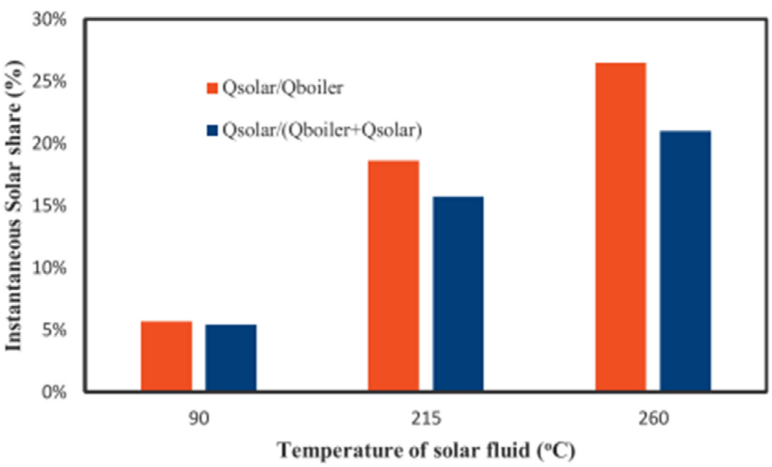

Fig. 5. Instantaneous solar share of an SAPG plant with various solar temperature [13].

definitions of instantaneous solar share can be written as:

$$x_{solar,1} = \frac{Q_{Solar}}{Q_{boiler}}, \tag{2}$$

$$x_{solar,2} = \frac{Q_{Solar}}{Q_{Solar} + Q_{boiler}}, \tag{3}$$

Figs. 4 and 5 present the solar thermal to power efficiency and instantaneous solar share of an SAPG plant for solar input at different temperatures [13].

It can be seen from Fig. 4 that the SAPG plant is more efficient than the stand-alone solar thermal power plant at the same solar input temperature, in terms of solar to power efficiency. Furthermore, the efficiency in the supercritical power plant at a given solar input temperature is higher than that in the subcritical power plant at the same temperature. The reason is that in an SAPG plant, the SAPG is actually piggy back solar energy on the original power plant, so its solar to power efficiency depends not only on the solar input temperature but also on the thermal efficiency of the original plant.

Fig. 4 also reveals/demonstrates the thermodynamic advantage of the SAPG technology that its solar to power efficiency is not limited/capped by solar temperature. In the 260 °C case in Fig. 4, the solar to power efficiency in a 600 MW supercritical SAPG power plant could be higher than the Carnot efficiency between 260 °C and 35 °C, the assumed plant's condensing temperature. An explanation for this "impossible" result is that solar heat (at 260 °C) in the SAPG plant is not used to generate power directly, instead used to preheat feed water, so the highest temperature in the SAPG plant is the temperature of the superheated/supercritical steam entering the (high pressure) turbine, which is higher than 500 °C if not 600 °C. From Fig. 5, it can be seen that with the higher temperature solar heat input, the instantaneous solar share in the SAPG plant could be higher, for the solar heat at higher temperature could be used to displace more stages of extraction steam.

3. Modellings of SAPG plants

As there is no real SAPG plants existing in the world yet, almost all studies on the SAPG technology and plants are modelling based. In previous studies, most of models developed were for SAPG plant designing and/or design optimisation purposes, namely focusing on the performance of the plant at the design point. Recently, since 2016, the research on SAPG starts to progress from plant design to plant operation stages.

3.1. Static and semi-dynamic modelling of the SAPG technology

Most early studies of the SAPG plant are based on static or steady state modelling, in which the solar thermal input is assumed at a given value, i.e. unchanged. The static performances of an SAPG plant with a given solar thermal input were simulated by these models. This modelling can be used to evaluate the thermodynamic performance of the SAPG plant with a given solar thermal input. Based on static modelling, Yan et al. found that, for the SAPG plant operated in the power boosting mode, the greater amount of solar thermal input leads to higher technical performance [46,47]. Later, Yang et al. [36] found that this conclusion are suitable for the SAPG plant operated for both power boosting and fuel saving modes.

As the SAPG plant should be operated under various solar radiation condition, the impact of solar radiation on the SAPG plant and annual technical performance of the SAPG plant should be evaluated. However, static modelling cannot achieve these goals. Therefore, most recent studies were based on a semi-dynamic or pseudo-dynamic modelling, in which the SAPG plant is simulated in series of time intervals (e.g. 1 h). In each time interval, the performance of the SAPG plant was assumed at steady state. The annual performance of the SAPG plant is then calculated as the sum of its performance at each time interval. Therefore, this modelling can be used to evaluate the annual performance of an SAPG plant under variable solar resources. Based on the semi-dynamic modelling, Hou et al. evaluated the Levelised Cost of Electricity (LCOE) of the SAPG plant under variable solar radiation conditions [48]. The results indicated that the optimal solar collector areas for lowest LCOE is influenced by the annual solar radiation conditions. Although the semi-dynamic modelling can be used to evaluate the impact the solar radiation on the SAPG plant, this modelling is still based on steady state modelling, by which the start-up and shut-down losses of integration process is not able to be simulated.

Most of previous static models and semi-dynamic models developed were for the purpose of designing of an SAPG plant. Namely, they were to determine which stage of extraction steam should be displaced, what size of solar field should be installed, and what is economic returns e.g. LCOE and/or payback time for a particular design. Recently, Qin et al. developed a semi-dynamic model for the purpose of operation of an SAPG plant [49–51]. Namely, how to adjust the mass flow rate of extraction steam to respond to the change of solar thermal input, and when to operate the PB or FS mode under variable solar radiation, fuel price and electricity tariff to achieve maximum profitability. It was found that even with same annual solar radiation, different method to adjust the mass flow rate of extraction steam would lead to variable annual technical performance [49,50]. It was also found that mixed PB and FS mode can achieve higher annual economic profitability than single PB or FS mode [51].

3.2. Approaches in the SAPG technology modelling

Modelling an SAPG plant is actually modelling the energy and mass flows in the plant based on the mass and energy conservation principles. Matrix Method is an often used approach for simulating the SAPG plant by previous studies, in which the heat and mass flow balances of the FWH system are expressed in Matrix form. In the Matrix Method, the enthalpies of the working fluid (i.e. extraction steam and feedwater) at different location of the plant, the mass flow rate of the extraction steam are presented in a Matrix form.

Eq. (4) presents an example of the Matrix for a power plant with 8 FWHs (1 deaerator and 7 closed FWHs) [49]:

$$\begin{pmatrix} q_1 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ r_2 & q_2 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_3 & r_3 & q_3 & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_4 & r_4 & r_4 & q_4 & \ddots & \ddots & \ddots & \vdots \\ \tau_5 & \tau_5 & \tau_5 & \tau_5 & q_5 & \ddots & \ddots & \vdots \\ \tau_6 & \tau_6 & \tau_6 & \tau_6 & r_6 & q_6 & \ddots & \vdots \\ \tau_7 & \tau_7 & \tau_7 & \tau_7 & r_7 & r_7 & q_7 & \vdots \\ \tau_8 & \tau_8 & \tau_8 & \tau_8 & r_8 & r_8 & r_8 & q_8 \end{pmatrix} \cdot \begin{pmatrix} y_A \\ y_B \\ y_C \\ y_D \\ y_E \\ y_F \\ y_G \\ y_H \end{pmatrix} = \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_7 \\ \tau_5 \\ \tau_6 \\ \tau_7 \\ \tau_8 \end{pmatrix} \tag{4}$$

In Eq (4), q_i (kJ/kg) is the specific enthalpy decrease of the extraction steam in the i^{th} FWH; τ_i (kJ/kg) is the specific enthalpy increase of the FW in the i^{th} FWH; r_i (kJ/kg) is the specific enthalpy decrease of the drained steam from the $(i\text{-}1)^{th}$ FWH in the i^{th} FWH; and y_i is the mass flow rate of the each stages of extraction steam. Eq. (4) is the core of the Matrix for an RRC plant. After knowing the q_i, τ_i and r_i for each FWH, the mass flow rate of the extraction steam can be calculated.

After solar input added, a new Matrix (for the SAPG plant) has been added into Eq. (4), which is given as Eq (5),

$$\begin{pmatrix} q_1 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ r_2 & q_2 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_3 & r_3 & q_3 & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_4 & r_4 & r_4 & q_4 & \ddots & \ddots & \ddots & \vdots \\ \tau_5 & \tau_5 & \tau_5 & \tau_5 & q_5 & \ddots & \ddots & \vdots \\ \tau_6 & \tau_6 & \tau_6 & \tau_6 & r_6 & q_6 & \ddots & \vdots \\ \tau_7 & \tau_7 & \tau_7 & \tau_7 & r_7 & r_7 & q_7 & \vdots \\ \tau_8 & \tau_8 & \tau_8 & \tau_8 & r_8 & r_8 & r_8 & q_8 \end{pmatrix} \begin{pmatrix} y_A \\ y_B \\ y_C \\ y_D \\ y_E \\ y_F \\ y_G \\ y_H \end{pmatrix} + \begin{pmatrix} \dot{Q}_{Solar,1}/\dot{m}_0 \\ \dot{Q}_{Solar,2}/\dot{m}_0 \\ \dot{Q}_{Solar,3}/\dot{m}_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_7 \\ \tau_5 \\ \tau_6 \\ \tau_7 \\ \tau_8 \end{pmatrix}, \tag{5}$$

where $\dot{Q}_{Solar,i}$ (kJ/s) is the solar thermal power displacing the extraction steam of i^{th} FWH; and $\dot{m}_0$ (kg/s) is the mass flow rate of steam outlet boiler. The $\dot{Q}_{Solar}$ is equal to $\sum^{\dot{Q}_{Solar,i}}$. The mass flow rates of each extraction steam required with various solar input could be calculated by solving Eq. (5), which is the necessary information required to operate a SAPG plant.

However, the Eq. (5) is based on an assumption that the specific enthalpy of the extraction steam entering FWHs system remains unchanged with the addition of the solar heat input.

In an SAPG plant, after the solar thermal input, the steam mass flow rate through the steam turbine would change, which means that the steam turbine would be operated under off-design condition. Some studies were using Flugel's formula (i.e. Stodola's Law) to simulate the off-design condition for steam turbine [19,48,52]. By using this formula, the variations of steam enthalpy at each extraction points after the change of the steam flow rates can be calculated. Flugel's formula can be written as:

$$p'_k = \sqrt{p_k^2 - \frac{T_k}{T_{k0}} \left(\frac{\dot{m}_k}{\dot{m}_{k0}}\right)^2 \left(p_{k0}^2 - {p'_{k0}}^2\right)}, \tag{6}$$

where: $\dot{m}_k$ is the flow rate of steam turbine after solar input; $\dot{m}_{k0}$ is the designed flow rate; p_k is the changed inlet pressure; p'_k is the changed outlet pressure; p_{k0} is the designed inlet pressure; p'_{k0} is the designed outlet pressure; and T_{k0} and T_k are the inlet temperatures under the designed load and part load conditions, respectively.

Fig. 6 presents a logic flow for an SAPG plant modelling by using Matrix method and Flugel's formula [48]. In Fig. 6, it shows that after the calculation of new flow rate of steam by using Eq. (5), the new pressure at each extraction points is calculated by using Eq. (6) until the deviation achieve a setting number.

When the solar input into the SAPG plant changes, the mass flow rate of water/steam entering boiler would change as well, especially when the plant is operated at FS mode. The change would lead to the variations of steam parameters at outlets of the boiler. However, most studies assumed the boiler as a black box, which means that the parameters of steam at inlet and outlet of the boiler remain unchanged even when solar thermal input changes. Recently, Wu et al. [53], Li et al. [54,55] and Huang et al. [56] modelled the boiler as a series of heat exchangers, in which the parameters of steam outlet the boiler after the integration of solar thermal energy can be calculated. It was found that the parameters of the steam outlet boiler and reheater would be decreased after the solar thermal integration [53]. However, these results are only suitable for fuel saving mode and for a subcritical power plant [54].

There are also SAPG plant's simulation models developed based on commercial software. Popov et al. used THERMOFLEX software to build the SAPG's simulation model [57]. Bakos et al. [58] and Alam et al. [59] built an SAPG plant by using the Solar Thermal Electric Component (STEC) of the TRNSYS software.

4. Configurations of the SAPG technology

An SAPG plant consists of an RRC power plant, a solar field and a heat exchanger system which is used to facilitate the thermal energy

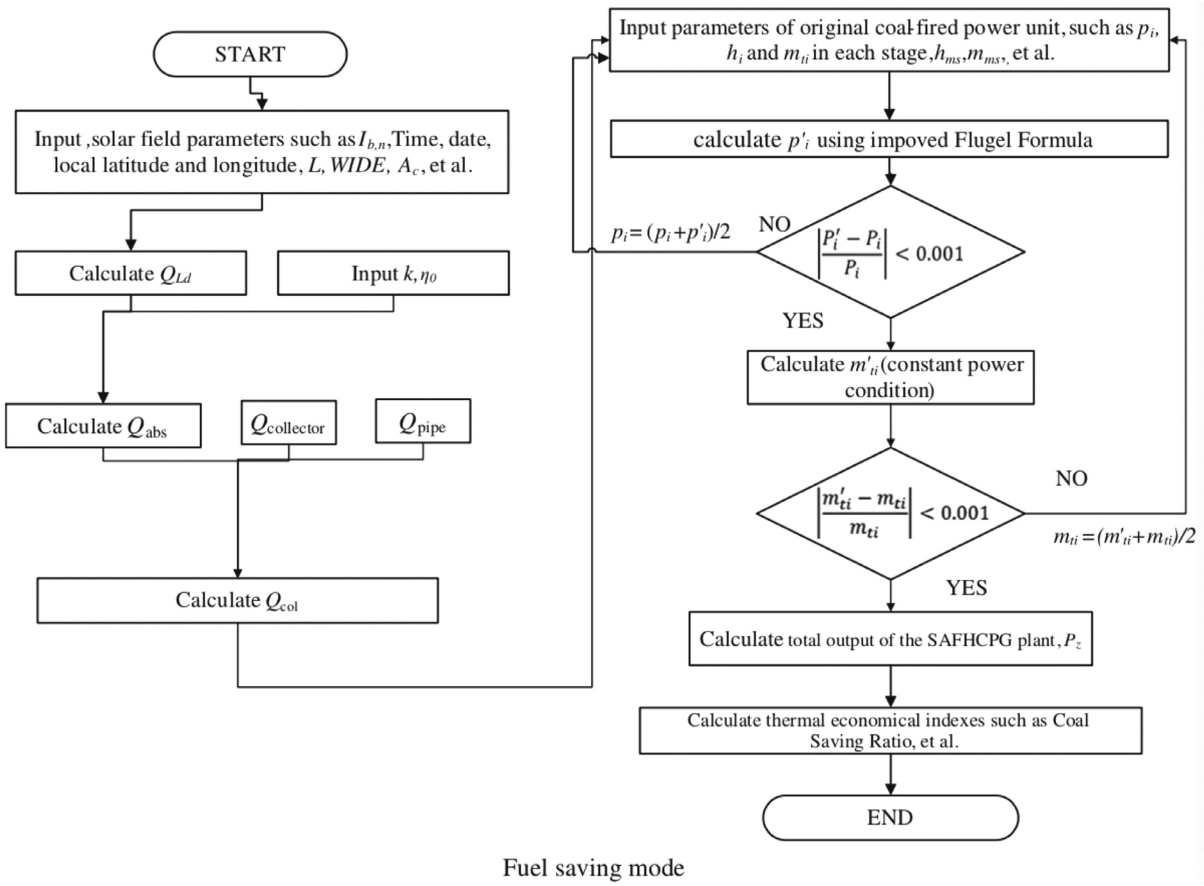

Fig. 6. Logic flow or an SAPG plant modelling for fuel saving mode by using Matrix method and Flugel's formula [48].

transfer between the solar field and RRC power plant. SAPG plants may have different configurations for the heat exchanger and the solar field arrangement.

4.1. Solar preheaters configuration

In an SAPG plant, in order to preheat the feedwater of an RRC power plant, a heat exchanger system is needed [13]. This heat exchanger system is termed the Solar Preheater (SP) [49]. The SP in an SAPG plant is used to facilitate the heat exchange process between the HTF and the feedwater of the RRC power plant. Therefore, the SP in an SAPG plant is used to displace the function of the FWHs in an RRC power plant. Depending on the arrangement of the SP according to the FWHs, an SAPG plant has different configurations, which is termed as Solar Preheater configuration [49].

Most studies are based on a SP configuration that SP is arranged in parallel with the displaced FWHs, which is termed as parallel configuration [49]. Fig. 7 presents the schematic diagram of the parallel configuration. As shown in Fig. 7, there is a SP in parallel with all high pressure/temperature FWHs, which is used to displace extraction steam to these FWHs. In such configuration, the mass flow rate of the feedwater flowing through the FWH and SP is needed to be controlled, which is dependent on the available solar thermal energy [22]. When the solar thermal energy level is sufficient, all the feedwater is directed to the SP system, bypassing the FWH.

Few studies are based on another SP configuration, in which the SP is arranged in series with the FWHs of the RRC power plant, which is termed as Series configuration [49]. Fig. 8 presents an SAPG plant based on Series configuration by Wu et al. [61]. As shown in Fig. 8, the SP (i.e. Ex1 in Fig. 8) is in series with the deaerator and the high pressure/temperature FWHs (i.e. HP1 to HP3 in Fig. 8), and the solar thermal energy is used to displace extraction steam to all high pressure/temperature FWHs. In such a configuration, all of the mass flow rate of the feedwater enters the SP and is preheated by the solar thermal energy, then, the preheated feedwater is directed to the FWH and preheated by the extraction steam [62–64].

Early studies by Bloomfield and Calogeras [20] and by Energy Research Development Administration of the U.S. [21] compared the operation of the Parallel and Series configurations. It was pointed that for the parallel configuration, as controls are required to balance the mass flow rate of the feedwater between the SP the FWH system, the operation of such a configuration is relatively complex [20,21]. However, for the series configuration, as the controls are only required to adjust the mass flow rate of the extraction steam, the operation of such a configuration is relatively easier to control than that of a parallel configuration [20,21]. Recently, Suojanen et al. [65] pointed that configuration would have great effect on the solar share of the SAPG plant. The reason is that different configurations leads to different turbine sections and heat surfaces of the steam boiler being imbalances.

In early studies of the SAPG plant, Pai proposed another structure of the series configuration, which is shown in Fig. 9 [66]. In this structure, each FWH has one series of SP. After the solar thermal input, the mass flow rates of the extraction steam at all extraction points should be adjusted. As it is needed to balance the energy of all FWHs and the SP for this structure, the operation of such a structure would be complex.

A recent study by Qin et al. identified four possible configurations for the SAPG plant, which is given in Fig. 10 [49]. Fig. 10(a) and Fig. 9(b) presents two structures for parallel configuration. In Fig. 10(a), each displaced FWH has one parallel SP, and in Fig 10(b), one bigger SP is arranged in parallel with all displaced FWHs. Comparing the two Parallel configuration, the Parallel 1 configuration is flexible in displacement with variable solar thermal temperature. Fig. 10(c)

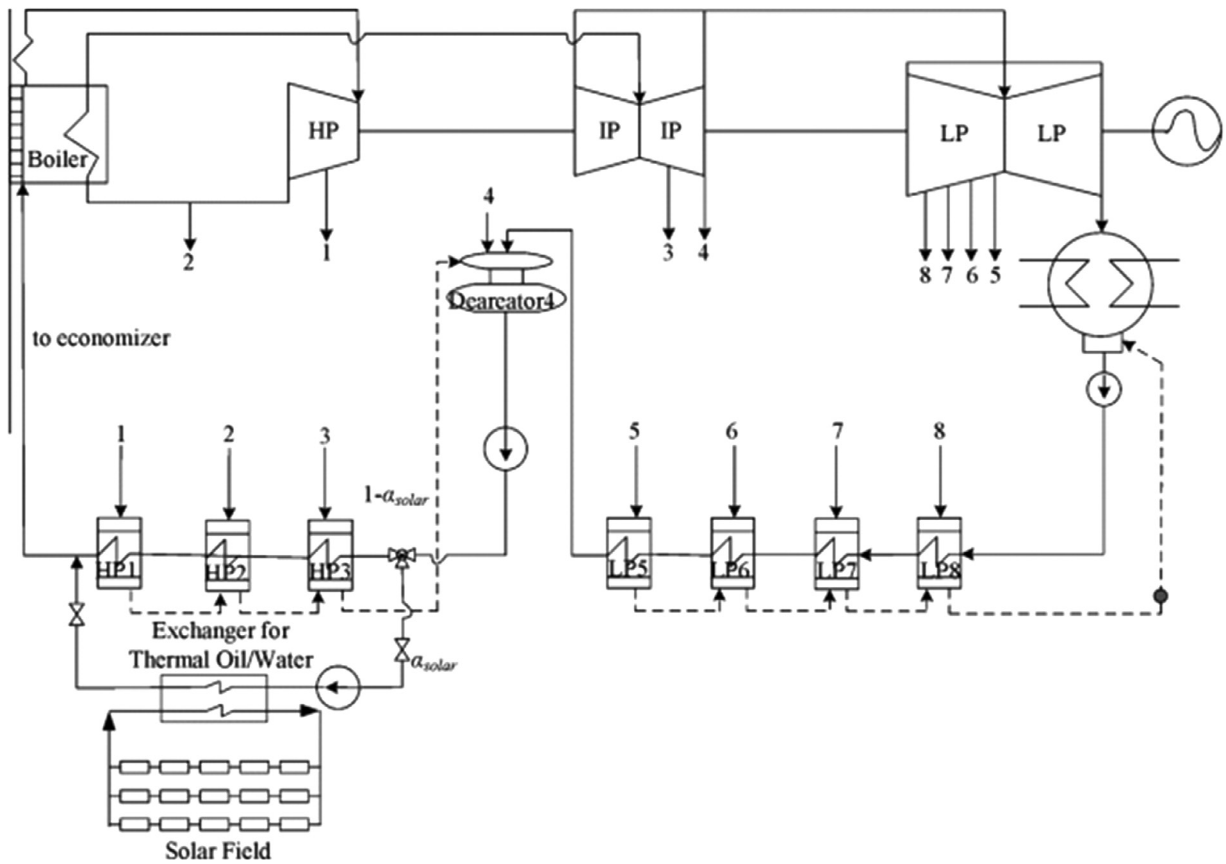

Fig. 7. A schematic diagram for demonstrating the Solar Aided Power Generation plant with parallel configuration [60].

and Fig. 10(d) presents two structures for series configuration, in which solar thermal energy is used to displace extraction steam to all high pressure/temperature FWHs (i.e. FWH1 to FWH3 in Fig. 10). In Fig. 10(c), the SP is placed in series between the FWH3 and DEA, while in Fig. 10(d), SP is located in series between the FWH1 and the boiler.

4.2. Solar field of the SAPG technology: concentrating and non-concentrating solar collectors

In an SAPG plant, solar field is used to provide the solar thermal energy. Medium to low temperature solar collectors can be used in the SAPG plant [19]. Hu et al. evaluated the SAPG plant with flat plate, evacuated tube and parabolic trough collectors, respectively [22]. It was pointed that SAPG plant using parabolic trough collectors has higher efficiency than that of using flat plate and evacuated tube collectors. The reason is that medium temperature concentrating solar collectors (i.e., parabolic trough collectors, PT) can be used to displace extraction steam to high pressure/temperature FWHs, which can achieve higher efficiency that be used to displace extraction steam to low pressure/temperature FWHs.

Medium temperature (i.e. 200 °C to 300 °C) concentrating solar collectors (i.e., parabolic trough, PT) were the most common selection in previous studies of SAPG plant. Most studies are based on the assumptions that PT collectors are used to displace high pressure FWHs. It was found that performance of PT collectors would have impacts on technical performance of the SAPG plants. Hong et al. evaluated the influence of the incident angle on the performance of the SAPG plant [67]. The result indicated that with the increase of incident angle, the solar thermal to power efficiency firstly keeps constant and then decrease. Peng et al. pointed that the solar field area for an SAPG plant would decrease by 4% if the rotatable-axis tracing system for the PT collectors is used [68]. Later, Peng et al. found that changing the direction of tracking axis in different season would improve the annual solar to power efficiency for an SAPG plant [69]. Recently, Wu et al. compared the SAPG plant's performance with three tracking modes for PT collectors, i.e. N-S titled tracking mode, N-S horizontal tracking mode, E-W titled horizontal tracking mode and dual-tracking mode [52]. The results indicated that row spacing to aperture width ratio greatly affects the shadowing factor. The N-S titled tacking mode can reach 93.2% level of the dual-tracking mode. While, the N-S and E-W horizontal tracking modes can reach the 81.8% and 59.4% levels.

In an SAPG plant, using low temperature non-concentrating collectors to displace extraction steam to all low temperature/pressure FWHs still has net land-based technical advantages. Zhou et al. found that considering the layout of solar collectors, using evacuated tube (ET) collectors (i.e., non-concentrating solar collectors), has net land-based solar thermal to power efficiency over using PT collectors [70]. In the paper, Zhou et al. proposed a concept of net solar to power efficiency, which is defined as the ratio of annual power output of an SAPG plant and the annual solar radiation falling on a given piece of land. It was found that, on a given piece of land, the total collector area of the ET collectors arranged in a solar field is higher than that of the PT collectors. Therefore, under some layouts for ET and PT collectors, an SAPG plant using ET collectors has a better annual performance than that using PT collectors. However, the tile angle in the paper of Zhou et al. was assumed to be fixed, and annual solar radiation in only one location has been analysed. Later, Qin et al. compared the ET and PT collectors using in an SAPG plant in a given piece of land. In this paper, in terms of net land based solar to power efficiency and annual solar power output per collector capital cost of an SAPG plant in three locations (Singapore; Multan, Pakistan and St. Petersburg, Russia) [38]. It was found that an SAPG plant using ET solar collectors has higher net land based solar to

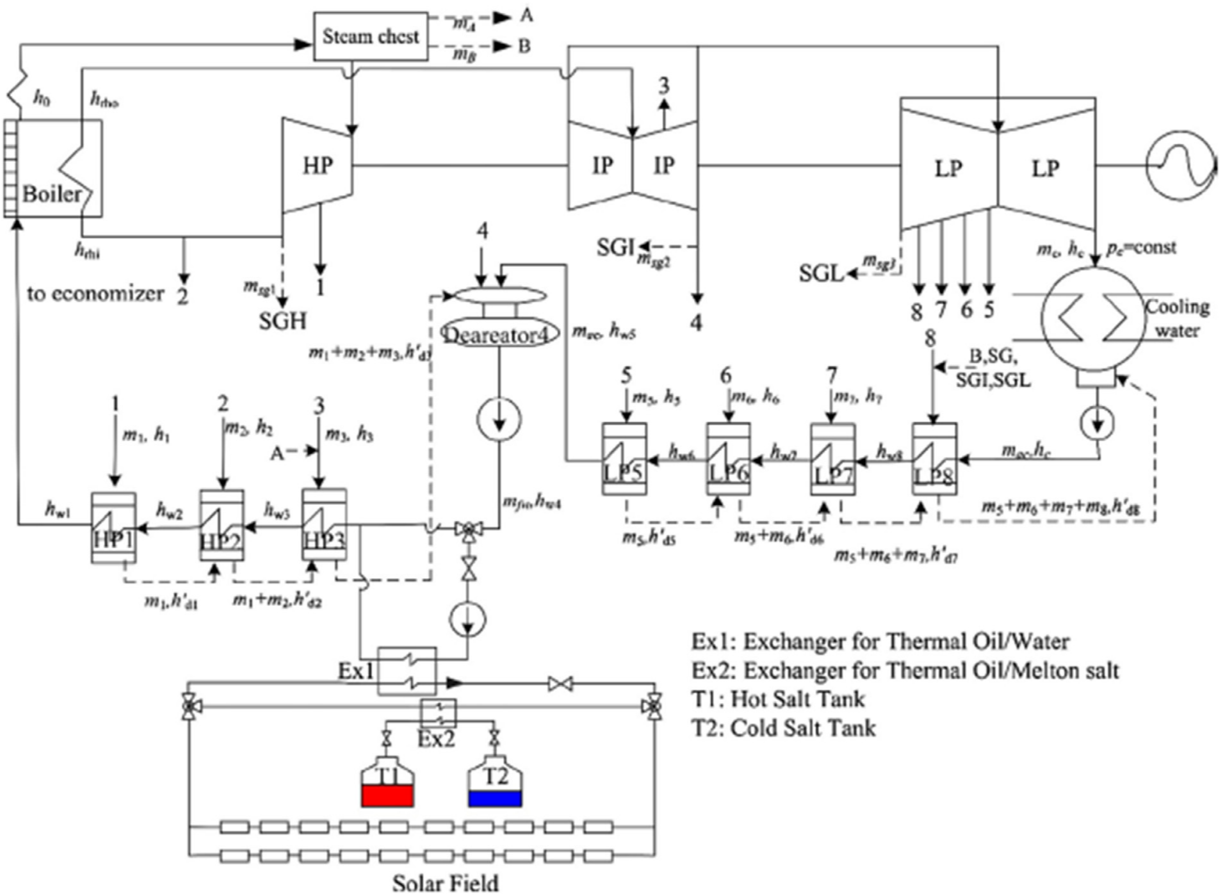

Fig. 8. A schematic diagram for demonstrating the Solar Aided Power Generation plant with series configuration [61].

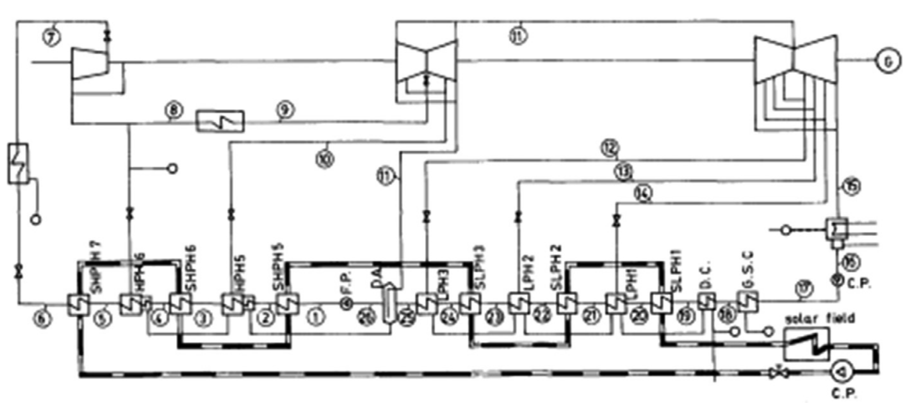

Fig. 9. Solar Preheater configuration that proposed by Pai [66].

power efficiency than that using PT solar collectors. Also, it was pointed that in solar low latitude locations e.g. Singapore, using ET solar collectors even have advantages of lower solar power output per capital cost over using the PT solar collectors in an SAPG plant.

5. Operation strategies of the SAPG technology

In an SAPG plant, the technical benefit comes from the displaced high grade thermal energy of the extraction steam [14,22]. Therefore, the performance of an SAPG plant is dependent on the strategies to adjust the mass flow rate of the extraction steam, according to the solar thermal input. These strategies are termed operation strategies for the SAPG technology.

5.1. Solar preheater operation strategies

In an SAPG plant, the solar thermal energy used to displace extraction steam at higher temperature/pressure stage leads to higher technical performance [36,46,47]. Therefore, when the solar thermal energy is assumed to displace more than one stage of extraction steam, the performance of an SAPG plant would be dependent on the strategies used to adjust the mass flow rate of the extraction steam to displaced extraction points/stages. These strategies have not been clearly defined by most studies until the studies of Qin et al. [49]. Qin et al. named these operation strategies as Solar Preheater operation strategies.

The Solar Preheater operation strategies that most previous studies adopted have not been clearly indicated. For the studies that indicated their strategy adopted, they were all based on a constant temperature

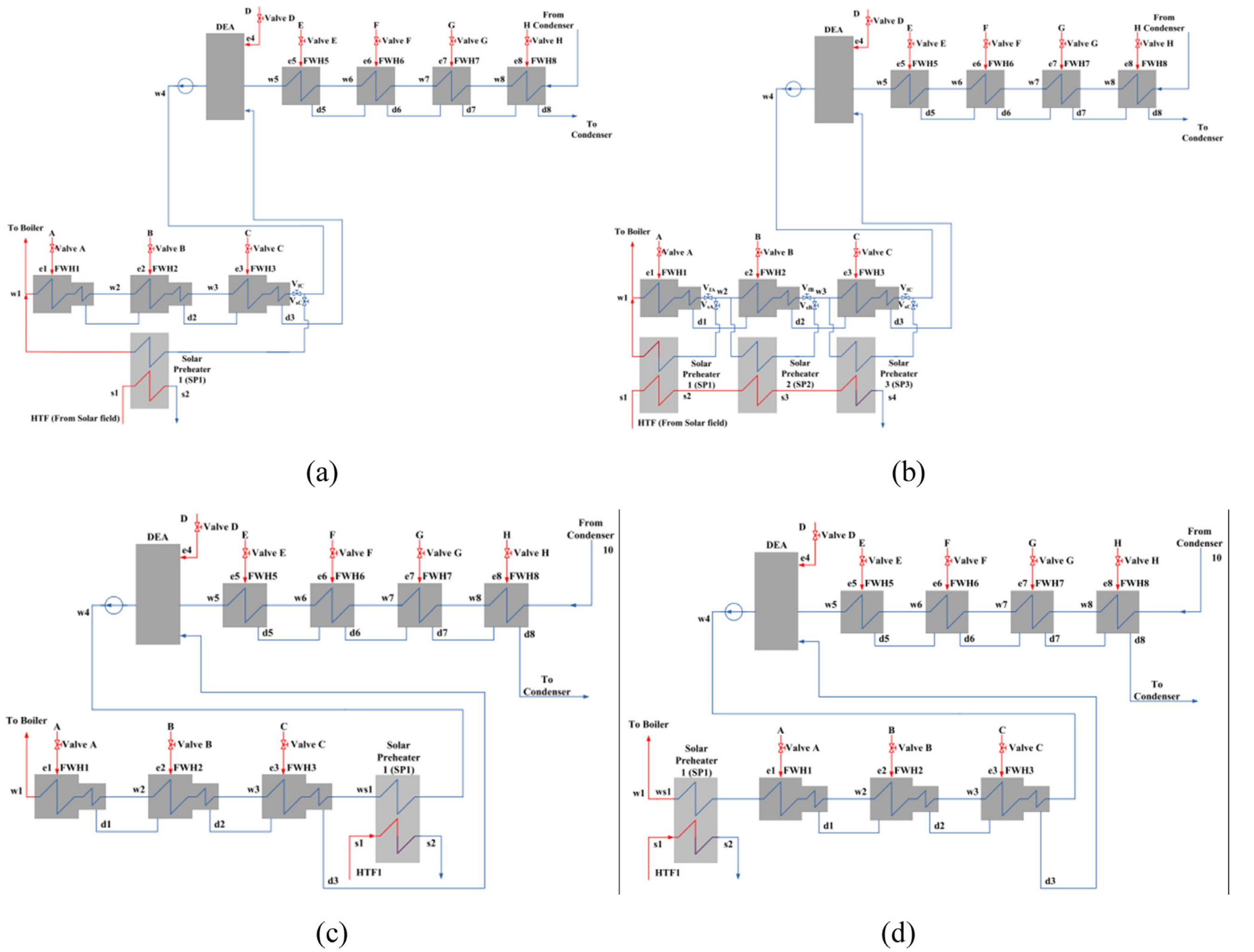

Fig. 10. Schematic diagram of an SAPG plant FWH system proposed by Qin et al.: (a) Parallel 1 configuration; (b) Parallel 2 configuration (c) Series 1 configuration; (d) Series 2 configuration [49].

(CT) strategy, which means that mass flow rates of extraction steam at displaced points are adjusted to maintain the feedwater outlet temperature of FWHS unchanged. SAPG plant with different configurations adopting the CT strategy would have different method to adjust the mass flor rate of extraction steam to displaced extraction points.

Hou et al. [48], Wu et al. [52,53,61] and Zhai et al. [62–64] evaluated the performance of an SAPG plant based on the Series 2 configuration. They were all assumed that solar thermal energy is used to displace extraction steam to all high pressure/temperature FWHs, which is shown in Fig. 11. Zhai et al. pointed that after the solar thermal input, the extraction steam is displaced from low pressure/temperature stages from high pressure/temperature stages with the incremental solar thermal input (i.e. from FWH 3 to FWH 1 in Fig. 11) [62–64]. That is, the extraction steam is displaced stage by stage.

Wu et al. [71], Hou et al. [60], Zhao et al. [72,73] evaluated the SAPG plant's performance based on the parallel configuration and adopting the CT strategy. They are all assumed that solar thermal energy is used to displace extraction steam to all high pressure/temperature FWHs. These paper indicated that, after the solar thermal input, the mass flow rate of the extraction to all displaced extraction point should be decreases simultaneously [60,71]. This is different from the series configuration.

As the technical performance of the SAPG plant dependent on the displaced extraction steam, different order to displace extraction steam leads to different technical returns. Therefore, the performance of the SAPG plant adopting different Solar Preheater operation strategies is needed to be evaluated and compared. Also, whether there are other possible Solar Preheater operation strategies is needed to be identified.

Qin et al. identified three possible Solar Preheater operation strategies, *constant temperature* strategy, *high to low varying temperature* (VT-HL) strategy, and *low to high varying temperature* (VT-LH) strategy [49]. The CT strategy requires to adjust the extraction steam to displaced points (point A and point B in Fig. 12) to maintain the feedwater outlet temperatures (point 1 and point 2 in Fig. 12) unchanged. The VT-HL strategy is to adjust the extraction steam flow rate at the highest temperature/pressure stage (point A in Fig. 12) first, while maintaining the mass flow rates at the rest stages (point B in Fig. 12) unchanged until this stage if fully displaced. In contrast, the VT-LH strategy is to adjust the extraction steam flow rate at the lowest temperature/pressure stage (point B in Fig. 12) first. Comparing with three operation strategies, it was found that Series configurations adopting CT strategy would have best annual performance. However, the findings of this paper was only for SAPG plants operated in PB mode.

5.2. Non-displaced feedwater heater operation strategies

Most studies of an SAPG plant are based on the assumption that solar thermal energy is used to displace extraction steam to high temperature/pressure FWHs. In an RRC power plant, there are often multiple

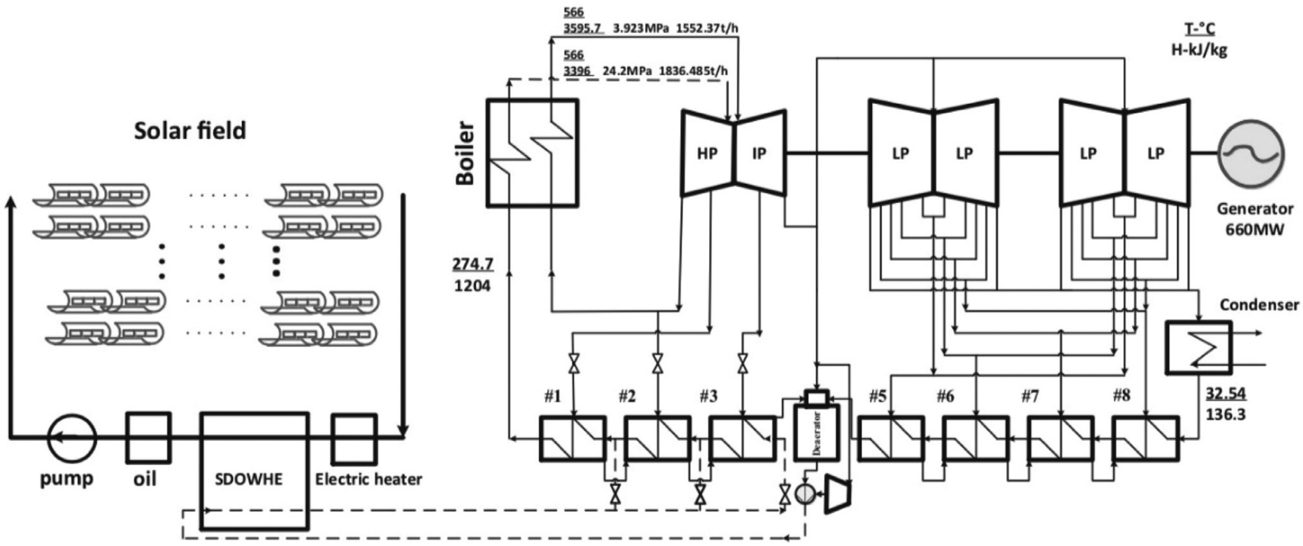

Fig. 11. A schematic diagram of an SAPG plant based on series configuration, which solar thermal energy is used to displace extraction to all high pressure/temperature FWHs [62].

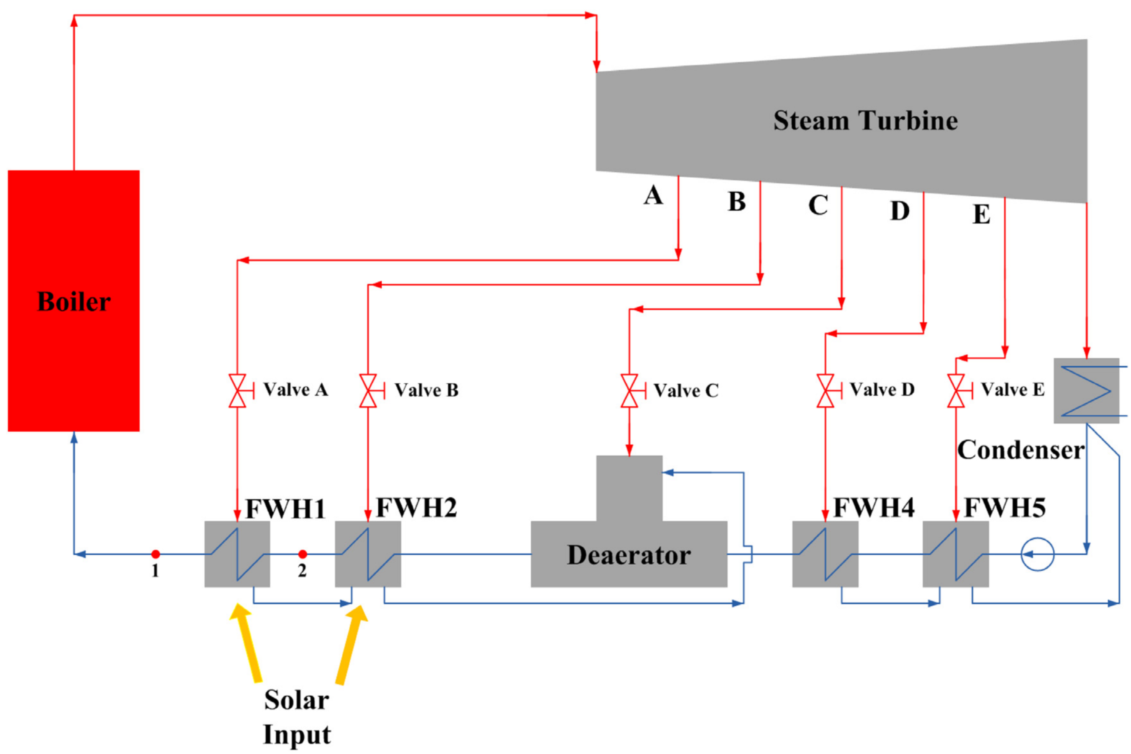

Fig. 12. A schematic diagram for demonstrating Solar Preheater operation strategies identified by Qin et al. Solar thermal energy is used to displace extraction steam to FWH1 and FWH2, the method to adjust mass flow rate of extraction steam at point A and point B is termed as Solar Preheater operation strategy by Qin et al. [49].

stages of extraction steam. In terms of the overloading of the steam turbine after the displacement of extraction steam, solar thermal energy used to displace extraction steam to all high temperature/pressure FWHs is the best option for an SAPG plant to achieve highest technical returns with same solar thermal input [57]. Under this condition, the mass flow rate of the extraction steam to all high temperature/pressure FWHs should be decreased to respond to the solar thermal input. For the low temperature/pressure FWHs, Qin et al. defined as Non-displaced FWHs, which is shown in Fig. 13 [50].

The method to adjust extraction steam to these Non-displaced FWHs is termed as Non-displaced FWH operation strategy [50]. Two Non-displaced FWH operation strategies, *constant temperature* strategy and *constant mass flow rate* (CM) strategy, have been identified by Qin et al. [50]. The CT strategy requires adjusting the mass flow rate of extraction steam to Non-displaced FWH (DEA, FWH5 to FWH8 in Fig. 13) to maintain the feedwater outlet temperature of each Non-displaced FWHs (i.e. points 7 to 10 in Fig. 13) unchanged. While, the CM strategy does not require to adjust the extraction steam flow rates (to the Non-displaced

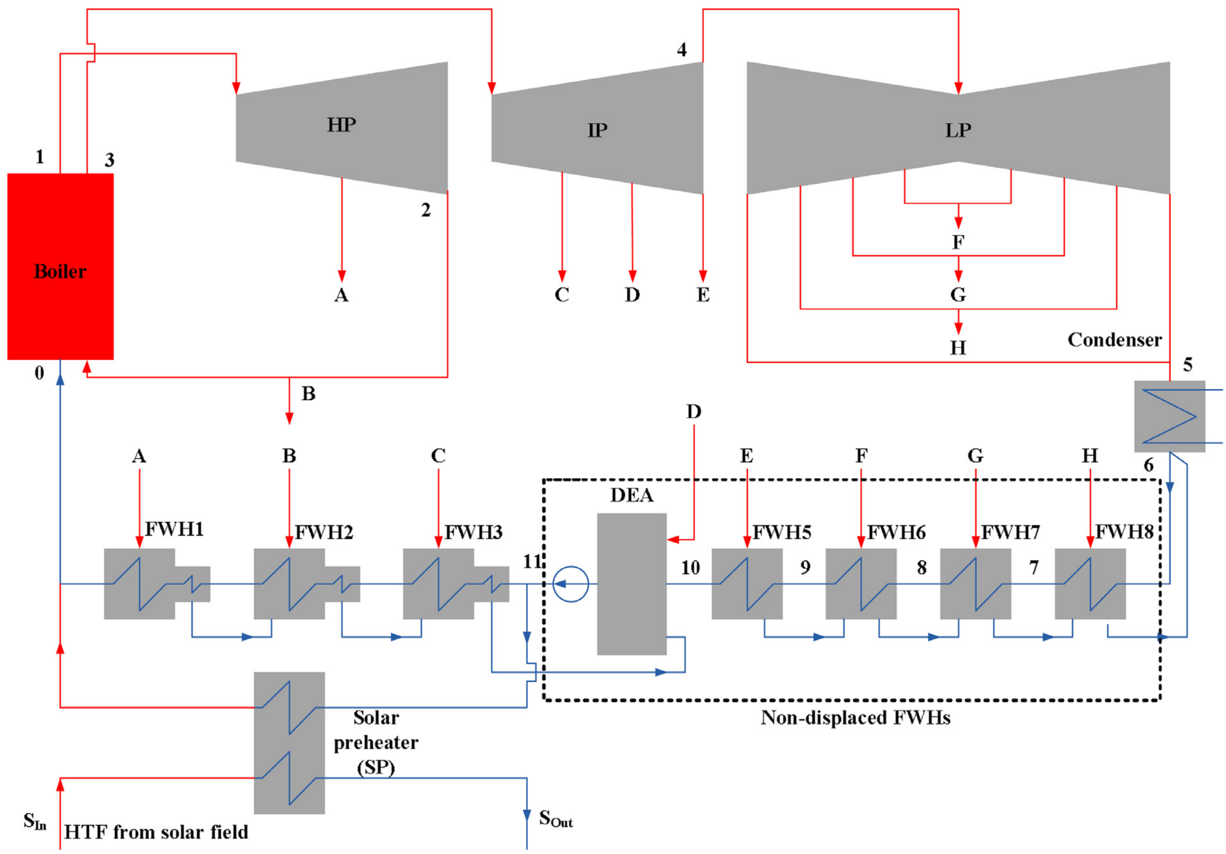

Fig. 13. A schematic diagram for demonstrating the Non-displaced FWHs, DEA, FWH5 and FWH8 are Non-displaced FWHs, and method to adjust the mass flow rate of extraction steam at points D to H is termed as Non-displaced FWH operation strategy [50].

FWHs) at all by allowing the feedwater outlet temperature of each Non-displaced FWHs (DEA, FWH5 to FWH8 in Fig. 12) to vary [50].

The Non-displaced FWH operation strategies of an SAPG plant have been overlooked by most studies. Most studies have not defined or indicated the Non-displaced FWH operation strategy that they adopted clearly. Hou et al. [60] evaluated the performance of an SAPG plant operated in FS mode based on the CT Non-displaced FWH operation strategy. Hou et al. [60] pointed that the mass flow rate of the extraction steam to non-displaced FWHs would increase after the solar thermal input, even for the SAPG plant operated in the FS mode. Yang et al. [36]. evaluated the performance of an SAPG plant operated in PB and FS modes based on the CM strategy. However, the impact of the CT or CM Non-displaced operation strategies on the performance of an SAPG plant and the comparison between two strategies have not been analysed.

Qin et al. [50] evaluated the impact of the Non-displaced FWH operation strategies on an SAPG's performance. The instantaneous and annual performance of the SAPG plant adopting CT and CM operation strategies with different solar collector areas have been evaluated and compared. A 300 MW Rankine cycle power plant is used as case study. The annual hourly solar radiation in three locations with different annual solar radiation are used for simulation. It was found that generally, the SAPG plant adopting the CT strategy produces higher annual solar power output than that adopting with the CM strategy. The difference between the SAPG plant with the CT and CM strategy decreases with the incremental solar collector area. However, the SAPG plant adopting the CM strategy could achieve higher annual solar power output, if the solar field area is oversized and the plant is located in the high solar resources area. Although Qin et al. analysed the influence of the Non-displaced operation strategy on the SAPG plant's performance, the assessment of this paper is only based on the SAPG plant operated in PB mode. The impact on the plant's performance when the SAPG plant is operated in FS mode has not been evaluated.

6. Energy analysis of the SAPG technology

The energy analysis of the SAPG technology, which is based on the 1st law of thermodynamics show that integrating solar thermal into the RRC power plant would have impact on the whole plant's efficiency. However, results from early energy analysis varied a lot.

Some studies found that, after solar thermal input, the cycle efficiency would be increased. Hu et al. evaluated an SAPG plant modified from a 500 MW subcritical power plant [35]. It was found that when the SAPG plant operated in the PB mode, the steam cycle efficiency would increase 2.94%. Later, Suresh et al. also evaluated a 500 MW SAPG plant, which the solar thermal energy is used to for fuel saving purpose [74]. The results indicated that the cycle efficiency could increase from 35.9% to 38.4%, increased by 2.5%. Bakos and Tsechelidou found that up to 4% increase for the cycle efficiency of an SAPG plant modified from a 300 MW power plant was possible [58]. Wang et al. evaluated a 300 MW SAPG plant with different stages displacement [75]. It was also found that the cycle efficiency increase from 2% to 4%. For an 1320 MW power plant, this improvement for the cycle efficiency increased to about 6% [76]. Ye et al. found that cycle efficiency improvement for a 300 MW SAPG plant was higher than a 600 MW SAPG plant [77]. Recently, some researchers found that when solar thermal energy is used to displace extraction steam to all high pressure/temperature FWH, the improvement of cycle efficiency can achieve to about 18% [78], and to lowest pressure/temperature FWH, the improvement can also achieve to 1.4% [79].

Above results are thought to be caused by the definition of the cycle efficiency after solar thermal input. The cycle efficiency is defined as the ratio of power output to the thermal energy (from fuel) input in the boiler. This means that the solar thermal energy, which resulted extra power output or saved fuel consumption, had not been considered. Therefore, the cycle efficiency would increase after solar thermal input.

However, with another definition of cycle efficiency that is the ratio of power output to the total thermal energy inputs (i.e. both from fuel and solar heat), the cycle efficiency of an SAPG plant would be decreased after the solar integration. Zhao et al. found that for a 600 MW SAPG plant, the cycle efficiency would decrease from 41.3% to 39.3%, dropping by about 2% [80]. Based on another 600 MW SAPG plant, Zhai et al. got the conclusion that the integration of solar energy would lead to the decrease of cycle efficiency from 47.7% to 46.3% [81]. For a 330 MW SAPG plant, the decrease of cycle efficiency is found to be about 1.8% [82]. Previous studies based on an assumption that solar thermal energy is used to displace extraction to all high pressure/temperature FWHs. For another study, Popov evaluate cycle efficiency of a 200 MW SAPG plant, it was found that when the solar thermal energy is used to displace high pressure/temperature FWHs, the cycle efficiency decreases by about 0.6% [57]. However, when the solar thermal energy is used to displace low pressure/temperature FWHs, the cycle efficiency decreases by about 2.6%. This means that displacement of low pressure/temperature FWHs has higher influence than that of high pressure/temperature FWHs.

Based on the 1st law evaluation, the results indicated that the technical performance of the SAPG technology is dependent on the displacement method (i.e. which FWHs are displaced). Yan et al. [46,47], Yang et al. [36] and Ye et al. [77] pointed that the displacement of the extraction steam to higher pressure/temperature stages leads to higher technical performance, in terms of solar to power efficiency, solar share, increased power output in power boosting mode, or reduced coal consumption in fuel saving mode.

However, it was found in some cases that complete displacement of extraction steam to other extraction steam stages has highest increased power output in power boosting mode, or reduced coal consumption in fuel saving mode than that of the 1st i.e. the highest stage of extraction steam. Wang et al. found that displacement of extraction steam to second stages produces highest extra power output [83]. Some other studies found that this result also suit for the fuel saving mode [53,80]. Adibhatla et al. [84,85] and Patel et al. [86] found that displacement of all low stages extraction steam would save more fuel than that displacement of all high stages extraction steam. In another study, Suresh et al. found that for a 500 MW SAPG plant, displacement of highest stage of extraction team would have highest technical performance, while for a 660 MW SAPG plant, displacement of second stage is more beneficial [74].

There might be two reasons for this result. The first reason may be that for some power plants, the mass flow rate of extraction steam to second stage or low stages is much higher than that other stages, which have potential to produce more extra power output or reduce more fuel consumption. The second reason may be that considering the boiler's off-design performance, the displacement of highest stages extraction team leads to the change of steam flow rate in reheater [71], which would make the boiler working at off-design condition.

An SAPG plant can be operated in the PB or FS mode. Studies use different criteria to analyse the performance the SAPG plant operated in the PB and FS modes.

When the SAPG plant was operated in the PB mode, in addition to the economic criteria e.g. LCOE and payback time, Solar power output, Solar to power efficiency, and solar share have often been used to evaluate the SAPG plant's performance. The solar power output of the SAPG plant for PB mode is defined as the increased power output of steam turbine after the solar integration [13]. The solar thermal to power efficiency is defined as solar thermal output on the total solar thermal integration [13]. For the solar share or solar contribution, there are two different definitions. The first definition is defined as solar thermal input on the boiler load of the plant [13]. Another definition is the ratio of solar thermal input to the total plant thermal loads including boiler load and solar thermal input [13].

There could be two solar thermal to power efficiencies for an SAPG plant, the instantaneous solar thermal to power efficiency and annual solar thermal to power efficiency. For the instantaneous solar thermal to power efficiency, Yan et al. and Yang et al. [36,46,47] found that the displacement of higher stages of extraction steam leads to higher instantaneous efficiency. Also, the higher capacity of SAPG plant leads to higher instantaneous efficiency [87]. It was found that when the extraction steam to all high pressure/temperature stages FWHs has been displaced, the instantaneous efficiency ranges from 27% to 38% [35,69,88]. For the annual solar to power efficiency, it was found that for an SAPG plant with different solar collector area, there is an optimal annual solar thermal to power efficiency existing [56]. The reason is that the annual efficiency is limited by the mass flow rate of the displaced extraction steam. It was also found that the track mode of the solar collector also can influence the annual efficiency of the SAPG plant [68]. Beside this, Ye et al. [77] and Yan et al. [47] pointed that the annual efficiency can also be influenced by the capacity of the SAPG plant. It was found that the annual efficiency for a 300 MW SAPG plant is higher than a 600 MW SAPG plant.

For the solar share of the SAPG plant operated in the PB mode, it was found that when solar thermal energy is used to displace extraction to all high pressure stages FWHs, the annual solar share for an SAPG plant modified from RRC plant with different capacity range from 4% to 20%, which is dependent on the capacity of power plant [89,90]. Bakos et al. [58] found that with same displacement selection, the annual solar share of an SAPG plant modified from a 200 MW power plant can reach to 7.9%.

Most of studies of the SAPG plant operated in the PB mode are based on a single strategy to adjust the extraction steam. Recently, Qin et al. found that the technical performance of the SAPG plant is also dependent on the configuration of the SAPG plant and the strategies to adjust the extraction steam [49,50,87,91]. The results found that with same annual solar radiation, different strategies to adjust the extraction steam leads to different annual technical performance.

When an SAPG plant was operated in the FS mode, the Saved fuel consumption is the most widely used criterion to evaluate the performance of the FS mode. Suresh et al. evaluated the SAPG plant modified from a 500 MW subcritical and 660 MW supercritical power plant [74]. The results indicated that when all the extraction steam has been displaced by the solar thermal energy, the instantaneous fuel consumption reduction can achieve to 14% to 19%. Based on a 120 MW subcritical power plant, Suojanen et al. found that when the extraction steam to all high pressure/temperature stages has been displaced, the peak saved fuel consumption, i.e. instantaneous saved fuel consumption, can achieve to 20% [65]. With the same displacement selection, it was found that the annual fuel consumption reduction for an SAPG plant modified from a 220 MW subcritical power plant can achieve to about 14% [76]. Adibhatla and Kaushik evaluated an SAPG plant based on a 500 MW subcritical power plant [84,85]. It was found that displacement of second stage of low pressure/temperature FWHs can achieve higher annual saved fuel consumption than that displacement of first stage of low pressure/temperature FWHs.

Besides the reduction of the fuel consumption, solar contribution is another widely criterion for evaluation technical performance of the SAPG plant in FS mode. Sahoo et al. [92] found that when all the extraction steam has been displaced, the peak solar contribution for an SAPG plant based on a 5 MW biomass power plant can reach to about 80%. The solar contribution in this study was defined as solar thermal input in the total energy consumption including solar thermal integration and boiler consumption. Zhu et al. [89,90] used five methods to evaluate the solar contribution of the SAPG plant, which are taking solar heat as basis, variation of main steam as basis, coal consumption as basis, thermal economics as basis and experimental efficiency curve as basis. It was found that different method would lead to different solar contribution.

In an SAPG plant operated in the FS mode, as the power output of steam turbine remains unchanged, there is a challenge of how to define the solar thermal output for FS mode. Therefore, the solar thermal to power efficiency of the FS mode is still difficult to define. In studies by Hou et al. [48,93,94] and Wu et al. [52,61], the solar to power efficiency for the SAPG plant operated in the FS mode has been defined. In their definition, the solar power output for the FS mode is the difference between the plant's power output at a reduced boiler flow rate (in FS mode) but without any solar input. This efficiency can reach to 24% when all high pressure/temperature stages extraction steam has been displaced.

In another paper, Hou et al. [94] defined a new criterion to calculate the contribution of solar energy from exergy analysis. In this new criterion, the FWH and corresponding stage steam turbine is defined as a subsystem. The new definition of solar contribution is:

$$W_{Sol} = \frac{1}{1000} m_0 \left(e_{sol} - \sum_{i=1}^{9} e_D^i \alpha_{sol}^i \right) \eta_m \eta_g, \tag{7}$$

where, m_0 is the mass flow rate of main steam, e_{sol} is the solar exergy absorbed by feedwater, η_m is mechanical efficiency, η_g is the generator efficiency, e_D^i, is exergy destruction of subsystem i and α_{sol}^i is solar proportion in work output. It was found that the solar contribution calculated by new definition is lower than pervious definitions of Hou et al. [48].

Li et al. in another paper proposed a new definition to calculate the solar thermal to power efficiency for fuel saving mode, which is given as [54,55]:

$$\eta_{solar} = \frac{P_{SACFPP}\left(1 - \frac{Q_{SACFPP}}{Q_{CFPP}}\right)}{Q_{Sol}}, \tag{8}$$

where, P_{SACFPP} is the total power output of the SAPG plant, Q_{SACFPP} is the boiler capacity of the SAPG plant, Q_{CFPP} is the boiler capacity in a stand-alone power plant with same main steam flow rate. Results in Li et al. [54,55] indicated that the solar thermal to power efficiency calculated by this definition ranged from 20% to 26%.

7. Exergy analysis of the SAPG technology

The exergy analysis of the SAPG technology, which is based on the 2rd law of thermodynamics show that integrating solar thermal into the RRC power plant would have impact on exergy losses of power plant. The SAPG plant can both reduce the exergy losses for the RRC power plant and improve the exergy efficiency for the solar utilization. Also, the SAPG plant has exergy-economic benefit than the RRC power plant [95]. The exergy advantages of the SAPG technology come from the low grade solar thermal energy used to displace the high grade extraction steam of an RRC power plant [96,97]. The exergy advantages of the SAPG plant over the stand alone solar thermal power plant comes from the high boiler temperature of the RRC power plant and sensitive to the energy level of the solar thermal energy [98].

By integrating solar thermal energy into the RRC power plant to preheat the feedwater to boiler, it was found that the exergy losses RRC power plant and solar field would be both reduced. Gupta et al. [99,100] found that after the solar thermal input, the SAPG plant can help to reduce the exergy losses in the FWH as well. After the solar thermal input, the exergy losses in the boiler, and condenser would be reduced [101]. Peng et al. [88] found that the reduction of exergy losses for an RRC power plant is possible for power plant with different capacities of SAPG plants. Also, the exergy destruction of the SAPG plant is lower than that of the stand-alone solar thermal power plant with the same capacity [88]. However, it was also found that the exergy losses of the SAPG plant is dependent on the power plant load and displacement selection [77]. Zhai et al. evaluated the exergy performance based on an SAPG plant modified from a 600 MW supercritical power plant [81,102]. The results indicated that the largest exergy loss for an RRC power plant comes from the boiler. Without solar thermal input, the exergy loss from boiler account for about 86% of the exergy loss for an RRC power plant. After the solar thermal input, this percentage decrease to about 76%. Besides the boiler, it was also found that the second largest exergy loss for an SAPG plant occurs in the solar field [84,85]. Beside reduction the exergy loss for the RRC power plant, the SAPG plant can still reduce the exergy destruction of solar radiation exergy [73]. The reason is still caused by the reduction of exergy destruction of the extraction steam.

Some studies also evaluated the exergy efficiency of SAPG plants. Zhai et al. [81,102] found that the exergy efficiency for a 600 MW supercritical SAPG plant is about 45%, which is 3% lower than the RRC plant's exergy efficiency. The exergy efficiency of the SAPG plant in the study by Zhai et al. was defined as:

$$\eta_{exergy} = \frac{w_{output}}{E_{coal} + E_{solar}}, \tag{9}$$

where, w_{output} is the total power output of steam turbine, E_{coal} is the exergy of fuel, and E_{solar} is the exergy of solar thermal input. Zhao and Bai evaluated the exergy efficiency of an SAPG plant modified from a 600 MW subcritical power plant [80]. The result indicated that the exergy efficiency of the SAPG plant was about 39% and the RRC cycle exergy efficiency is about 40%. It was also found that with the increasing in the load of the power plant, the exergy efficiency of the SAPG plant would be increased. Compared with the stand alone solar thermal power plant, Zhu et al. found that the exergy efficiency of a 100 MW SAPG plant is about 1.8% higher than that of the stand-alone solar thermal power plant with same capacity [103,104].

8. Economics of the SAPG technology

Evaluation criterion is important for the economics of the SAPG technology. Most studies used the LCOE as the economic criterion, when designing an SAPG plant or comparing it with other power plants. An SAPG plant can be operated in the PB or FS mode which leads to different LCOE, it was found that the LCOE of an SAPG plant operated in the PB mode is lower than that of the same plant operated in the FS mode [58]. Comparing with the stand-alone solar power plant, the SAPG plant operated both in the PB and FS mode would has lower LCOE than the stand-alone solar power plant [23,88,105,106]. However, the LCOE for an SAPG plant is higher than an RRC power plant if the same power output has been generated [107], the increased LCOE is caused by the capital cost of the solar field or heat exchangers.

The LCOE of an SAPG plant depends on many factors, such as annual solar radiation [48], solar field area [108,109], solar multiple [110,111], integration method [75,83], and heat exchanger area [112]. In studies by Hou et al. and Wu et al., it was found that there is an optimal aperture area for an SAPG plant to achieve the lowest LCOE. This optimal aperture area is dependent on the annual direct normal irradiance (DNI) [48,82,60], solar storage capacity [52,53,61], and capacity of the power plant [71]. Zhao et al. pointed out that the SAPG plant modified from RRC power plant with higher capacity can achieve lower LCOE [110]. Later, Zhao et al. found that there is an optimal solar multiple to achieve lowest LCOE and the government need to offer feed-in-tariff for the SAPG plant [97,110,111,113]. Zhong et al. found that there is a minimum LCOE for an SAPG plant with different SP heat exchanger area [112].

Recently, it was found that the LCOE can also be influenced by some financial factors. Wang et al. found that the Carbon tax still has impact on the LCOE of the SAPG plant [75]. The LCOE of the SAPG plant with CO_2 capture is more sensitive with the variation of carbon tax than that without the CO_2 capture. In another study, Adibhatla et al. made a sensitivity analysis to found out the sensitivity of the LCOE with variation of discount rate, plant capacity and fuel cost [84].

Few studies looked into the capital cost of the SAPG plant closely, however pointed that the investment costs for solar field and related infrastructure are still high, but not prohibitive [31]. Comparing with the stand-alone solar power plant, investment cost of an SAPG plant is about 25% lower than the same capacity stand-alone solar power plant [114]. The solar multiple has an impact on the capital cost of the SAPG plant, it was found that the capital cost increase with the incremental in solar multiple [113].

There were also some studies evaluated the profitability of an SAPG plant. Zhai et al. found that with different solar storage capacity, solar field area, displacement options and plant capacity, an SAPG plant can achieve different annual profitability, and there is an optimal condition to achieve the highest annual profitability [63]. However, this study is based on the SAPG plant operated in the FS mode only. Qin et al. proposed an operation mode which mixes the PB and FS mode. It was found that this mixed operation mode can achieve higher annual profitability than single operation mode (i.e. PB or FS mode) [51].

9. Storage system used in the SAPG technology

In the early studies of the SAPG plant, Hu et al. pointed that the solar thermal storage system is not necessary for an SAPG plant [22]. The reason is that the solar contribution and power demand are peak at the same time. However, later studies still evaluated the benefit and the function of the solar thermal storage system used in the SAPG plant.

Zhai et al. [64] discussed whether the storage system is needed for an SAPG plant and evaluated the relevant storage capacity. In this study, a concept named coal saving in solar unit investment per hour has been proposed as the evaluation criteria. This criteria is defined as the annual amount of saved coal consumption per investment for solar collectors. The results indicate that the thermal storage system can help to reduce the coal consumption of the SAPG plant. However, with a given storage capacity, there is a maximum value for the coal saving in solar unit investment per hour with different solar collectors area. In other studies, Zhai et al. pointed that the storage system can help to improve the annual saved fuel consumption per solar collector investment [63,115,116].

Wu et al. [61] discussed an SAPG plant with a storage system. The results indicated that there is a threshold aperture area for an SAPG plant with storage system. When the solar field aperture area is larger than the threshold aperture area, the SAPG plant with different storage capacity has same technical performance. From economic point of view, the SAPG plant with thermal energy storage capacity at 0.5 h has lowest LCOE. Later, Wu et al. [52] pointed that the solar thermal storage system can not only be used to increase the annual solar generation but also improve the annual solar to electricity efficiency. However, the optimised capacity of the solar thermal storage system is determined by the cost of the solar field and the storage system. A balance point is proposed by Wu et al. to determine on the conditions to set a storage system.

In an SAPG plant, there is maximum value of solar thermal input existing, which is the amount of solar thermal energy input is just enough to displace all extraction steams. For SAPG plants without storage system, if the solar thermal input was greater than the maximum value of solar thermal input, the extra solar thermal energy would have to be dumped. For SAPG plants with a storage system, the storage system could be used to store the extra solar thermal energy. Therefore, that the storage system can help to increase the annual saved fuel consumption or annual power output of the SAPG plant [61].

10. Summary and further research on SAPG

This paper reviews the researches on the Solar Aided Power Generation (SAPG) technology and plants. An SAPG plant is a solar hybrid power system in which low grade solar thermal energy is used to displace the high grade heat of the extraction steam in a regenerative Rankine cycle (RRC) power plant. In such a SAPG plant, the solar thermal energy carried by the heat transfer fluid (HTF) is integrated into the RRC power plant to preheat the feedwater to the boiler. The heat of the extraction steam which is bled from the steam turbine to preheat the feedwater is displaced by the solar thermal energy. The displaced extraction steam is then expended further in the steam turbine.

The studies of the SAPG plant mainly focused on identifying the technical and economic advantages of the SAPG plant over other power generation technologies (e.g. solar alone power generation), designing and optimising the design of the SAPG plant. Recently, a few studies refer to the plant configuration, especially the arrangement to connect the solar field and the RRC power plant, and the operation of the SAPG plant. While the potential benefits of the SAPG technology are significant, there is no operating SAPG plants existing in the world yet. Further research and technology development regarding SAPG are still required:

- The different strategies to adjust the extraction steam's flow rate have great impact on the SAPG plant's performance. The plant's performance is also influenced by the plant's configuration to connect the solar field and the RRC power plant. However, most previous studies did not mention the operation strategies and configurations they adopted. Further studies for the SAPG plant is to deeply assess the influence of different operation strategies and configuration on SAPG plant's performance. Also, whether there are other configurations and operation strategies for the SAPG plant is still needed to be demonstrated.
- An SAPG plant can be operated in Power Boosting (PB) or Fuel Saving (FS) modes. As the SAPG plant is operated under variable electricity on-grid tariffs and fuel prices, an SAPG plant operated in PB or FS modes for a whole year would achieve a different annual profitability. Mixing the PB and FS modes may achieve greater annual economic returns for the SAPG plant. However, previous studies are based on a single mode of operation, the knowledge of how to switch between PB and FS modes to achieve greater annual economic returns is lack of study.
- In an SAPG plant, the RRC plant i.e. the boiler, steam turbine, condenser and FWH system, is actually operated under off-design conditions when the solar thermal energy is integrated into the plant. The simulation models of most existing studies only consider the off-design condition for the steam turbine. Few previous studies considered the off-design condition for both the steam turbine and the boiler. In addition, the off-design condition for the condenser has not been considered at all in previous studies. A simulation model comprising off-design condition for the boiler, steam turbine, condenser and FWH system could help to evaluate an SAPG plant's performance more accurately.
- One of advantages of an SAPG plant is that the thermal storage is not necessary, as the coal (or other fuel) in the RCC plant is actually the storage to ensure the plant power output steady all the time. However, as solar radiation varies all the time, from the practical control/operation of an SAPG plant point of view, it is necessary for an SAPG plant to have "buffer tanks". Buffer tanks are storage tanks for HTF, which are used to store enough hot THF to make the SAPPG plant run steadily for a time interval eg. 1 h in order to avoid too frequent control/adjust of valves in the plant. In other words, only one adjustment/control every time interval is required, even solar radiation may vary continuously. The function of the "buffer tanks" is different from storage tanks that are to store extra/surplus solar energy to be used when there is no or less solar available and require to have enlarged solar field to produce the extra/surplus solar heat. The buffer tanks however are to be used to stabilize the plant operation i.e. reduce the operation of valve or (steam) flows control if solar radiant keeps varying. The concept of the buffer tanks has been proposed by the authors, but no further study has been undertaken yet.
- Daily start-up and shut-down process is necessary for the operation of an SAPG plant. However, these processes have never been

simulated before and thus their impact on SAPG plant performance remain unknown. Therefore, a dynamic simulation model which can evaluate the start-up and shut-down process for the SAPG plant is required. With this model, the true benefits of the SAPG technology and the start-up and shut-down losses can be assessed.

Declaration of Competing Interest

None.

Acknowledgment

The authors gratefully acknowledge the support of the National Natural Science Foundation of China (Grant no. 51875332).

References

[1] U.S. Energy Information Administration, International Energy Outlook 2016, U.S. Energy Information Administration, Washington, DC, 2016.
[2] International Energy Agency, World Energy Outlook 2016, OECD/IEA, Paris, 2016.
[3] The World Bank, Electricity Production from Coal Sources (% of Total), The World Bank, 2014 [Online]. Available http://data.worldbank.org/indicator/EG.ELC.COAL.ZS Accessed 30 December 2016.
[4] J. Figueroa, T. Fout, S. Plasynski, H. Mcllvired, R. Srivastava, Int. J. Greenh. Gas Control 2 (2008) 9–20.
[5] C. Authority, Reducing Australia's Greenhouse Gas Emissions: Targets and Progress Review-Final Report, Australia Government, Climate Change Authority, Melbourne, 2014.
[6] Renewable Energy Policy Network, Renewable Global Status Report 2016, REN21, Paris, 2016.
[7] M. Jamel, A.A. Rahman, A. Shamsuddin, Renew. Sustain. Energy Rev. 20 (2013) 71–81.
[8] M. Gupta, S. Kaushik, K. Ranjan, N. Panwar, V.S. Reddy, S. Tyagi, Renw. Sustain. Energy Rev. 50 (2015) 567–582.
[9] K.M. Powell, K. Rashid, K. Ellingwood, J. Tuttle, B.D. Iverson, Renew. Sustain. Energy Rev. 80 (2017) 215–237.
[10] S. Pramanik, R. Ravikrishna, Appl. Therm. Eng. 127 (2017) 602–637.
[11] S.K. Sansaniwal, V. Sharma, J. Mathur, Renew. Sustain. Energy Rev. 82 (2018) 1576–1601.
[12] G.J. Kolb, Sol. Energy 62 (1998) 51–61.
[13] E. Hu, G. Nathan, D. Battye, G. Perignon, A. Nishimura, in: Proceedings of the Chemeca 2010: Engineering at the Edge, Adelaide, South Australia, Australia, 2010.
[14] E. Hu, Y. Yang, A. Nishimura, Thermal Power Plants, InTech, 2012.
[15] G. Nathan, M. Jafarian, B. Dally, W. Saw, P. Ashman, E. Hu, A. Steinfeld, Prog. Energy Combust. Sci. 64 (2018) 4–28.
[16] L. Griffith, H. Brandt, Sol. Energy 33 (1984) 265–276.
[17] E. Hu, C. Baziotopoulos, Solar 29 (2000) 570–574.
[18] Y. Ying, E.J. Hu, Appl. Therm. Eng. 19 (1999) 1173–1180.
[19] R. Zoschak, S. Wu, Sol. Energy 17 (1975) 297–305.
[20] H. Bloomfield and J. Calogeras, Technical and economic feasibility study of solar/fossil hybrid power systems, NASA report, NASA TM 73820, 1977.
[21] USA Office of Energy Conservation, Technical and economic feasibility of solar augmentation for boiler feedwater heating in steam-electric power plants, 1976.
[22] E. Hu, Y. Yang, A. Nishimura, F. Yilmaz, A. Kouzani, Appl. Energy 87 (2010) 2881–2885.
[23] E.K. Burin, T. Vogel, S. Multhaupt, A. Thelen, G. Oeljeklaus, K. Gorner, E. Bazzo, Energy 117 (2016) 416–428.
[24] K. Reddy, V.A. Devaraj, J. Fundam. Renew. Energy Appl. 2 (2012) 1–6.
[25] Y. Yang, Y. Cui, H. Hou, X. Guo, Z. Yang, N. Wang, Sci. China Ser. E Technol. Sci. 51 (2008) 1211–1221.
[26] Y. Cui, Y. Yang, J. Chen, in: Proceedings of the Challenges of Power Engineering and Environment, 2007.
[27] S. Pramanik, R. Ravikrishna, Appl. Therm. Eng. 127 (2017) 602–637.
[28] S. Deng, J. Sol. Energy Eng. 136 (2014).
[29] M. Jamel, A. Rahman, A. Shamsuddin, Renew. Sustain. Energy Rev. 20 (2013) 71–81.
[30] M. ZekiYilmazoglu, A. Durmaz, D. Baker, Energy Convers. Manag. 64 (2012) 232–237.
[31] M.P. Petrov, M. Salomon Popa, T.H. Fransson, in: Proceedings of the World Renewable Energy Forum, WREF 2012, Including World Renewable Energy Congress XII and Colorado Renewable Society (CRES) Annual Conference, American Solar Energy Society, 2012.
[32] S.D. Odeh, Renew. Energy 28 (2003) 755–767.
[33] S. Odeh, M. Behnia, G. Morrison, Energy Convers. Manag. 44 (2003) 2425–2443.
[34] Y. You, E.J. Hu, R. Beebe, in: Proceedings of the 1997 Joint Power Generation Conference, 1997.
[35] E. Hu, D.R. Mills, G.L. Morrison, P. LeLievre, in: Proceedings of the International Solar Energy Congress, 2003.
[36] Y. Yang, Q. Yan, R. Zhai, A. Kouzani, E. Hu, Appl. Therm. Eng. 31 (2011) 157–162.
[37] N. O'Connell, P. Pinson, H. Madsen, M. O'Malley, Renew. Sustain. Energy Rev. 39 (2014) 686–699.
[38] J. Qin, E. Hu, G.J. Nathan, L. Chen, Energy Convers. Manag. 152 (2017) 281–290.
[39] M. Bruhn, Energy 27 (2002) 329–346.
[40] J. Buchta, in: Proceedings of the IEEE International Conference on Industrial Technology, ICIT 2009, 2009.
[41] D. Battye, P. Ashman, G. Nathan, in: Proceedings of the Australian Geothermal Conference 2010, 2010.
[42] B.-G. Aleksandra, Geothemics 39 (2010) 170–176.
[43] J. Buchta, A. Wawszczak, in: Proceedings of the IEEE Electric Power and Energy Conference (EPEC), 2010, 2010.
[44] C. Zhou, E. Doroodchi, B. Moghtaderi, Energy Convers. Manag. 82 (2014) 283–300.
[45] Q. Liu, L. Shang, Y. Duan, Appl. Energy 162 (2016) 149–162.
[46] Q. Yan, Y. Yang, A. Nishimura, A. Kouzani, E. Hu, Energy Fuels 24 (2010) 3733–3738.
[47] Q. Yan, E. Hu, Y. Yang, R. Zhai, Int. J. Energy Res. 35 (2011) 909–922.
[48] H. Hou, Z. Yu, Y. Yang, S. Chen, N. Luo, J. Wu, Appl. Energy 112 (2013) 710–718.
[49] J. Qin, E. Hu, G.J. Nathan, Energy Convers. Manag. 124 (2016) 155–167.
[50] J. Qin, E. Hu, G.J. Nathan, Energy Convers. Manag. 135 (2017) 1–8.
[51] J. Qin, H. Eric, G.J. Nathan, L. Chen, Appl. Therm. Eng. 139 (2018) 177–186.
[52] J. Wu, H. Hou, Y. Yang, Appl. Therm. Eng. 104 (2016) 319–332.
[53] J. Wu, H. Hou, Y. Yang, Energy Convers. Manag. 126 (2016) 774–789.
[54] J. Li, X. Yu, J. Wang, S. Huang, Appl. Therm. Eng. 106 (2016) 613–624.
[55] J. Li, Z. Wu, K. Zeng, G. Flamant, A. Ding, J. Wang, Energy Convers. Manag. 150 (2017) 714–724.
[56] C. Huang, H. Hou, E. Hu, M. Liang, Y. Yang, Energy 139 (2017) 667–679.
[57] D. Popov, Sol. Energy 85 (2011) 344–349.
[58] G. Bakos, C. Tsechelidou, Renew. Energy 60 (2013) 540–547.
[59] A. Alam, M.A. Siddiqui, N. ur Rehman, J. Mech. Sci. Technol. 31 (2017) 3573–3580.
[60] H. Hou, J. Wu, Y. Yang, E. Hu, S. Chen, Appl. Energy 160 (2015) 873–881.
[61] J. Wu, H. Hou, Y. Yang, E. Hu, Appl. Energy 157 (2015) 123–133.
[62] R. Zhai, M. Zhao, C. Li, Y. Chen, Y. Yang, Energy Procedia 75 (2015) 479–484.
[63] R. Zhai, M. Zhao, C. Li, P. Peng, Y. Yang, Int. J. Photoenergy (2015).
[64] R. Zhai, M. Zhao, K. Tan, Y. Yang, Appl. Energy 146 (2015) 328–334.
[65] S. Suojanen, E. Hakkarainen, M. Tahtinen, T. Sihvonen, Energy Convers. Manag. 134 (2017) 327–339.
[66] B. Pai, Sadhana 16 (1991) 59–74.
[67] H. Hong, S. Peng, H. Zhang, J. Sun, H. Jin, Energy 128 (2017) 830–838.
[68] S. Peng, H. Hong, H. Jin, Z. Zhang, Sol. Energy 98 (2013) 492–502.
[69] S. Peng, H. Hong, Y. Wang, Z. Wang, H. Jin, Appl. Energy 130 (2014) 500–509.
[70] L. Zhou, Y. Li, E. Hu, J. Qin, Y. Yang, Appl. Therm. Eng. 75 (2015) 685–691.
[71] J. Wu, H. Hou, Y. Yang, Energy Procedia 61 (2014) 791–794.
[72] Y. Zhao, H. Hong, H. Jin, Appl. Therm. Eng. 73 (2014) 577–587.
[73] Y. Zhao, H. Hong, H. Jin, Energy 74 (2014) 78–87.
[74] M. Suresh, K. Reddy, A.K. Kolar, Energy Sustain. Dev. 14 (2010) 267–279.
[75] F. Wang, H. Li, J. Zhao, S. Deng, J. Yan, Energy Convers. Manag. 112 (2016) 459–469.
[76] M. Sulaiman, M. Waheed, B. Adewunmi, O. Alamu, Int. Energy J. 16 (2016) 167–176.
[77] X. Ye, J. Wang, C. Li, Energy 113 (2016) 966–979.
[78] G. Ahmadi, D. Toghraie, O.A. Akbari, Renew. Sustain. Energy Rev. 77 (2017) 475–485.
[79] H. Chen, H. Zhang, Y. Bu, H. Liu, X. Zhang, Int. J. Energy Res. 42 (2017) 863–876.
[80] H. Zhao, Y. Bai, Int. J. Energy Res. 38 (2014) 1446–1456.
[81] R. Zhai, Y. Zhu, Y. Yang, K. Tan, E. Hu, Entropy 15 (2013) 1014–1034.
[82] H. Hou, M. Wang, Y. Yang, S. Chen, E. Hu, Sci. China Technol. Sci. 59 (2015) 1–8.
[83] Y. Wang, J. Xu, Z. Chen, H. Cao, B. Zhang, Appl. Therm. Eng. 115 (2017) 549–557.
[84] S. Adibhatla, S. Kaushik, Sustain. Energy Technol. Assess. 21 (2017) 89–99.
[85] S. Adibhatla, S. Kaushik, Appl. Therm. Eng. 123 (2017) 340–352.
[86] V. Patel, B. Saha, K. Chatterjee, in: Proceedings of the IEEE International Conference on Power, Control and Embedded System (ICPCES), 2014, 2014.
[87] J. Qin, E. Hu, Energy Procedia 61 (2014) 1505–1510.
[88] S. Peng, Z. Wang, H. Hong, D. Xu, H. Jin, Energy Convers. Manag. 85 (2014) 848–855.
[89] Y. Zhu, R. Zhai, M. Zhao, Y. Yang, Energy Procedia 61 (2014) 1610–1613.
[90] Y. Zhu, Y. Zhu, R. Zhai, M. Zhao, Y. Yang, Q. Yan, Energy Convers. Manag. (2015).
[91] J. Qin, E. Hu, Energy Procedia 105 (2017) 149–154.
[92] U. Sahoo, R. Kumar, P. Pant, R. Chaudhary, Sol. Energy 139 (2016) 47–57.
[93] H. Hou, M. Wang, Y. Yang, S. Chen, E. Hu, Science China Technol. Sci. 59 (2016) 322–329.
[94] H. Hou, Z. Xu, Y. Yang, Appl. Energy 182 (2016) 1–8.
[95] L. Feng, H. Chen, Y. Zhou, S. Zhang, T. Yang, L. An, Energy Convers. Manag. 116 (2016) 112–119.
[96] Y. You, E.J. Hu, Appl. Therm. Eng. 22 (2002) 357–354.
[97] Y. Zhao, H. Hong, H. Jin, P. Li, Energy 133 (2017) 832–842.
[98] R. Wang, J. Sun, H. Hong, H. Jin, Energy 143 (2017) 151–167.
[99] M. Gupta, S. Kaushik, Int. J. Energy Res. 33 (2009) 593–604.
[100] M. Gupta, S. Kaushik, Renew Energy 35 (2010) 1228–1235.
[101] V.S. Reddy, S. Kaushik, S. Tyagi, Clean Technol. Environ. Policy 15 (2013) 133–145.
[102] R. Zhai, Y. Yang, Y. Zhu, D. Chen, Int. J. Photoenergy (2013).
[103] Y. Zhu, R. Zhai, J. Qi, Y. Yang, M. Reyes-Belmonte, M. Romero, Q. Yan, Energy 119 (2017) 662–674.
[104] Y. Zhu, R. Zhai, Y. Yang, M.A. Reyes-Belmonte, Energies 10 (2017).
[105] H. Hong, S. Peng, Y. Zhao, Q. Liu, H. Jin, Energy Procedia 49 (2014) 1777–1783.

[106] E.K. Burin, L. Buranello, P.L. Giudice, T. Vogel, K. Gorner, E. Bazzo, Appl. Energy 154 (2015) 232–241.
[107] W. Van Rooy, C. Storm, in: Proceedings of the Third Southern African Solar Energy Conference, South Africa, 2015.
[108] H. Hou, Y. Yang, E. Hu, J. Song, C. Dong, J. Mao, Science China Technological Sciences 54 (2011) 1455–1461.
[109] H. Hou, J. Mao, Y. Yang, N. Luo, Int. J. Energy Eng. 2 (2012) 137–142.
[110] Y. Zhao, H. Hong, H. Jin, Energy Procedia 75 (2015) 457–461.
[111] Y. Zhao, H. Hong, H. Jin, Appl. Therm. Eng. 108 (2016) 378–387.
[112] W. Zhong, X. Chen, Y. Zhou, Y. Wu, C. Lopez, Sol. Energy 150 (2017) 437–446.
[113] Y. Zhao, H. Hong, H. Jin, Appl. Energy 185 (2017) 1162–1172.
[114] W. Pierce, P. Gauche, T. v. Backstorm, A.C. Brent, A. Tadros, Appl. Therm. Eng. 61 (2013) 657–662.
[115] R. Zhai, C. Li, Y. Chen, Y. Yang, K. Patchigolla, J.E. Oakey, Energy Convers. Manag. 111 (2016) 453–465.
[116] R. Zhai, H. Liu, C. Li, M. Zhao, Y. Yang, Energy 102 (2016) 375–387.