Study on Configuration and Operation Strategies of Solar Aided Power Generation Plant

PhD Thesis

By

Ji Yun Qin

School of Mechanical Engineering

Faculty of Engineering, Computer and Mathematical Sciences

The University of Adelaide

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Executive Summary

This thesis presents the outcomes of a study on the impact of configuration and operation strategies on the techno-economic performance of a Solar Aided Power Generation (SAPG) plant. An SAPG plant is a solar thermal hybrid power system. In such a power system, the solar thermal energy is used to displace the heat of the extraction steam in a regenerative Rankine cycle (RRC) power plant to preheat the feedwater to the boiler. The displaced extraction steam can, therefore, expand further in a steam turbine to generate power.

The research and development of SAPG technology started in the 1990s. However, previous studies mainly focus on identifying the advantages of SAPG technology, design and optimising the design of the SAPG plants, and comparing the economic performance of SAPG performance with other power generation technologies (e.g. solar alone power generation). Few studies on the operation of SAPG plants have been undertaken before. There are, therefore, four research questions that remain to be answered:

- How many possible SAPG plant configurations to connect the RRC plant and the solar field are available, and what is the impact of combinations of these possible configurations and operation strategies on adjusting the displaced extraction steam's

flow rate on an SAPG plant's technical performance?

- Should only concentrating solar collectors be used in SAPG plants to achieve better plant performance?
- What are the impacts of the operation of non-displaced feedwater heaters on the SAPG plant's performance?
- How should an SAPG plant be operated under different market conditions in order to maximize the plant's economic returns?

Therefore, the aim of this research is to advance the use of SAPG technology from the design and optimisation stages to its operation stage by addressing the four research questions above.

A pseudo-dynamic thermodynamic and economic model has been developed, validated and used as a tool in this study. In this model, the performance of an SAPG plant is simulated at a series of time intervals (i.e. 1 hour intervals). At each time interval, it is assumed that the SAPG plant is operated in a steady state. Furthermore, this model can simulate an SAPG plant with all its proposed configurations/structures and operation strategies/modes. In addition, a criterion that can be used to evaluate the economic profitability of an SAPG plant with different operation modes has been proposed. Based on this criterion, an optimal operation mode that can maximise plant's economic profitability will be determined and adopted to operate the plant.

The main conclusions drawn from this research are:

- An SAPG plant's technical performance is dependent on the combination of the plant's configuration and operation strategies. There are 12 such combinations identified for SAPG plants. It is found that combinations 2, 5 and 8 (detailed in Chapter 3) can enable the plant to achieve the maximum annual technical performance.
- Non-concentrating solar collectors can and should be used in SAPG plants as they are superior to concentrating collectors in terms of net land based solar to power efficiency and even economics in some cases.
- The operation of non-displaced feedwater heaters (i.e. adjusting the extraction steam flow rate to the non-displaced feedwater heaters when the solar input changes) does have an impact on an SAPG plant's technical performance. It was found that a "constant temperature" operation of the non-displaced feedwater heaters is generally more effective than a "constant mass flow" operation that is, however, easier to manage. The only exception for this finding is in rich solar resources areas.
- An SAPG plant can be operated in either power boosting or fuel saving mode at any given time. Different modes would give the SAPG plant different economic benefits under given market conditions (i.e. for on-grid tariffs and fuel prices). A new criterion termed "Relative Profitability" (RP) which links the plant's profitability with its operation mode has been proposed and developed in this study. Based on this criterion, a "mixed mode" operation has been developed: at a given time interval (e.g. 1 hour) the plant should be operated in either power boosting or fuel saving mode: whichever gives the higher RP. Through case studies, it has been demonstrated that mixed mode operation could guarantee the best economic outcomes for the SAPG plants over the single (power boosting or fuel saving) mode of operation in all kinds of market conditions.

This thesis has been submitted in publication format, as it includes journal articles that have either been published or are currently under review by international, reputable journals. The four articles that have been chosen here best demonstrate the outcomes of the study and so form the main part of this thesis. Additional background information and a literature review are provided to establish the context and significance of this work.

Declarations

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, at my university or any other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide.

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Ji Yun Qin

List of Publications

Journal Paper I:

J.Y. Qin, E. Hu, G.J. Nathan, *The performance of a Solar Aided Power Generation plant with diverse "configuration-operation" combinations*, Energy Conversion and Management, 124 (2016), 155-167.

Journal Paper II:

J.Y. Qin, E. Hu, G.J. Nathan, L. Chen, *Concentrating or non-concentrating solar collectors for Solar Aided Power Generation*, Energy Conversion and Management, 152 (2017), 281-290.

Journal Paper III:

J.Y. Qin, E. Hu, G.J. Nathan, *Impact of the operation of non-displaced feedwater heaters on the performance of Solar Aided Power Generation plants*, Energy Conversion and Management, 135 (2017), 1-8.

Journal Paper IV:

J.Y. Qin, E. Hu, G.J. Nathan, L. Chen, *Mixed mode operation for the Solar Aided Power Generation*, Applied Thermal Engineering, submitted Aug 2017-Manuscript number: ATE_2017_4805.

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Lastly, I would like to extend my greatest thanks to my father, Yun Feng Qin, mother, Wei Hua Guo, and my wife, Xin Ran Huang, whose support, love and understanding throughout the course of this research has enabled me to continue working on this study. This thesis is dedicated to them.

Notation

CM	Constant mass flow rate
CT	Constant temperature
DNI	Direct normal irradiance
ET	Evacuated tube
FS	Fuel saving
FWH	Feedwater heater
HTF	Heat transfer fluid
LCOE	Levelized cost of energy
PB	Power boosting
PT	Parabolic trough
RRC	Regenerative Rankine cycle
SAPG	Solar Aided Power Generation
SP	Solar preheater
VT	Varying temperature

1 Introduction

This subject of this study is Solar Aided Power Generation (SAPG) technology. In this chapter, the concept of SAPG technology, the aims and the specific objectives of this study have been introduced.

1.1 Overview

With each country's development and improving living standards, the need for energy is predicted to grow rapidly [1]. It has been reported that the world's energy consumption will increase by 48% in the next 30 years [1]. Meanwhile, the increase in electricity demand grows more rapidly than the demand for liquid fuels, natural gas and coal [2]. Generally, electricity comes from fossil fired power plants, hydraulic power plants, and nuclear power plants. Fossil fired power plants are the most widely used choice. In 2014, about 40% of electricity was produced by coal fired power plants, while 26% of electricity came from oil and gas fired power plants [3]. It was reported by the Energy Information Administration that fossil fired power plants will increase by 27% in the next 20 years [4].

The increase in fossil fuel consumption leads to environmental problems. It has been pointed out that such an increase will lead to a global temperature rise of about 1.4 ^{o}C at the end to this century [5]. In order to prevent the negative environmental impact from greenhouse gas emissions, the use of other kinds of energy resources to generate electricity is attracting more attention. Renewable energy, such as geothermal energy, solar energy and wind energy, are receiving growing attention for electricity generation purposes. It has been reported that the percentage of renewable electricity production will increase from 6% in 2015 to 38% in 2040 [6].

From the thermodynamic point of view, the efficiency of a stand-alone solar thermal power plant is capped by the temperature of the solar thermal energy. On the other hand, fossil-fuel combustion based power plants (i.e., regenerative Rankine cycle power plants, or RRC), which are currently the backbone of electricity production, have a better efficiency as the combustion temperature is much higher. Therefore, integrating solar thermal energy into an RRC power plant is a highly efficient method of using solar thermal energy and can reduce emissions from power production [7, 8]. This hybrid power system can both reduce the carbon dioxide emissions and promote the output of a power plant [9].

A typical RRC power plant consists of the boiler, steam turbine, condenser and a feedwater heater (FWH) system. In order to integrate the solar thermal energy into an RRC power plant, the solar thermal energy is often used to preheat the working fluid of the RRC power plant [10]. There are three main options for this solar hybrid power system [11], which are given in Figure 1.1. The first option is integrating the solar thermal energy into the boiler; the second option is using the solar thermal energy to preheat the feedwater to the boiler; and the third option is to combine the previous two options. Typically, the first and third options are available for high temperature solar thermal energy (i.e., higher than 300° C), while the feedwater preheating option is suitable for medium to low temperature solar thermal energy (i.e., less than 300° C).

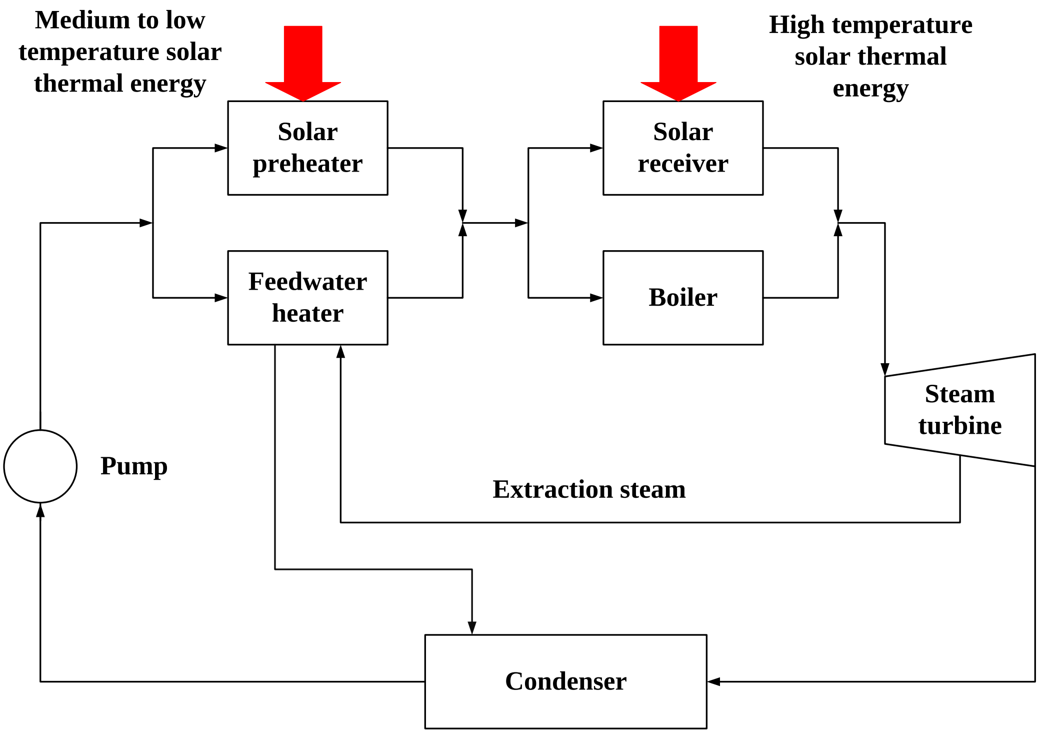

Fig. 1.1. Basic options for a solar thermal hybrid power system in which solar thermal energy is integrated into a Rankine cycle power plant.

For the first and third options of a solar hybrid power system, the solar thermal energy needs to be integrated into the boiler. Therefore, only high temperature solar collectors are suitable for these two options. In practice, solar tower collectors have often been used for these two options in previous studies [9-17]. It has been found that these two options can reduce the capital cost of a solar power system [9, 10]. Thus they have economic advantages over a stand-alone solar thermal power plant. Also, these two options can reduce the exergy losses in boilers [12, 18]. However, compared with a stand-alone solar thermal power plant, options one and three do not have obvious technical advantages [19].

For the second option of a solar hybrid power system, medium or even low temperature solar collectors can be used for power generation purposes [20]. The technical performance of this option is better than that of a stand-alone solar thermal power plant with the same solar thermal temperature [21, 22]. Also, this option has economic advantages due to lower capital costs [23, 24]. Other renewable thermal energy can also be used in this power system. Some previous studies have analysed a hybrid power system where geothermal energy is used to preheat the feedwater of a power plant [25-31]. It was found that this geothermal hybrid system has higher geothermal to power efficiency than a stand-alone geothermal thermal power plant.

Comparing the three options, it was found that integrating solar thermal energy into a boiler has a higher technical performance than that of using solar thermal energy to preheat the feedwater of an RRC power plant [32-37]. However, using solar thermal energy to preheat the feedwater of an RRC power plant has the advantage of lower capital costs [11, 38, 39]. Also, this option is easier to control and build than the other two options [41-42]. Therefore, the option of preheating the feedwater is studied in this work.

Solar Aided Power Generation 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 power plant for feedwater preheating purposes [20]. A heat exchanger system is used to connect the RRC power plant and the solar collectors. This heat exchanger is called a solar preheater (SP) and is used to facilitate the thermal energy between the heat transfer fluid (HTF) from the solar field and the feedwater of the RRC power plant. In an SAPG plant, after the solar thermal input, the mass flow rate of the extraction steam should be adjusted (i.e., displaced). Then, the displaced extraction steam expends further energy in the lower stages of the steam turbine. The technical benefit of an SAPG plant comes from this displaced extraction steam [20].

Based on the literature review of the field, the research gaps and research questions are identified (detailed in Chapter 2). Generally speaking, the R&D of SAPG technology started in 1990s. However, previous studies mainly focused on identifying the advantages of SAPG technology, designing and optimising the design of the SAPG plants, and comparing the economic performance of an SAPG's performance with other power generation technologies (e.g. solar alone power generation). Few studies on the operation of an SAPG plant have been undertaken before.

1.2 Thesis aim and objectives

The aim of this research is to advance SAPG technology from the design and optimisation stages to the plant's operation stage by addressing the gaps and research questions identified in section 2.6.

The specific objectives of the project include:

- Developing a pseudo-dynamic thermodynamic sub-models for RRC power plants and different solar collectors, respectively. After validation and integrating the sub-models, the integrated model would be able to simulate an SAPG plant with different configurations and different operation strategies.
- Using the model to compare the technical performance of an SAPG plant with various configurations and operation strategies.
- Using the model to assess the technical performance of an SAPG plant with using different types of solar collectors.
- Studying the impact of the operation of non-displaced feedwater heaters on the plant's performance.
- Proposing and developing a new technical criterion that can be used to determine the plant's operation mode.
- Based on the new criterion, proposing an operation mode that would maximise the plant's economic returns under various market conditions.

1.3 Thesis outline

This thesis consists of a portfolio of publications that are either published or submitted for publication. This thesis is presented in seven chapters, as outlined below:

Chapter 1 presents the background of the study. In this chapter, a general solar hybrid power concept has been introduced, and the SAPG system has been proposed. The aims and specific objectives of this research have been stated in this Chapter.

The previous literature in the area of SAPG technology research has been reviewed critically in Chapter 2. In this chapter, configurations, solar collectors, and operation strategies used in SAPG technology by previous studies have been summarised. In addition, the previous simulation models of SAPG plants have also been summarised. Based on the review, the gaps in the current knowledge of SAPG technologies have been identified in this chapter.

Chapter 3 is a published journal paper entitled: "The performance of a Solar Aided Power Generation plant with diverse 'configuration-operation' combinations". This paper introduces four possible SP configurations of the SAPG plant and three typical operation strategies to adjust the mass flow of displaced extraction steam when the solar thermal input changes. Based on different SP configurations and their operation strategies, an SAPG plant has 12 'configuration-operation' combinations. The instantaneous and annual technical performance of an SAPG plant with 12 combinations under the conditions of different solar collector areas have been evaluated and compared in the paper.

Chapter 4 is a published journal paper entitled: "Concentrating or non-concentrating solar collectors for Solar Aided Power Generation". This paper studies the SAPG plant's performance using medium temperature (200^o C to 300^o C) concentrating solar collectors (e.g. parabolic trough collectors) and low temperature (100^o C to 200^o C) non-concentrating solar collectors (e.g. evacuated tube collectors) in different locations.

The paper entitled “Impact of the operation of non-displaced feedwater heaters on the performance of Solar Aided Power Generation plants” has been published in *Energy Conversion and Management*, which forms Chapter 5 of the thesis. This paper identifies two possible operation strategies to adjust the extraction steam’s mass flow rate to non-displaced feedwater heaters in an SAPG plant. The impact of the non-displaced feedwater heater operation strategies on an SAPG’s performance has been evaluated in this paper. The instantaneous and annual performance of the SAPG plant adopting these two operation strategies with different solar collector areas have been evaluated and compared.

Chapter 6 is a manuscript submitted for publication in *Applied Thermal Engineering* titled: “Mixed mode operation for the Solar Aided Power Generation”. In this paper, in order to optimise the operation of the plant and maximise the economic benefits, a concept of mixed mode operation is proposed for the first time. The mixed mode operation is where the hourly operation mode (power boosting or fuel saving) is determined by the hourly Relative Profitability (RP) values calculated. In the hourly RP calculation, the local electricity and fuel markets conditions are taken into consideration to estimate the plant’s hourly profitability in both power boosting and fuel saving modes, thereby determining the optimum mode in which the plant should be operated in that hour. In this paper, the advantages of mixed mode operation have been demonstrated through two case studies.

The conclusions of the study and the recommendations for further research on SAPG technology are presented as Chapter 7.

1.4 Format

This thesis has been submitted in publication format, as it includes publications that have either been published or are currently under review. It follows the formatting requirements of the University of Adelaide. The printed and online copies of the thesis are identical. The online version is available and can be viewed with any PDF viewing software.

2 Literature Review

An SAPG plant is a solar hybrid power system that integrates solar thermal energy into an RRC power plant for solar power generation purposes. The performance of an SAPG plant is influenced by the configurations used to connect the RRC plant and the solar field, solar collectors, and the operation strategies used to adjust the extraction of steam, and the operation mode used in SAPG plants. In this chapter, previous studies of SAPG plants in terms of configuration, solar collectors used in the SAPG plant, operation strategies, operation modes, and the simulation model of an SAPG plant have been summarised.

2.1 Configurations of an SAPG plant

In an SAPG plant, in order to preheat the feedwater of an RRC power plant, a heat exchanger system is needed [20]. This heat exchanger system is termed the Solar Preheater (SP) in this study. 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. In an RRC power plant, the feedwater heater (FWH) is used to facilitate the heat exchange process between the extraction steam from the turbine and the feedwater of the 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. In this study, these configurations are called the Solar Preheater configurations.

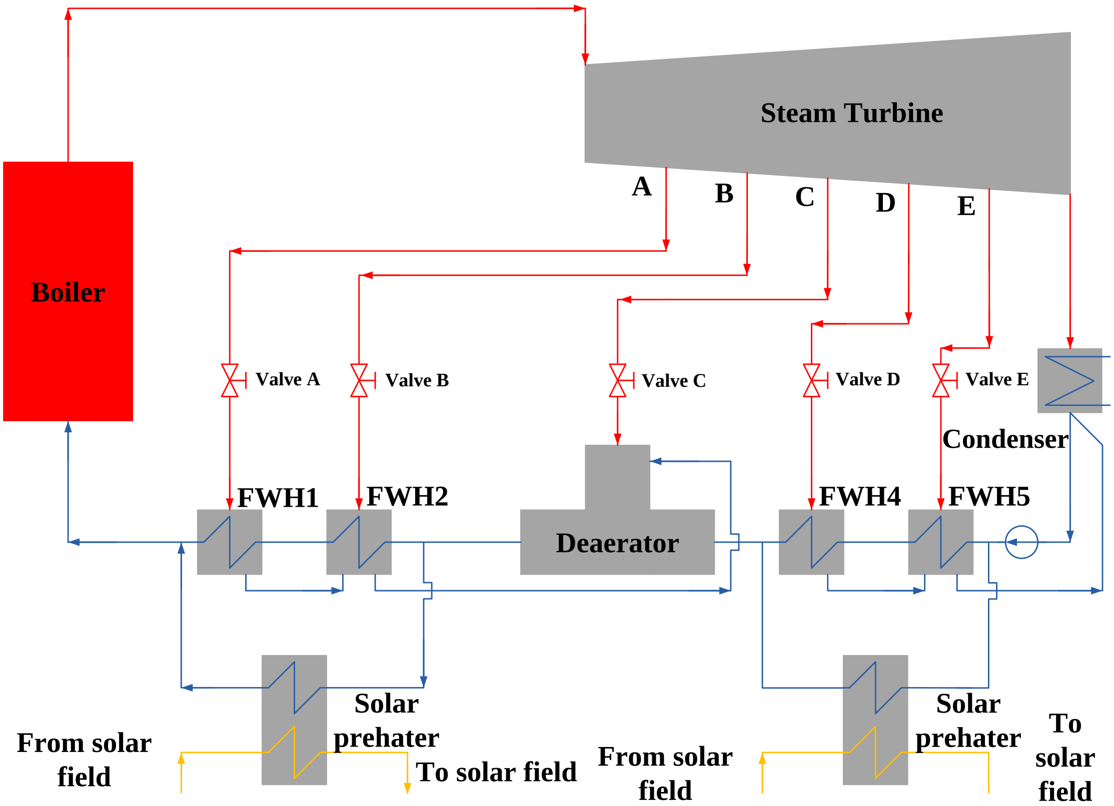

Fig. 2.1. Schematic diagram of an SAPG plant in which a solar preheater is arranged in parallel with the feedwater heater of the power plant.

One SP configuration is where the SP is arranged in parallel with the FWH of the RRC power plant. Most previous studies about the SAPG plant are based on this configuration [43-52]. In this study, this configuration is called a parallel configuration. Figure 2.1 presents a schematic diagram of the parallel configuration. As shown in Fig. 2.1, in the parallel configuration, valves (i.e., Valve A to Valve E) are used to control the mass flow rate of the feedwater flowing through the FWH and SP. In such a configuration, the mass flow rate of the feedwater entering the SP is dependent on the available solar thermal energy [45]. When the solar thermal energy level is sufficient, all the feedwater is directed to the SP system, bypassing the FWH. For the parallel configuration, as controls are required to balance the mass flow of the feedwater between the SP and the FWH system, the operation of such a configuration is relatively complex [53, 54].

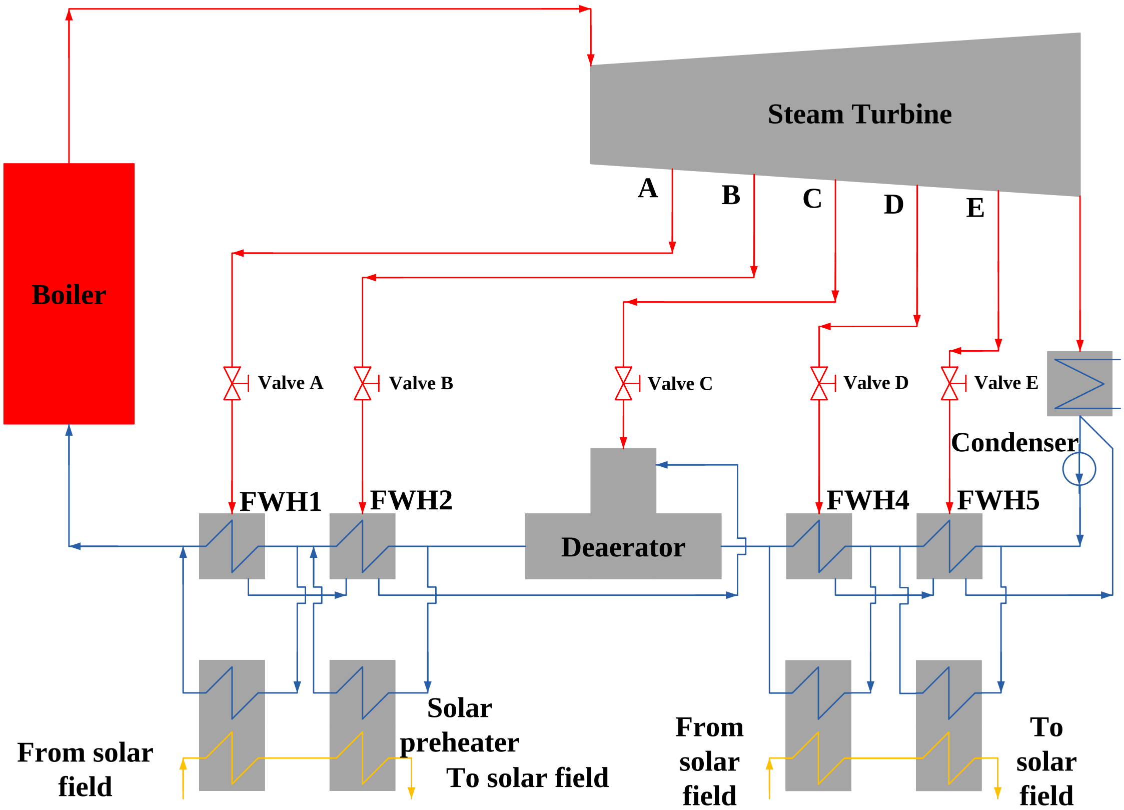

Fig. 2.2. Schematic diagram of a parallel configuration where each FWH has one parallel SP.

There are two different structures for the parallel configuration. One structure is where each FWH has one parallel SP [44, 45, 47, 55], as shown in Figure 2.2. The other structure uses one bigger SP in parallel with all the FWHs [49, 51, 52], which is shown in Figure. 2.3. Comparing the two parallel structures, the first structure is flexible in displacement with variable solar thermal temperature.

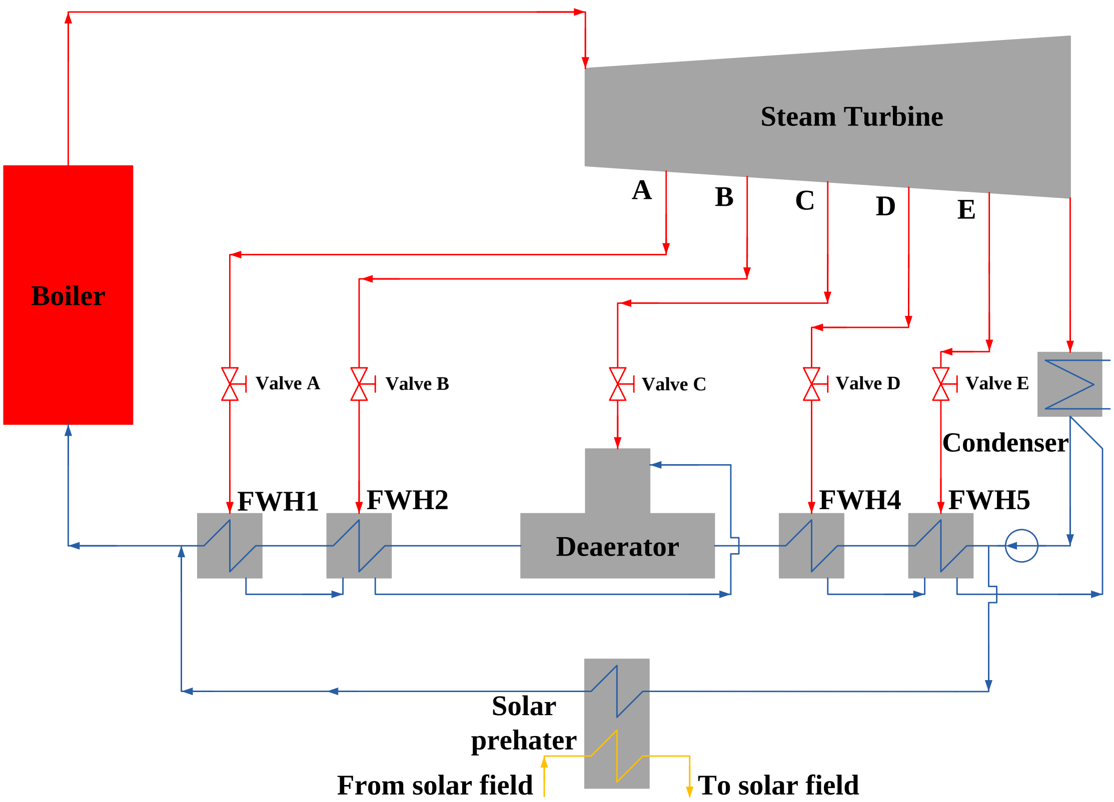

Fig. 2.3. Schematic diagram of a parallel configuration where one SP is parallel with all the FWHs.

Another SP configuration is where the SP is arranged in series with the FWH of the RRC power plant. In this study, this configuration is termed a series configuration. Some recent studies about the SAPG plant are based on this configuration [56-65]. The series configurations in these studies are given in Figure 2.4. As shown in Fig. 2.4, the SP is in series with the deaerator and the 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 [60]. As the feedwater is first preheated by the solar thermal energy, the mass flow rate of the extraction steam should be adjusted according to the solar thermal energy. 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 [53].

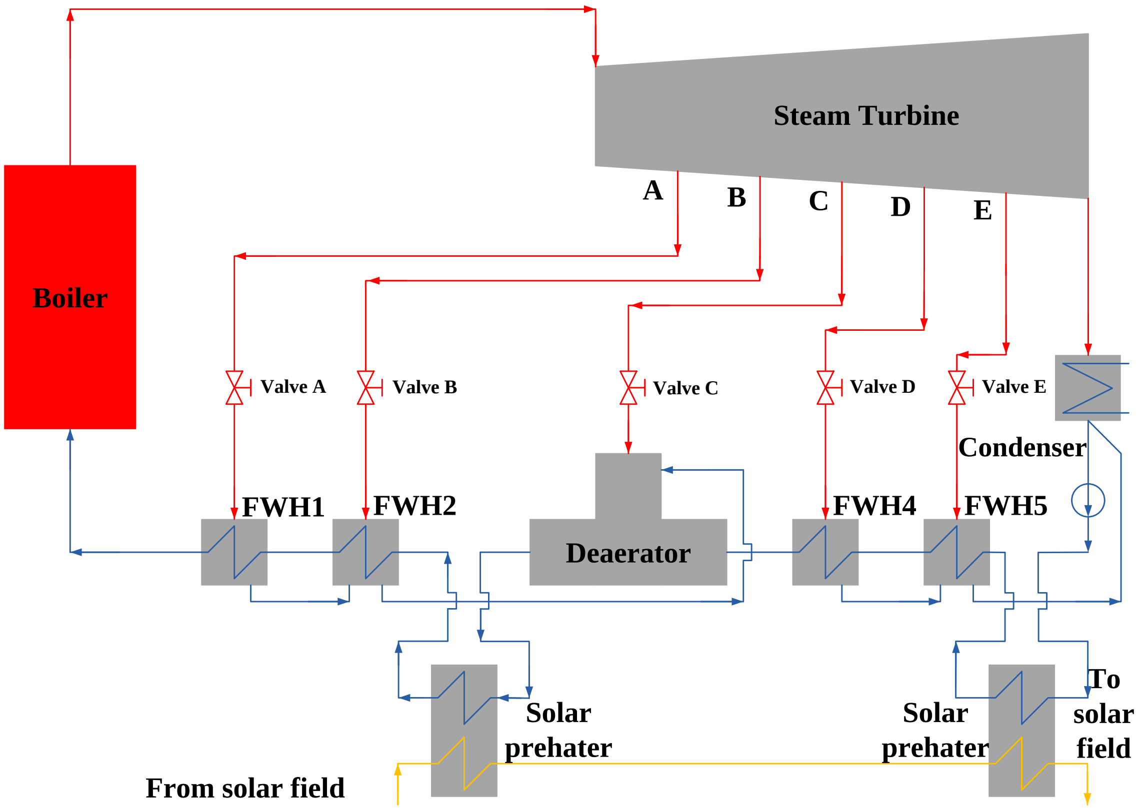

Fig. 2.4. Schematic diagram of an SAPG plant where a solar preheater is arranged in series with the feedwater heater of the power plant.

In the early studies of the SAPG plant, Pai proposed another structure of the series configuration [66]. In this structure, each FWH has one series of SP, as is shown in Figure 2.5. After the solar thermal input, the mass flow rates of the extraction steam at all extraction points should be adjusted. As it is necessary to balance the energy of all the FWHs and the SP for this structure, the operation of such a structure may be complex.

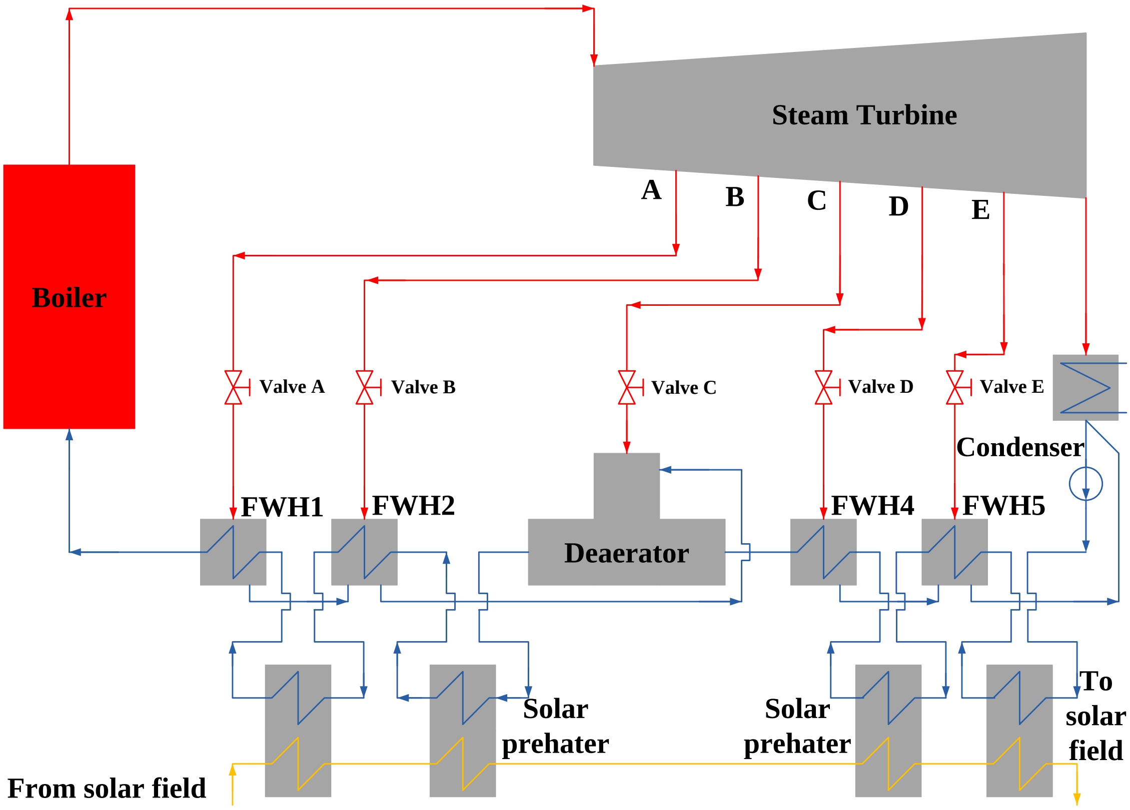

Fig. 2.5. Schematic diagram of an SAPG plant where each feedwater heater of the power plant has a series of solar preheaters [66].

From previous studies, it was found that all works were based on a single configuration of an SAPG plant, i.e. parallel or series configurations. In an SAPG plant with the same solar thermal input, different configurations might have different performances. However, an evaluation based on a single configuration cannot be used to understand the impact of different configurations on an SAPG plant's performance. Therefore, a comparison of different configurations of an SAPG plant is needed.

2.2 Low and Medium Temperature Collectors used in an SAPG Plant

In an SAPG plant, solar collectors are used to provide the solar thermal energy at the required temperature. The temperature of the solar thermal energy required is dependent on the temperature of the feedwater of the RRC power plant. Wu and Zoschak evaluated the solar hybrid system in which solar thermal energy is used to preheat the feedwater to the boiler and directly integrated into the boiler [11]. The high temperature solar collectors can be directly integrated into the boiler, while the low to medium temperature solar thermal energy can be integrated into the RRC power plant to preheat the feedwater of the power plant. Hu et al. evaluated the performance of the SAPG plant by using parabolic troughs, evacuated tubes and flat solar collectors [20]. It was found that medium temperature concentrating solar collectors (i.e., parabolic trough collectors) can be used to displace the extraction steam to high pressure/temperature FWHs, while low temperature non-concentrating solar collectors (i.e., evacuated tubes and flat collectors) can be used to displace the extraction steam to low pressure/temperature FWHs.

Medium temperature (i.e., 200^{o} C to 300^{o} C) concentrating solar collectors were the most common selection in previous studies of SAPG plants. It was found that the solar thermal energy used to displace extraction steam to all high temperature/pressure FWHs is the best operation for an SAPG plant to achieve the highest solar thermal to power efficiency [49]. This is suitable for SAPG plants operated for both power boosting and fuel saving purposes [50, 67]. Most previous studies of SAPG plants are based on this structure whereby solar thermal energy is used to displace the highest pressure/temperature stage FWH or all high pressure/temperature stage FWHs [68-77]. In an RRC power plant, the feedwater temperature of the high pressure/temperature stage FWHs ranges from 200^{o} C to 300^{o} C [78]. Therefore, parabolic trough (PT) collectors (i.e., concentrating solar collectors) are the most widely used collectors in the previous studies [49].

The performance of an SAPG plant using PT collectors is influenced by the collector area and tracking mode of the PT collectors. Peng et al. compared SAPG plants using PT collectors with a rotatable-axis tracking mode and a single-axis tracking mode [68]. It was found that an SAPG plant using the rotatable-axis tracking mode would decrease the solar collector area by 4 percent. In another paper by Peng et al, it was found that the solar field efficiency of the PT collector is impacted by the season [69]. On a typical day in summer, the solar field efficiency ranged from 65% to 70%, while on a typical day in winter, the solar field efficiency ranged from 20% to 40% [69]. Wu et al. evaluated the SAPG plant using PT collectors with North-South (N-S) dual-tracking, N-S horizontal-tracking, East-West (E-W) dual-tracking and E-W horizontal-tracking modes, respectively. The results show that PT collectors with E-W dual-tracking modes are the best option for an SAPG plant. It was also found that the N-S dual-tracking mode, E-W horizontal-tracking mode and N-S dual-tracking mode can reach 93.2%, 59.4% and 81.8%, respectively, of the E-W dual-tracking mode's annual performance [64]. Hou et al. and Wu et al. evaluated an SAPG plant using PT collectors to displace extraction steam to all high temperature/pressure FWHs and found that there is an optimum solar field area to achieve the lowest levelised cost of energy (LCOE) [59, 79]. As for the other previous studies of an SAPG plant using PT collectors, the PT collectors were only analysed as collectors to provide solar thermal energy [81-83].

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. It was pointed out that the solar thermal energy used to displace the extraction steam to low temperature/pressure FWHs has a lower efficiency than that used to displace extraction steam to high temperature/pressure FWHs [44]. However, this result did not consider the layout and collecting features of the different types of collectors. 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 [84]. 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 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. Also, in order to make a comparison of an SAPG plant using PT and ET collectors, the cost of the collectors and solar radiation also needs to be considered [85-88].

In practice, the layout of the solar collectors would also have impact on the SAPG plant's performance. However, most previous studies have not considered the impact of the layout of the solar collectors. Therefore, there is a gap in evaluating the influence of the layout of solar collectors on an SAPG plant's performance.

2.3 Operation Strategies of an SAPG Plant When Solar Radiation Changes

In an SAPG plant, the technical benefit comes from the displaced high quality thermal energy of the extraction steam [22]. An RRC power plant often has multiple stages of extraction steam. It was found that the solar thermal energy used to displace extraction steam at a higher temperature/pressure stage leads to higher technical performance [45]. Therefore, the performance of an SAPG plant is dependent on the strategies used to adjust the mass flow rate of the displaced extraction steam, according to the solar thermal input. In this study, these strategies are termed Solar Preheater Operation Strategies.

The Solar Preheater Operation Strategies of an SAPG plant have not been clearly defined by previous studies. Some previous studies are based on a *constant temperature (CT)* Solar Preheater Operation Strategy [89-92]. By using this strategy, the mass flow rate of the extraction steam at displaced extraction points should be adjusted to keep the feedwater outlet temperature of the FWHs unchanged. For different configurations, this CT strategy has different methods to adjust the mass flow rate of the displaced extraction steam. For an SAPG plant with parallel configurations, when the SAPG plant is operated with the CT strategy, the extraction steam at the displaced points is displaced simultaneously [89]. Zhao et al. studied the performance of an SAPG plant with a parallel configuration, as shown in Figure 2.6. It indicates that, after the solar thermal input, the mass flow rate of the extraction steam at points A to B should be decreased simultaneously [89]. However, for an SAPG plant with series configuration, the CT strategy has a different method for adjusting the mass flow rate. As shown in Figure 2.7, Hou et al. evaluated the performance of an SAPG plant with a series configuration, where the solar thermal energy is used to displace the high temperature/pressure extraction steam (points A to B in Fig. 2.7). This study indicates that when this configuration is operated with the CT strategy, the extraction steam would be displaced from point B to point A [59]. That is, the extraction steam is displaced stage by stage. When the solar thermal energy is integrated into the RRC power plant, the extraction steam at point B is displaced first. With the increase in solar thermal input, the extraction steam at point B is fully displaced. Then, the extraction steam at point A is displaced until it has been fully displaced at this point.

As well, the mass flow rate of the extraction steam at displaced extraction points can also be adjusted by varying the feedwater temperature outlet FWHs. This strategy is termed the *varying temperature* (VT) Solar Preheater Operation Strategy in this study. By using this strategy, the higher temperature/pressure extraction steam can be displaced first by the solar thermal energy, which leads to greater technical benefits for the SAPG plant. However, this strategy has not been proposed or studied by previous research.

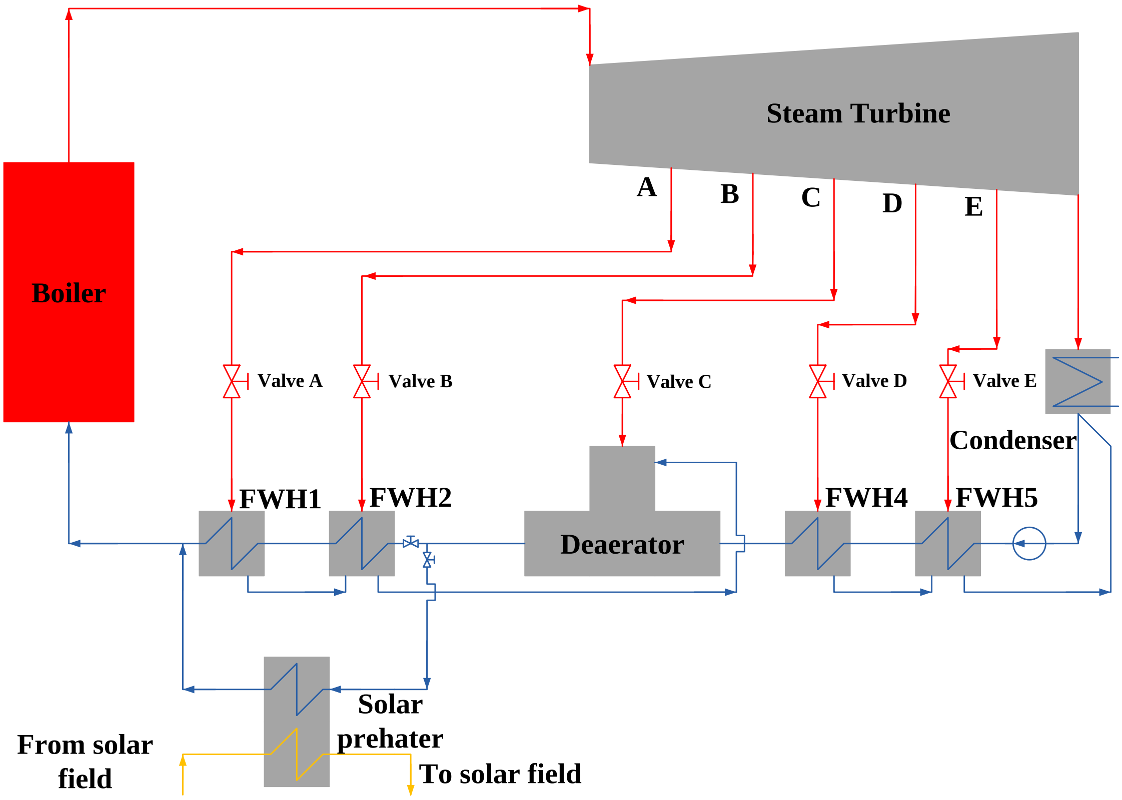

Fig. 2.6. Schematic diagram of an SAPG plant with a parallel configuration, in which the solar thermal energy is used to displace the high temperature/pressure extraction steam (points A to B).

In an SAPG plant, there are different combinations of a specific configuration (i.e., parallel or series configurations) and a Solar Preheater Operation Strategy (i.e., CT or VT strategies). This combination is termed 'configuration-operation' combinations. Previous studies of the SAPG plant are based on a single combination. The typical configuration-operation combinations for an SAPG plant need to be proposed and identified. Otherwise, as the displacement of extraction steam at different temperature/pressure stages leads to different technical performances, different combinations under the same solar resources conditions might have different technical performances. Therefore, the impact of the different configuration-operation combinations on an SAPG plant's performance need to be evaluated.

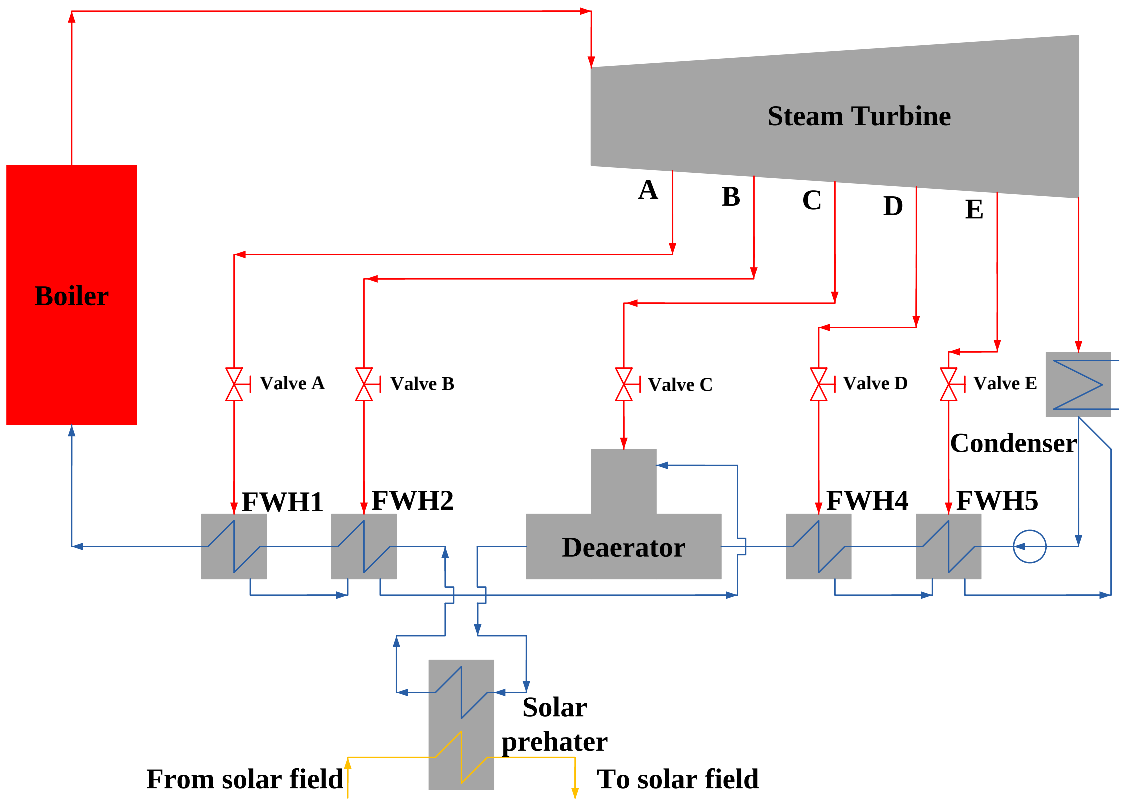

Fig. 2.7. Schematic diagram of an SAPG plant with a series configuration, in which the solar thermal energy is used to displace the high temperature/pressure extraction steam (points A to B).

Most previous 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 stages of extraction steam. In terms of the overloading of the steam turbine after the displacement of extraction steam, solar thermal energy is often used to displace part stages of extraction steam [49]. It was found that the solar thermal energy used to displace extraction steam to all high temperature/pressure FWHs is the best option for an SAPG plant [49]. Under this condition, the mass flow rate of the extraction should be decreased to respond to the solar thermal input. However, for the extraction steam to low temperature/pressure FWHs (DEA, FWH4 to FWH5 in Fig. 2.6 and Fig. 2.7), the strategies to adjust this extraction steam after the solar thermal input can still impact the SAPG plant's performance. These strategies are termed a non-displaced FWH operation strategy in this study. In Fig. 2.6 and Fig. 2.7, the DEA, FWH4 to FWH5 are termed as non-displaced FWHs.

The non-displaced FWH operation strategies of an SAPG plant have been overlooked by previous studies. Most previous studies have not clearly defined the non-displaced FWH operation strategies that they adopted. Some previous studies were based on an assumption that the feedwater outlet temperature of each non-displaced FWH remains unchanged [59]. Under this condition, the mass flow rate of the extraction steam to each non-displaced FWH increases after the solar thermal input [59]. In this study, this strategy is termed a *constant temperature* (CT) non-displaced FWH operation strategy. Besides this strategy, there is another strategy that keeps the mass flow rate of the extraction steam to each non-displaced FWH unchanged [93-97]. By using this strategy, the feedwater outlet temperature of each non-displaced FWH changes with the solar thermal input. In this study, this strategy is termed a *constant mass flow rate* (CM) non-displaced FWH operation strategy. However, for previous studies in which solar thermal energy is used to displaced extraction steam to high temperature/pressure FWHs, the non-displaced FWH operation strategy that was adopted has not been clearly defined or indicated.

For an SAPG plant, the thermodynamic benefits come from the displaced high grade extraction steam. Although the extraction steam to non-displaced FWHs would not be displaced by the solar thermal energy, the changes of this steam's mass flow rate would also have an impact on the SAPG plant's performance. However, it is obvious that the impact of the non-displaced FWH operation strategies has not been evaluated by previous studies. Therefore, a comparison of an SAPG plant operated with different non-displaced FWH operation strategies is a gap in the extant studies.

2.4 Operation Mode of an SAPG Plant

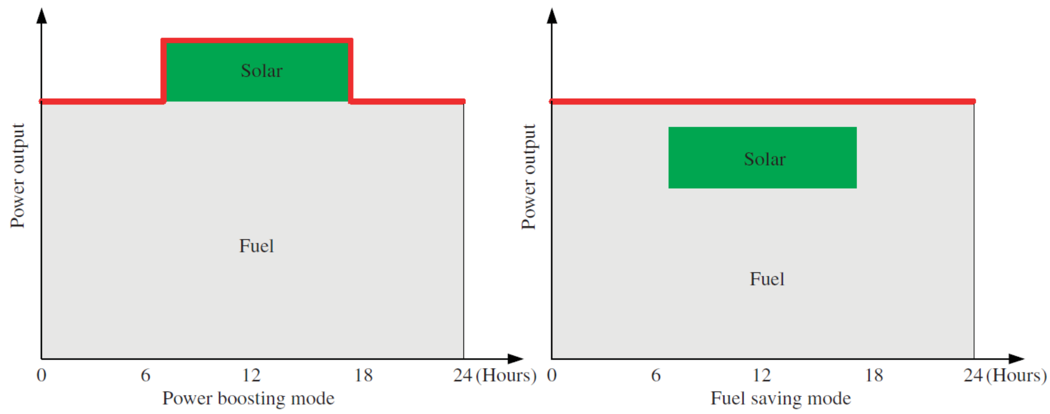

Fig. 2.8. The alternative daily "power boosting" and "fuel saving" modes for an SAPG plant [46].

An SAPG plant can be operated in two modes: a power boosting (PB) mode and a fuel saving (FS) mode [9], as illustrated in Figure 2.8. The PB mode is defined as when the solar thermal energy is being used to increase the power output of the power plant.

Under this condition, the SAPG plant is operated without changing the steam flow rates of 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 SAPG plant is operated by reducing the steam flow rates of the boiler.

The assessment of the SAPG plant in previous studies was based on a single operation mode; i.e., it was assumed to be operated always in either PB or FS mode. When an SAPG plant is operated in PB mode, the benefit of this mode comes from the increased power output. Under the condition of rising electricity on-grid tariffs, this would have great economic potential [93]. This increased power output is usually seen as the power output from solar thermal energy by previous studies. It was found that the solar thermal to power efficiency for an SAPG plant operated in PB mode is higher than the solar thermal to power efficiency for a stand-alone solar thermal power plant [24]. The solar contribution can be up to 18% for a 330 MW power plant [91, 92]. Also, the displacement of extraction steam for PB purposes can help to reduce the exergy loss in FWHs, especially for low pressure FWHs [18, 50, 96, 98]. The thermo-economic benefit of an SAPG plant is higher than a coal-fired power plant with the same power output [80]. It was also pointed out that the solar thermal to power efficiency of an SAPG plant is not capped by the solar collector's temperature [23]. When the solar thermal energy is used to displace extraction steam at different stage FWHs, the results indicate that the solar thermal energy used to displace the higher grade extraction steam leads to higher solar thermal to power efficiency and solar power output [37, 44]. Later, Popov pointed out that the displacement of extraction steam to all high pressure FWHs is the best option for power boosting purposes [49].

For the economic assessment of an SAPG plant operated in PB mode, it was found that the *levelized cost of energy* (LCOE) for an SAPG plant is about 20% to 30% lower than a stand-alone solar power plant [69, 70]. However, the LCOE for an SAPG plant is higher than an RRC power plant if the same power output has been generated [81]. The capital cost of an SAPG plant is 25% lower than the same capacity stand-alone solar power plant [52]. It was also found that there is an optimal solar field size that can help to achieve the minimum LCOE or payback time of an SAPG plant [93, 99, 100]. Also, this optimal solar field size is influenced by the local solar radiation resources and turbine operation load conditions [93, 99, 100].

Several other studies have evaluated an SAPG plant operated in FS mode. The benefit of an SAPG plant operated in FS mode comes from the saved boiler fuel consumption. This would present great potential in the face of rising fuel prices or a carbon tax [67]. Hu et al. pointed that for a 500 MW power plant, if the extraction steam to all FWHs has been fully displaced, 16% of fuel consumption could be saved [23]. For a small capacity biomass plant, peak saved fuel consumption could even achieve up to about 90% [83]. Also, as with the PB mode, the displacement of higher grade extraction steam leads to higher saved boiler fuel consumption [82]. For the FS mode, after the solar thermal input, the parameters of the working fluid (i.e., main steam, reheat steam, extraction steam, and feedwater) would all be changed [97]. It was also found that when solar thermal energy is used to displace extraction steam to each stage of the FWHs respectively, the displacement of extraction steam to the second stage of high pressure FWHs is the best displacement option to achieve the highest saved fuel consumption for an SAPG plant modified from a 500 MW subcritical power plant and a 660 MW supercritical power plant [43].

When making an economic evaluation of an SAPG plant operated in the FS mode, it was indicated that there is a 5% to 7% increase in the LCOE for an SAPG plant [43]. In the previous 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), solar storage capacity, and capacity of the power plant [59, 64]. Zhai et al. optimised the operation of an SAPG plant in a series of conditions based on the FS mode. It was found that with a 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 [71, 77].

Few previous studies compared an SAPG plant operated in PB and FS modes, respectively. It was found that when the extraction steam has been fully displaced by the solar thermal energy, more solar thermal energy is needed for the PB mode than the FS mode [44, 46]. Bakos made a comparison of an SAPG plant's LCOE between PB and FS modes [51]. It was found that the LCOE of the SAPG plant operated in FS mode operation is higher than that in PB mode operation. It was also pointed out by Bakos that there is an increase in the LCOE for an SAPG plant [51].

Due to the volatile nature of solar resources and variations in the electricity and fuel markets, an SAPG plant operated in a single mode might not deliver the best economic profitability. Mixing the PB and FS mode, depending on the electricity and fuel markets, may achieve greater annual economic benefits for an SAPG plant. However, as previous studies were based on a single mode of operation (i.e., PB or FS), there is a gap in the knowledge as to how to switch between PB and FS modes to achieve greater annual economic profitability. Based on this proposed mixed mode of operation, an assessment of the potential economic advantages of a mixed mode of operation over a single mode operation is required.

2.5 Simulation Model of an SAPG plant

An SAPG plant is a hybrid power system which comprises an RRC power plant and solar collectors. Therefore, when building a simulation model for an SAPG plant, simulation models for the RRC power plant and the solar collectors, respectively, are needed. For an SAPG plant, after the solar thermal input, the RRC power plant is operated in the off-design condition. The simulation model of an SAPG plant should, therefore, consider the off-design condition of the RRC power plant.

In an SAPG plant, the solar thermal energy is integrated into the RRC power plant by preheating the feedwater to the boiler. The focus of the SAPG plant's simulation model is the simulation of the FWH system. The simulation models in some previous studies are based on a Matrix Method [59]. In this model, the heat and mass balance of the FWH system has been expressed in Matrix form. Typically, the enthalpy of the working fluid (i.e., steam or feedwater) is input into this Matrix. Then, the mass flow rate of the extraction steam can be calculated. As the extraction steam's flow rate after the solar thermal input should be calculated, the Matrix Method is suitable for an SAPG plant. However, considering the off-design condition after the solar thermal input, the input of the Matrix (i.e., the enthalpy of the working fluid) should be re-calculated, according to the solar thermal input.

A typical RRC power plant consists of a steam turbine, boiler, condenser, and an FWH system. After the solar thermal input, each part is operated in the off-design condition, which means the parameters of the working fluid would be changed. Some previous studies were based on the Matrix Method using Flugel's formula to simulate the plant's off-design condition [58-63]. By using this formula, the variations of the extraction steam's enthalpy can be calculated. Namely, the off-design condition of the steam turbine can be calculated. However, if only the Flugel formula has been used, the influence of the solar thermal input on the boiler's parameters cannot be calculated. Some previous studies assumed that the boiler's parameters remain unchanged, which means that the boiler is assumed to be a black box [58-63]. Recently, some studies have considered the off-design condition of the boiler [64, 65]. The boiler is assumed to consist of a series of heat exchangers. After the solar thermal input, the parameters of the boiler's working fluid has been calculated. It was found that after the solar thermal input, the parameters of the main steam, and reheat steam outlet of the boiler would be changed [64]. However, these results are only suitable for fuel saving purposes and for a subcritical power plant. The results for the power boosting purpose and other kinds of plants (i.e., a supercritical power plant, or an ultracritical power plant) are needed. After the solar thermal input, the condenser and the FWHs are also operated in off-design conditions.

However, there are no studies considering the off-design condition of the condenser and FWHs. Therefore, a simulation model considering the off-design condition of the condenser and FWHs is needed.

Some previous studies built an SAPG plant's simulation model based on commercial software. Popov et al. used THERMOFLEX software to evaluate SAPG performance [49]. Bakos et al. built an SAPG plant by using the Solar Thermal Electric Component (STEC) of the TRNSYS software [51]. As this commercial software already has successful modules for an RRC power plant and solar collectors, building an SAPG plant simulation model based on this software might be easier than using the Matrix Method. However, as the RRC plant in the SAPG plant is operated in the off-design condition, whether this commercial software can consider the off-design condition for each part of the RRC plant needs to be validated.

An SAPG plant always operates under variable solar radiation. Therefore, a simulation model of the SAPG plant should consider the impact of variable solar radiation. Early studies of an SAPG plant are based on steady state simulation [44]. This means that the variable solar radiation has not been considered. Later, the SAPG plant's simulation model was based on a pseudo-dynamic model [59] which can be used to simulate the annual performance of an SAPG plant. In this model, the performance of the SAPG plant is simulated in time series intervals. In each time interval, the SAPG plant is assumed to be operated in a steady state. The annual performance of the SAPG plant is calculated as the sum of its performance at each time interval. However, the pseudo-dynamic model cannot be used to analyse the start-up and shut-down problems for an SAPG plant. These start-up and shut-down problems can help to solve the problem of how to integrate the solar thermal energy into the RRC power plant. There are no previous studies focusing on this problem. In order to solve this problem, a dynamic simulation model is required.

2.6 Summary of the Literature Review and Gaps

Through the author's critical review of the previous literature in the area of SAPG technology research, it was found that previous studies mainly focused on identifying the advantages of the SAPG plant over other power generation technologies (i.e. solar alone power generation), along with the design and optimising the design of the SAPG plants. Table 2.1 and Table 2.2 present the summary of previous literature. The detailed plant configuration, especially the arrangement to connect the solar field and the RRC power plant, and the operation of the SAPG plant have been overlooked. Based on the literature review, the following research gaps have been identified:

Gap 1: How many possible configurations are available for an SAPG plant? For these possible configurations, the impact of different operation strategies on an SAPG plant's performance is unknown.

An SAPG plant has different configurations to connect the RRC power plant and the solar field. Each configuration can be operated by diverse strategies to adjust the mass flow rate of the displaced extraction steam. This means that the configurations and operation strategies have diverse combinations. However, previous studies are only based on a single combination. The plant's performances with different combinations have not been studied before.

Table 2.1. Major works on configuration, solar collector, and simulation model of SAPG plant.

Reference	Configuration	Solar Collector	Model
Hu et al. 2010	Parallel	N/A	Steady
Yan et al. 2010	Parallel	N/A	Steady
Yang et al. 2011	Parallel	N/A	Steady
Bakos and Teschelidou 2013	Parallel	PT	Pseudo-dynamic
Popov 2011	Parallel	N/A	Steady
Hou et al. 2013	Series	PT	Pseudo-dynamic
Pierce et al. 2013	Parallel	PT	Pseudo-dynamic
Zhai et al. 2014	Parallel	PT	Pseudo-dynamic
Zhao and Bai 2014	Parallel	PT	Pseudo-dynamic
Zhao et al. 2014	Parallel	PT	Pseudo-dynamic
Burin et al. 2015	Series	PT	Pseudo-dynamic
Hou et al. 2015	Series	PT	Pseudo-dynamic
Wu et al. 2015	Parallel	PT	Pseudo-dynamic
Zhai et al. 2015	Parallel	PT	Pseudo-dynamic
Zhu et al. 2015	Parallel	PT	Pseudo-dynamic
Feng et al. 2015	Parallel	PT	Pseudo-dynamic
Hou et al . 2016	Series	PT	Pseudo-dynamic
Wang et al. 2016	Parallel	PT	Pseudo-dynamic
Wu et al. 2016	Series	PT	Pseudo-dynamic
Adibhatla and Kaushik 2017	Parallel	PT	Pseudo-dynamic

Gap 2: Most previous studies were based on the SAPG plant using concentrating solar collectors. “Should only concentrating solar collectors be used in the SAPG plant in order to achieve high plant performance?” remains as a question.

The concentrating solar collectors (i.e. parabolic trough solar collectors) are the most widely used collectors in SAPG plants in previous studies. However, it is thought that using the non-concentrating collectors to displace the extraction steam to lower pressure FWHs in an SAPG plant may have advantages over using the concentrating collectors, given the differences in possible layout, costs and collecting features of these types of collectors. This hypothesis that SAPG plants using non-concentrating solar collectors may be superior to those using concentrating solar collectors needs to be explored.

Table 2.2. Major works on operation strategy and operation mode of SAPG plant.

Reference	Operation Strategy	Non-Displace Operation Strategy	Operation Mode
Hu et al. 2010	N/A	N/A	PB
Yan et al. 2010	N/A	N/A	PB
Yang et al. 2011	N/A	N/A	PB; FS
Bakos and Teschelidou 2013	CT	CT	PB; FS
Popov 2011	CT	CT	PB; FS
Hou et al. 2013	CT	CT	PB
Pierce et al. 2013	CT	CT	PB
Zhai et al. 2014	CT	CT	PB
Zhao and Bai 2014	CT	CT	PB; FS
Zhao et al. 2014	CT	CT	PB
Burin et al. 2015	CT	CT	PB
Hou et al. 2015	CT	CT	FS
Wu et al. 2015	CT	CT	FS
Zhai et al. 2015	CT	CT	PB
Zhu et al. 2015	CT	CT	PB
Feng et al. 2015	CT	CT	PB
Hou et al . 2016	CT	CT	FS
Wang et al. 2016	CT	CM	PB
Wu et al. 2016	CT	CT	FS
Adibhatla and Kaushik 2017	CT	CT	FS

Gap 3: When solar thermal energy is used to displace the high pressure/temperature extraction steam, the impact of different operation strategies to adjust the mass flow rate of non-displaced extraction steam (i.e., low pressure/temperature extraction steam) has not been studied.

Most previous studies of an SAPG plant were based on the assumption that the extraction steam to the high pressure/temperature FWHs has been displaced. Under this condition, the mass flow rate of this extraction steam should be adjusted when the solar thermal input changes. However, for the extraction steam to low pressure/temperature FWHs, which have not been displaced by the solar thermal energy, there are different operation strategies to adjust the mass flow rate of this extraction steam in response to solar variation. The impact of these operation strategies on an SAPG plant's performance has been overlooked by previous studies.

Gap 4: Once an SAPG plant has been built, how to operate the SAPG plant to achieve maximum economic returns under different market conditions has not be explored before.

The SAPG plants in previous studies were assumed to be operated in a single operation mode (i.e. PB or FS mode). In practice, under the condition of variable electricity on-grid tariff and fuel prices, mixing the PB and FS may achieve greater annual economic returns for the SAPG plant. Therefore, the economic advantage of mixing PB and FS modes needs to be analysed.

Gap 5: The off-design conditions for the boiler and condenser of an SAPG plant have not been considered by previous simulation models.

When solar thermal energy is integrated into an SAPG plant, the power plant is operated under the off-design condition. Some previous studies have considered the impact of a steam turbine's off-design condition on the plant's performance. However, the off-design condition for the boiler and condenser have not been fully considered.

Through the literature review and the gaps in our current knowledge identified above, the aim of the study (stated in Section 1.2) is validated. However, this study focuses on addressing the first four gaps (Gaps 1 to 4) identified above. Gap 5 is not addressed in this study. Specifically, Gap 1 and Gap 2 are addressed in Chapter 3 and Chapter 4, which are about the configurations of plants, while Gap 3 and Gap 4 are addressed in Chapter 5 and Chapter 6, which are about the operation of an SAPG plant.

Statement of Authorship

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Principal Author

Name of Principal Author (Candidate)	Jiyun Qin
Contribution to the Paper	Performed the literature review, wrote the manuscript. Developed the pseudo-dynamic model required to simulate Solar Aided Power Generation with different "configuration-operation" combinations. Took primary responsibility for responding to the reviewers.
Overall percentage (%)	60
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature	Date 20/6/2017

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Associate Professor Eric Hu
Contribution to the Paper	Supervised the work done. Provided assistance in developing the pseudo-dynamic model. Assisted with editing and finalising the manuscript. Provided assistance with addressing comments from reviewers.
Signature	Date 20/6/2017

Name of Co-Author	Professor Graham J. Nathan
Contribution to the Paper	Supervised the work done. Provided suggestions and recommendations to improve modelling approach. Assisted with editing the manuscript.
Signature	Date 20/6/17.

Please cut and paste additional co-author panels here as required.

3 The performance of a Solar Aided Power Generation with diverse “configuration-operation” combinations

Jiyun Qin, Eric Hu, Graham J. Nathan

School of Mechanical Engineering, The University of Adelaide, Adelaide, Adelaide, SA 5005, Australia.

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Jiyun Qin, Eric Hu *, Graham J. Nathan

School of Mechanical Engineering, The University of Adelaide, Adelaide, SA 5005, Australia

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ABSTRACT

Solar Aided Power Generation is an efficient way to integrate solar thermal energy into a fossil fuel fired power plant for solar power generation purposes. In this particular power plant, the solar heat is used to displace the extraction steam to preheat the feedwater to the boiler. The heat exchanger, which facilitates the heat exchange between the solar heat carried by the heat transfer fluid and the feedwater, is termed a solar preheater. Four possible configurations of the solar preheater, namely Parallel 1, Parallel 2, Series 1 and Series 2, are proposed in this paper. In this type of plant, the extraction steam flow rates must be adjusted according to the solar input. The ways to control the extraction steam flow rates are termed solar preheater operation strategies. Three typical strategies: the Constant Temperature control, Variable Temperature control with high to low temperature feedwater heater displacement and Variable Temperature control with low to high temperature feedwater heater displacement have been identified. Each configuration can be operated with one of the three strategies, resulting in twelve "configuration-operation" combinations/scenarios (shown in Table 1). Previous assessments and modelling of such a plant have only been based on a single combination. In this paper, a Solar Aided Power Generation plant, modified from a typical 300 MW power plant, is used to understand the plant's performance for all twelve of the available combinations. The results show that the instantaneous and annual technical performances of such a plant are dependent on the combinations used. The scenario 10 (Table 1) is superior to the other combinations in terms of the plant's instantaneous technical performance, while the scenarios 2, 5, 8 (Table 1) has the best plant's annual technical performance.

1. Introduction

In recent years, integrating solar thermal energy into a fossil fired power plant has been attracting more attention [14]. It was found that this type of hybrid power plant has both technical advantages [16] and economic advantages [24,30], over a solar alone power plant. Solar Aided Power Generation (SAPG) is a technology in which solar thermal energy, carried by a heat transfer fluid (HTF), is used to displace the extraction steam of a Regenerative Rankine Cycle (RRC) power plant, by preheating the feedwater of a power plant. The displaced extraction steam can then be further expanded in the steam turbine to generate additional power. In such a power plant, the solar thermal to power efficiency of low-to-medium solar heat can be improved [10] and the exergy losses of the power plant can be reduced [8,9]. Recently, Feng et al. [6] found that the thermos-economic benefit of an SAPG plant is higher than that of a stand-alone solar power plant.

In an SAPG plant, the heat exchange between the HTF and feedwater occurs in solar preheaters (SP), i.e. heat exchangers. Hu et al. [10] evaluated an SAPG plant where the SP is in parallel with the feedwater heaters (FWHs). Furthermore, Hou et al. [11] assessed the SAPG's annual performance where an SP is in series with the FWHs. Depending on the SP's locations relative to the FWHs, the SPs could have either a parallel or a series configuration. Based on these different configurations, the mass flow rates of the extraction steam should be adjusted according to the solar input. The method of adjusting the extraction steam is termed an SP operation strategy. The specific configuration and their possible operation strategy are termed "configuration-operation" combinations. As the displacement of extraction steam at the higher temperature stage leads to higher thermodynamic benefit [27,28],, an SAPG plant with different combinations would have different thermodynamic performances.

The previous studies of SAPG plants were all based on a single configuration-operation combination. Thus, the SP configurations and their possible operation strategies have not been clearly defined, let alone studied. Most previous investigations of SAPG

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

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Nomenclature

C_F	specific heat capacity of the HTF, kJ/kg °C
h_i, h_i'	specific enthalpy of the steam at the inlet and outlet of the turbine stage, kJ/s
$\dot{m}_{Dr}$	flow rate of the drained steam, kg/s
$\dot{m}_{Ex}$	flow rate of the extraction steam, kg/s
$\dot{m}_{FW\ In}$	flow rate of the feedwater entering into the FWH, kg/s
$\dot{m}_{HTF}$	HTF flow rate sent to SPs from the solar field, kg/s
$\dot{m}_i$	flow rate of each stage through i (i = 1–8) stage of the steam turbine, kg/s
$\dot{m}_j$	flow rate of extraction steam at each extraction point (j = A to H), kg/s
$\dot{m}_0$	flow rate of steam inlet steam turbine, kg/s
q_i	specific enthalpy decrease of extraction steam in the *i*th FWH, kJ/kg
$\dot{Q}_{Solar}$	solar thermal energy carried by the HTF to replace the extraction steam, kJ/s
$\dot{Q}_{Solar,i}$	average solar thermal power input into the *i*th FWH to replace the extraction steam for each FWH, kJ/s
$\dot{Q}_{Solar,i,max}$	maximum solar energy needed for *i*th FWH, kJ/s
r_i	specific enthalpy decrease of the drained steam from the $(i-1)$th FWH in the *i*th FWH, kJ/kg
W	power output from the steam turbine, kW
W_{Solar}	power output from the SAPG plant, less that from the reference plant, kW
y_j	$\dot{m}_j/\dot{m}_0 (j = A\ to\ H)$
$\eta_{Net\ solar}$	annual net solar thermal to power efficiency, %
η_{Solar}	instantaneous solar thermal to power efficiency
τ_i	specific enthalpy increase of FW in the *i*th FWH, kJ/kg

Abbreviations

CT	constant temperature strategy
DEA	deaerator
DNI	Direct Normal Insulation
FWH	feedwater heater
HTF	heat transfer fluid
P1	Parallel 1
P2	Parallel 2
RRC	Regenerative Rankine Cycle
SAPG	Solar Aided Power Generation
SP	solar preheater
SPAME	Specific Parameters and Matrix Equation
S1	Series 1
S2	Series 2
VT-HL	high to low varying temperature strategy
VT-LH	low to high varying temperature strategy

Subscripts

i	*i*th stage FWH
j	stage of extraction point

plants have been undertaken with parallel configurations. Based on this configuration, Yang et al. [29] found that the displacement of extraction steam with the highest temperature (i.e. where the SP is in parallel with the highest temperature FWH) leads to the highest solar to power efficiency. Later, Zhao and Bai [31] found the same result by using the annual hourly solar radiation data. Therefore, some later studies were based on the configuration whereby the SP is only in parallel with the highest temperature FWH. The extraction steam to highest temperature FWH is adjusted to retain the feedwater outlet temperature, unchanged. Bakos and Tsechelidou [3] found that an SAPG plant based on this configuration would have the advantage of lower energy production costs. Also, Pierce et al. [19] indicated that the cost of the SAPG plant is about 72% of a stand-alone concentrating solar power plant. Based on the same configuration, Peng et al. [20] evaluated an SAPG plant with different solar collectors' axis tracking modes. Later, Peng et al. [21,22], used the hourly solar radiation data to simulate the same SAPG plant. It was found that the exergy destruction of the SAPG plant is lower than that for a stand-alone solar power plant. Recently, based on the same configuration, Zhu et al. [37] analysed an SAPG plant modified from a 1000 MW, 600 MW and 330 MW plant and Burin et al. [2] evaluated an SAPG plant modified from a sugarcane plant. Recently, Zhai et al. [36] evaluated the thermos-economic cost of an SAPG plant based on this configuration. In another study, Popov [18] indicated that having an SP in parallel with all high temperature FWHs is the best option for an SAPG plant. Therefore, some studies are based on the configuration whereby the SP is in parallel with all high temperature FWHs. Based on this configuration, Zhao et al. [32,33], analysed an SAPG plant with different loads of plant. Later, Hou et al. [12] evaluated an SAPG plant for fuel saving purposes by using the annual hourly solar radiation data and Zhai et al. [34] compared SAPG plants with and without any storage system. These studies are based on the operation strategy that the extraction steam to high temperature FWHs is adjusted to maintain the feedwater outlet temperature of each high temperature FWH unchanged, i.e. a constant temperature operation strategy. In this combination, the extraction steam to all high temperature FWHs is reduced simultaneously, according to solar input.

Some recent papers about SAPG plants are based on the series configuration. Hou et al. [11] and Wu et al. [25] evaluated a 300 MW SAPG plant using hourly solar radiation data in Lhasa. Zhai et al. [35] evaluated a 660 MW SAPG plant. In their studies, the SP is located between the deaerator and high temperature FWHs and used to displace extraction steam to all high temperature FWHs. Recently, Wu et al. [26] evaluated a series configuration's SAPG plant with different storage capacities. The operation strategy of their studies is based on the constant temperature strategy. In this combination, the extraction steam is displaced in order from lower to higher temperature extraction steam. In an SAPG plant, the mass flow rates of extraction steam can also be adjusted at varying the feedwater outlet temperature, i.e. the varying temperature operation strategy. By using this strategy, the higher temperature extraction steam can be prior displaced by the solar thermal energy, which leads to greater thermodynamic benefits. Each configuration can be operated with one operation strategy. This means that an SAPG plant has alternative "configuration-operation" combinations. However, the possible "configuration-operation" combinations of a SAPG plant have not been clearly proposed. Comparison of different combinations is a gap in the extant studies.

In the present paper, the first aim is to present the possible "configuration-operation" combinations of an SAPG plant. The second aim is to compare the technical performance of an SAPG plant with all possible "configuration-operation" combinations. In particular, the instantaneous technical performance of an SAPG plant with the same solar input and the annual technical performance of an SAPG plant with the same solar field area are evaluated.

2. "Configuration-operation combinations of an SAPG plant

Fig. 1 presents a typical RRC plant. In an RRC plant, the deaerator (DEA) is used for removing the oxygen in the feedwater, so that the extraction steam to the DEA is never displaced by the solar heat.

2.1. Four alternative configurations of SP

In an SAPG plant, depending on the locations of the SP, there are different configurations of SP. Figs. 2–5 present schematic diagrams of a power plant's FWH system with four typical configurations of the SP. These figures show where the solar heat is used to displace the high temperature extraction steam, i.e. A to C in Fig. 1, although similar configurations could also be applied to low temperature extraction steam, i.e. E to H in Fig. 1.

2.1.1. Parallel 1 (P1) configuration

In the Parallel 1 configuration, each of the high temperature FWHs is parallel with an SP.

2.1.2. Parallel 2 (P2) configuration

In the Parallel 2 configuration, one bigger SP (Solar Preheater 1, or SP1) is placed in parallel with all of the high temperature FWHs.

2.1.3. Series 1 (S1) configuration

In the Series 1 configuration, an SP (Solar Preheater 1, or SP1 in Fig. 4) is placed in series between the FWH (FWH3) and the DEA.

2.1.4. Series 2 (S2) configuration

In the Series 2 configuration, the SP is located between the highest temperature FWH (FWH1 in Fig. 5) and the boiler.

2.2. SP operation strategies

In an SAPG plant, the mass flow rates of the extraction steam need to be adjusted according to a variable solar input to maintain the temperature and pressure of the feedwater inlet at the boiler (point w1 in Fig. 1) unchanged. There are three typical ways (termed solar preheater operation strategies) to adjust these flow rates, which are:

(1) Adjusting the extraction steam flow rates to all high temperature FWHs (i.e. FWH1 to FWH3 in Fig. 1) to maintain the feedwater outlet temperatures (points w1 to w3 in Fig. 1) unchanged, which is called a constant temperature (CT) strategy;
(2) Adjusting the extraction steam flow rate at the highest temperature stage (i.e. point A in Fig. 1) first, while maintaining the mass flow rates at the rest of the stages (i.e. points B and C in Fig. 1) unchanged until the this stage is fully displaced. This strategy is termed a high to low varying temperature (VT-HL) strategy;
(3) Adjusting the extraction steam flow rate at the lowest temperature stage (i.e. point C in Fig. 1) first, while maintaining the mass flow rates at the rest of the stages (i.e. points A and B in Fig. 1) unchanged until this stage is fully displaced. This strategy is termed a low to high varying temperature (VT-LH) strategy.

2.3. Configuration-operation combinations

In an SAPG plant, each configuration can be operated according to one of the three strategies described above. Therefore, an SAPG plant has twelve configuration-operation combinations. Table 1 presents twelve possible configuration-operation combinations for an SAPG plant.

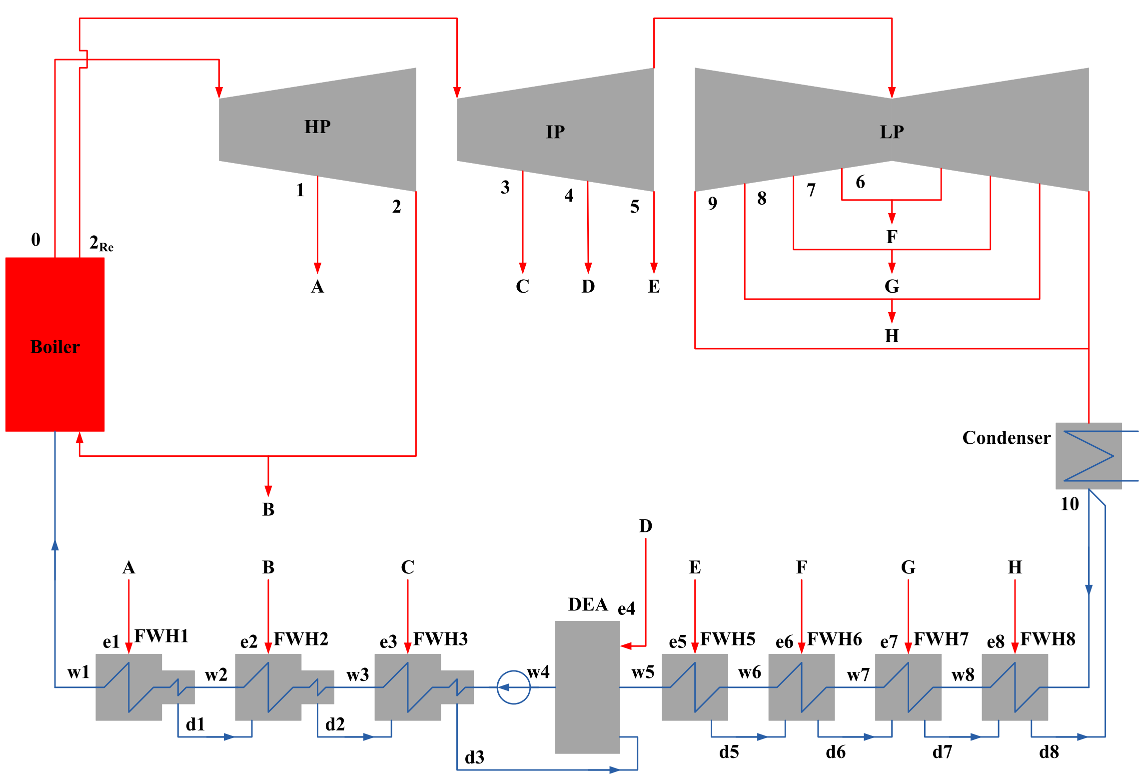

Fig. 1. Schematic diagram of a typical non-solar 300 MW regenerative Rankine cycle power plant with seven feedwater heaters (FWHs) and one deaerator.

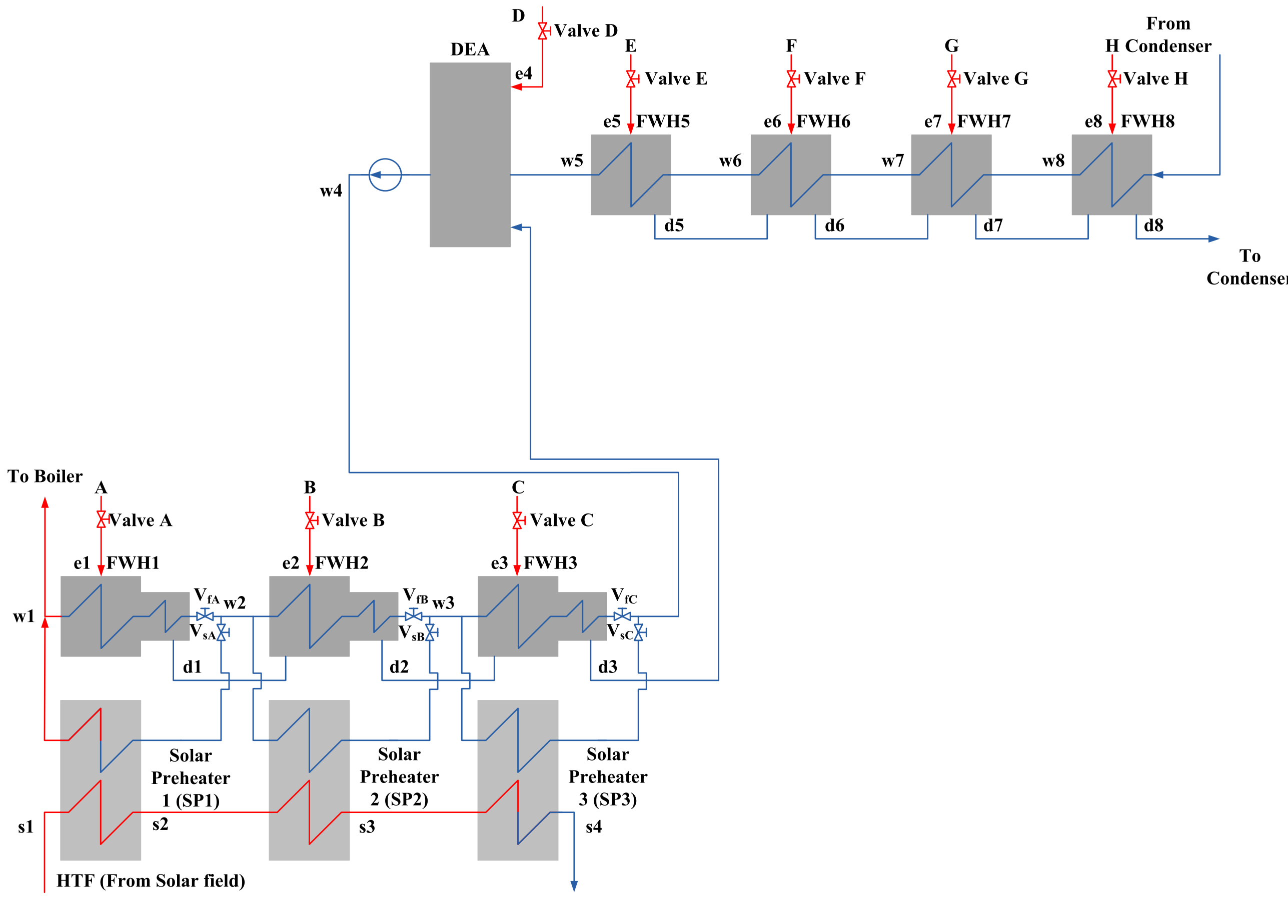

Fig. 2. Schematic diagram of an SAPG plant FWH system with Parallel 1 SP configuration.

3. Modelling of an SAPG plant

A pseudo-dynamic model has been developed for calculating the SAPG's performance. In the pseudo-dynamic model, the SAPG plant is simulated at a series of time intervals. At each time interval, it is assumed that the SAPG plant is operated in steady state. Steady state models of the SAPG plant and the solar field have been developed. The steady state model of the SAPG plant is modified from the Specific Parameters and Matrix Equation (SPAME) method [11]. The modified model can be used to simulate the SAPG plant with all twelve combinations. The in-house modified model has been created using a computer program written in Visual-Basic, i.e. Excel language, which can be used to simulate the SAPG plant with different Rankine cycles.

3.1. RRC plant

The energy balance across the FWHs (FWHs 1–3 and 5–8 in Fig. 1) is described as follows:

$$q_i = h_{ei} - h_{di}; \quad \tau_i = h_{fi} - h_{fi+1}; \quad r_i = h_{di-1} - h_{di},$$

where q_i (kJ/kg) is the specific enthalpy decrease of the extraction steam in the ith FWH; τ_i (kJ/kg) is the specific enthalpy increase of the FW in the ith FWH; and r_i (kJ/kg) is the specific enthalpy decrease of the drained steam from the $(i-1)$th FWH in the ith FWH.

The equivalent equation for the DEA (open FWH) is:

$$q_i = h_{e4} - h_{w5}; \quad \tau_i = h_{w4} - h_{w5}; \quad r_i = h_{d3} - h_{w5}.$$

By using the SPAME method, the heat and mass balance equation of the FWH can be given in matrix form:

$$[\dot{Q}_{EX}] \cdot [Y] = [\dot{Q}_{FWH}].$$

$$\text{Hence}: \quad [Y] = [\dot{Q}_{EX}]^{-1} \cdot [\dot{Q}_{FWH}]. \tag{1}$$

where

$$[\dot{Q}_{EX}] = \begin{pmatrix} q_1 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ r_2 & q_2 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_3 & r_3 & q_3 & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_4 & r_4 & r_4 & q_4 & \ddots & \ddots & \ddots & \vdots \\ \tau_5 & \tau_5 & \tau_5 & \tau_5 & q_5 & \ddots & \ddots & \vdots \\ \tau_6 & \tau_6 & \tau_6 & \tau_6 & r_6 & q_6 & \ddots & \vdots \\ \tau_7 & \tau_7 & \tau_7 & \tau_7 & r_7 & r_7 & q_7 & \vdots \\ \tau_8 & \tau_8 & \tau_8 & \tau_8 & r_8 & r_8 & r_8 & q_8 \end{pmatrix};$$

$$[Y] = \begin{pmatrix} y_A \\ y_B \\ y_C \\ y_D \\ y_E \\ y_F \\ y_G \\ y_H \end{pmatrix};$$

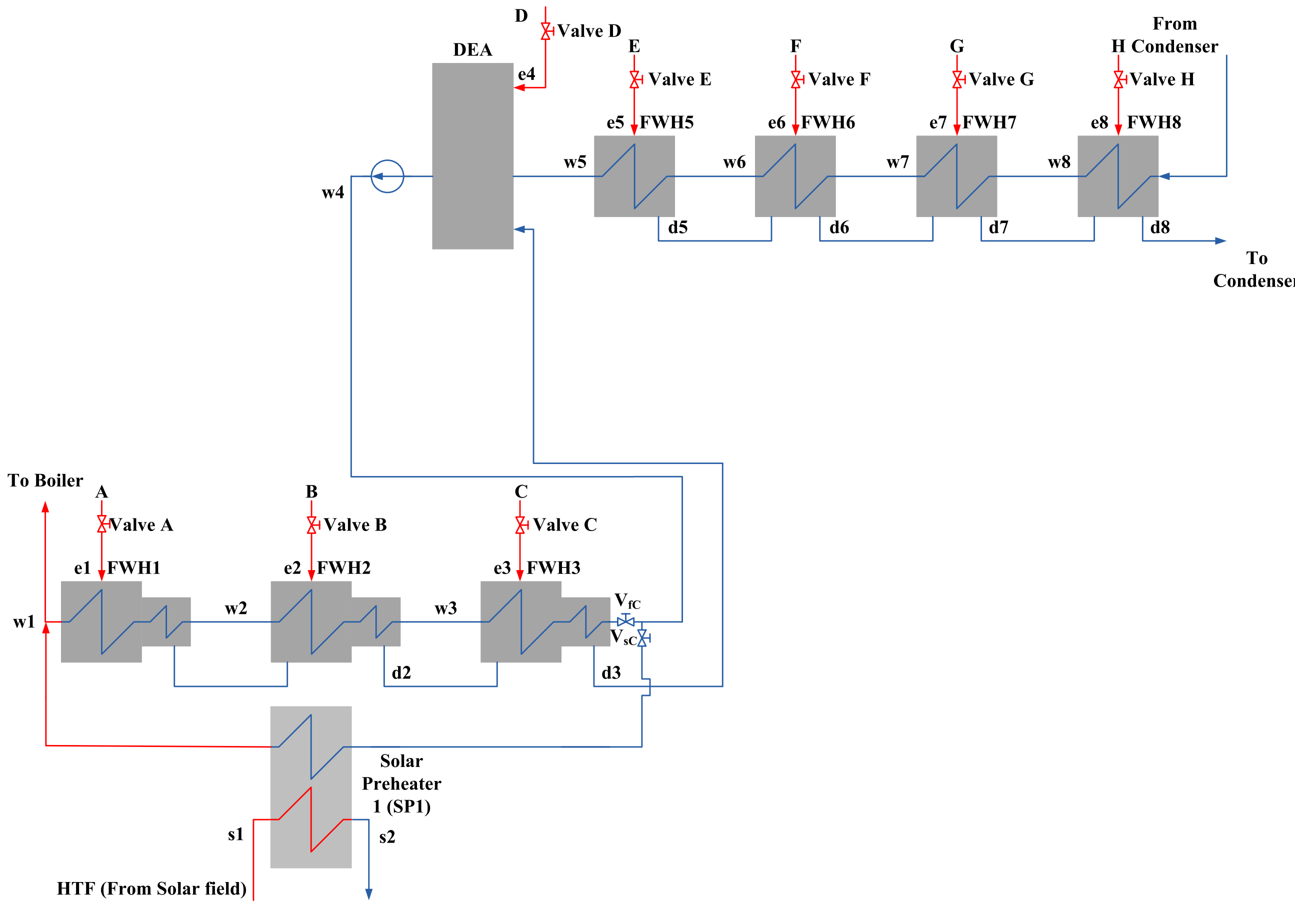

Fig. 3. Schematic diagram of an SAPG plant FWH system with Parallel 2 SP configuration.

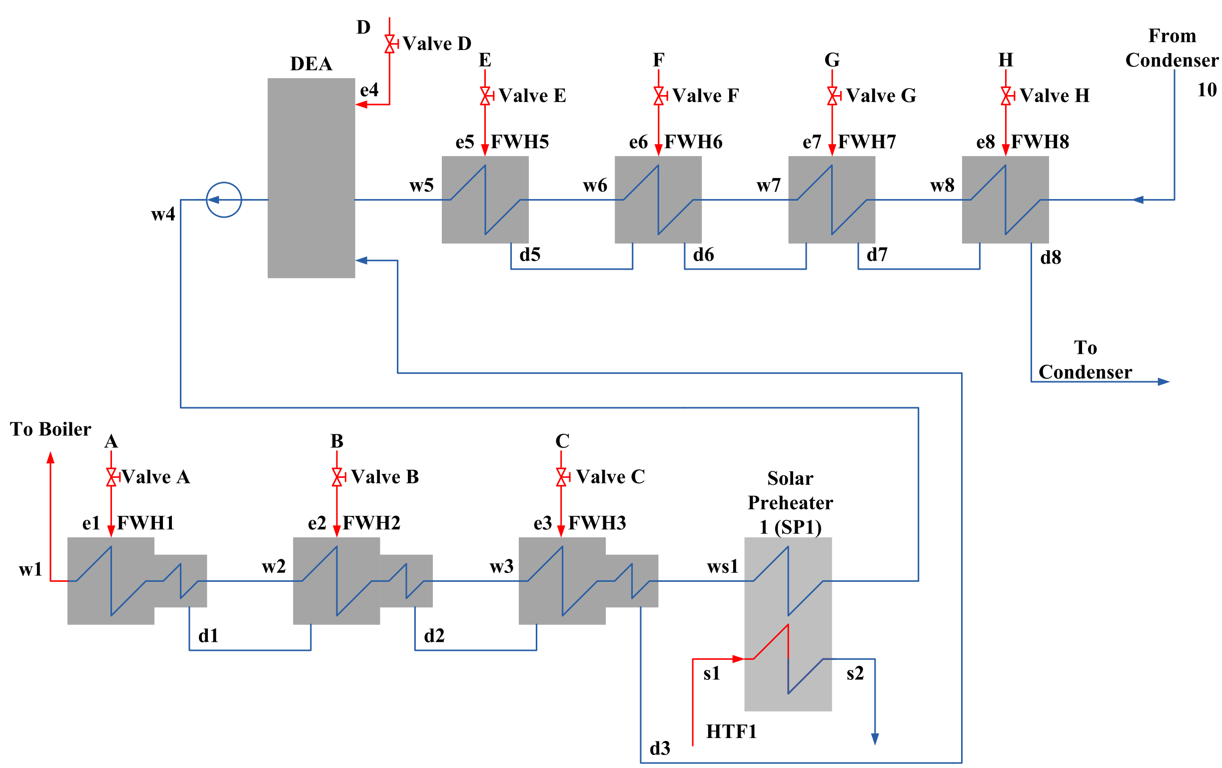

Fig. 4. Schematic diagram of an SAPG plant FWH system with Series 1 SP configuration.

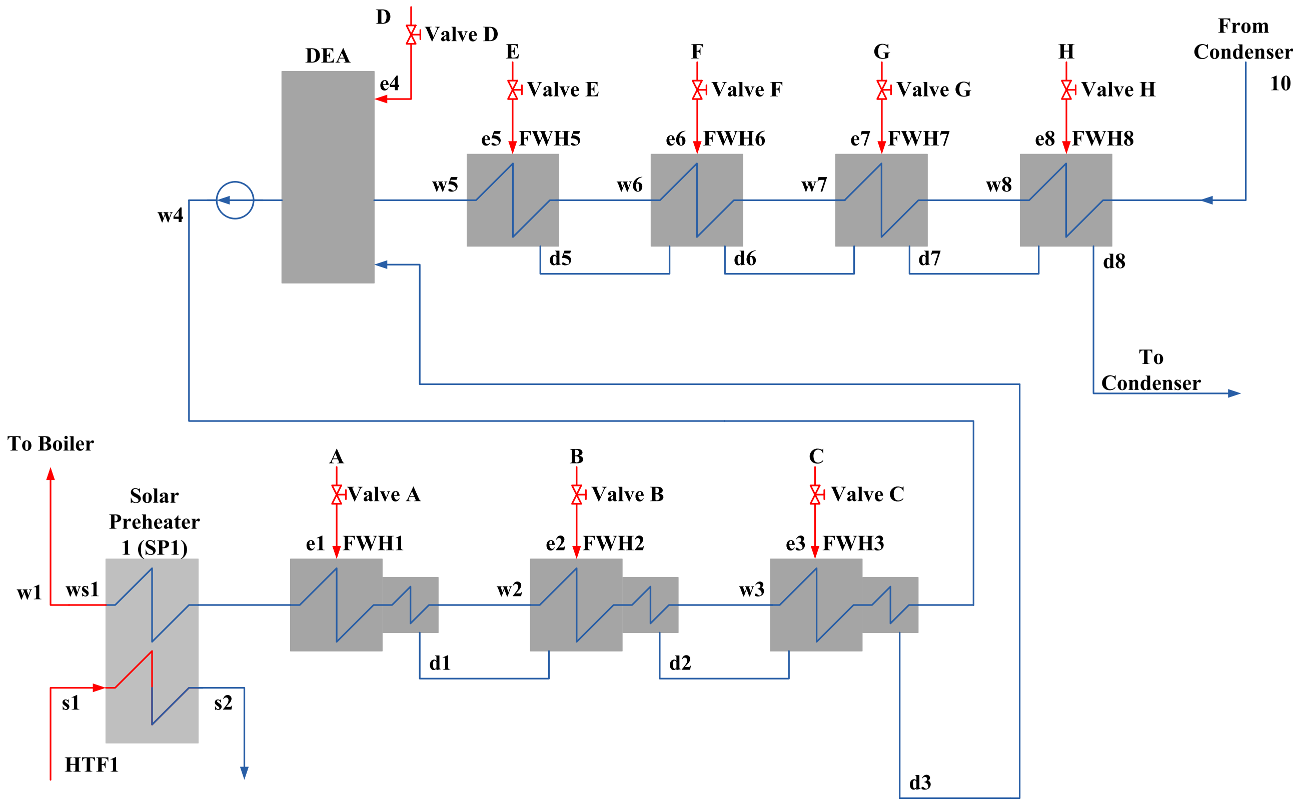

Fig. 5. Schematic diagram of an SAPG plant FWH system with Series 2 SP configuration.

Table 1
Possible "configuration-operation" combinations of an SAPG plant.

Combinations	SP configuration	SP operation strategy	Scenario no.
P1 CT	Parallel 1	CT	1
P1 VT-HL		VT-HL	2
P1 VT-LH		VT-LH	3
P2 CT	Parallel 2	CT	4
P2 VT-HL		VT-HL	5
P2 VT-LH		VT-LH	6
S1 CT	Series 1	CT	7
S1 VT-HL		VT-HL	8
S1 VT-LH		VT-LH	9
S2 CT	Series 2	CT	10
S2 VT-HL		VT-HL	11
S2 VT-LH		VT-LH	12

$$[\dot{Q}_{FWH}] = \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \\ \tau_7 \\ \tau_8 \end{pmatrix};$$

and $y_j = \dot{m}_j/\dot{m}_0 (j = A \text{ to } H)$.

Here Eq. (12) is the core of the SPAME model for an RRC plant. The output from the model is the matrix [Y]. The mass flow rates of the extraction steam can be calculated with the matrix [Y].

3.2. SAPG plant sub-model

The model of the SAPG plant is based on Eq. (1). If the RRC plant were modified to an SAPG plant by adding SPs to displace the extraction steam at points A to C in Fig. 1, a solar heat matrix ($[\dot{Q}_{Solar}]$) is introduced into Eq. (1).

3.2.1. Models for CT and VT strategies

In the CT strategy, the feedwater outlet temperature of the FWH (points w1 to w3 in Fig. 1) remain unchanged. This means that τ_1, τ_2 and τ_3 in Eq. (1) remain constant after the solar input. The simulation model of the CT strategy becomes as follows:

$$\begin{pmatrix} q_1 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ r_2 & q_2 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_3 & r_3 & q_3 & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_4 & r_4 & r_4 & q_4 & \ddots & \ddots & \ddots & \vdots \\ \tau_5 & \tau_5 & \tau_5 & \tau_5 & q_5 & \ddots & \ddots & \vdots \\ \tau_6 & \tau_6 & \tau_6 & \tau_6 & r_6 & q_6 & \ddots & \vdots \\ \tau_7 & \tau_7 & \tau_7 & \tau_7 & r_7 & r_7 & q_7 & \vdots \\ \tau_8 & \tau_8 & \tau_8 & \tau_8 & r_8 & r_8 & r_8 & q_8 \end{pmatrix} \begin{pmatrix} y_A \\ y_B \\ y_C \\ y_D \\ y_E \\ y_F \\ y_G \\ y_H \end{pmatrix} + \begin{pmatrix} \dot{Q}_{Solar,1}/\dot{m}_0 \\ \dot{Q}_{Solar,2}/\dot{m}_0 \\ \dot{Q}_{Solar,3}/\dot{m}_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \\ \tau_7 \\ \tau_8 \end{pmatrix}, \quad (2)$$

where $\dot{Q}_{Solar,i}$ (kJ/s) is the solar thermal power displacing the extraction steam of ith FWH. The $\dot{Q}_{Solar}$ is equal to $\sum \dot{Q}_{Solar,i}$.

Assuming

$$\left[\dot{Q}_{Solar}\right] = \begin{pmatrix} \dot{Q}_{Solar,1}/\dot{m}_0 \\ \dot{Q}_{Solar,2}/\dot{m}_0 \\ \dot{Q}_{Solar,3}/\dot{m}_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix},$$

then Eq. (2) can be written as:

$$\left[\dot{Q}_{EX}\right] \cdot [Y] + \left[\dot{Q}_{Solar}\right] = \left[\dot{Q}_{FWH}\right],$$

$$\text{Namely}: \ [Y] = \left[\dot{Q}_{EX}\right]^{-1} \cdot \left(\left[\dot{Q}_{FWH}\right] - \left[\dot{Q}_{Solar}\right]\right). \tag{3}$$

In the VT (i.e. VT-HL and VT-LH) strategy, τ_1, τ_2 and τ_3 in Eq. (1) cannot remain unchanged after the solar input. However, $\tau_1 + \tau_2 + \tau_3$ remains unchanged after the input. Then the simulation model of CT strategy can be written as:

$$\begin{pmatrix} q_1+r_2+r_3 & q_2+r_3 & q_3 & \cdots & \cdots & \cdots & \cdots & 0 \\ 0 & 0 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_4 & r_4 & r_4 & q_4 & \ddots & \ddots & \ddots & \vdots \\ \tau_5 & \tau_5 & \tau_5 & \tau_5 & q_5 & \ddots & \ddots & \vdots \\ \tau_6 & \tau_6 & \tau_6 & \tau_6 & \tau_6 & q_6 & \ddots & \vdots \\ \tau_7 & \tau_7 & \tau_7 & \tau_7 & \tau_7 & \tau_7 & q_7 & \vdots \\ \tau_8 & \tau_8 & \tau_8 & \tau_8 & \tau_8 & \tau_8 & \tau_8 & q_8 \end{pmatrix} \begin{pmatrix} y_A \\ y_B \\ y_C \\ y_D \\ y_E \\ y_F \\ y_G \\ y_H \end{pmatrix} + \begin{pmatrix} \dot{Q}_{Solar}/\dot{m}_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \tau_1+\tau_2+\tau_3 \\ 0 \\ 0 \\ \tau_4 \\ \tau_5 \\ \tau_6 \\ \tau_7 \\ \tau_8 \end{pmatrix}, \tag{4}$$

where $\dot{Q}_{Solar}$ (kJ/s) is the total solar thermal power input into the SP.

Setting

$$\left[\dot{Q}_{EX}\right] = \begin{pmatrix} q_1+r_2+r_3 & q_2+r_3 & q_3 & \cdots & \cdots & \cdots & \cdots & 0 \\ 0 & 0 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_4 & r_4 & r_4 & q_4 & \ddots & \ddots & \ddots & \vdots \\ \tau_5 & \tau_5 & \tau_5 & \tau_5 & q_5 & \ddots & \ddots & \vdots \\ \tau_6 & \tau_6 & \tau_6 & \tau_6 & \tau_6 & q_6 & \ddots & \vdots \\ \tau_7 & \tau_7 & \tau_7 & \tau_7 & \tau_7 & \tau_7 & q_7 & \vdots \\ \tau_8 & \tau_8 & \tau_8 & \tau_8 & \tau_8 & \tau_8 & \tau_8 & q_8 \end{pmatrix},$$

$$\left[\dot{Q}_{FWH}\right] = \begin{pmatrix} \tau_1+\tau_2+\tau_3 \\ 0 \\ 0 \\ \tau_4 \\ \tau_5 \\ \tau_6 \\ \tau_7 \\ \tau_8 \end{pmatrix}, \quad \text{and} \quad \left[\dot{Q}_{Solar}\right] = \begin{pmatrix} \dot{Q}_{Solar}/\dot{m}_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix},$$

then Eq. (4) can still be written as:

$$[Y] = \left[\dot{Q}_{EX}\right]^{-1} \cdot \left(\left[\dot{Q}_{FWH}\right] - \left[\dot{Q}_{Solar}\right]\right). \tag{5}$$

3.2.2. Simulation process of four configurations operated with three operation strategies

Eq. (2) is the core of the model for three operation strategies. By knowing the solar power input [$\dot{Q}_{Solar}$], the matrix [Y] is calculated from Eq. (2). There are three simulation processes for calculating the matrix [Y]:

(1) For the P1 and P2 configurations operated with the CT strategy, the extraction steam at points A to C is displaced simultaneously. The $\dot{Q}_{Solar,i}$ for ith FWH is calculated first. Then [Y] is calculated using Eq. (2).

(2) For all four configurations operated with the VT-HL strategy and S2 configuration operated with the CT strategy, the extraction steam is displaced according to the order from high to low temperature (from point A to C in Fig. 1). The maximum solar thermal power needed for ith FWH ($\dot{Q}_{Solar,i,max}$) is calculated first, which is defined as the solar energy required to displace the jth stage of extraction steam fully. Therefore:

- if $\dot{Q}_{Solar} \leqslant \dot{Q}_{Solar,1,max}$, $\dot{Q}_{Solar}$ can only partly displace extraction steam A in Fig. 1.
- if $\dot{Q}_{Solar,1,max} < \dot{Q}_{Solar} \leqslant (\dot{Q}_{Solar,1,max} + \dot{Q}_{Solar,2,max})$, the solar heat can fully displace extraction steam A and partly displace extraction steam B in Fig. 1.
- if $(\dot{Q}_{Solar,1,max} + \dot{Q}_{Solar,2,max}) < \dot{Q}_{Solar} \leqslant \left(\dot{Q}_{Solar,1,max} + \dot{Q}_{Solar,2,max} + \dot{Q}_{Solar,3,max}\right)$, the solar heat is sufficient to displace extraction steam A and B fully and partly displace extraction steam C in Fig. 1.
- if $\left(\dot{Q}_{Solar,1,max} + \dot{Q}_{Solar,2,max} + \dot{Q}_{Solar,3,max}\right) < \dot{Q}_{Solar}$, the solar heat is sufficient to displace all of extraction steam A, B and C fully. It is assumed that the surplus HTF will be dumped if there is no storage system.

Then [Y] is calculated from Eq. (2).

For different configurations, the $\dot{Q}_{Solar,i,max}$ is given as follows:

- For the S2 configuration operated with the CT strategy:

$$\dot{Q}_{Solar,1,max} = \dot{m}_0\tau_1;$$

$$\dot{Q}_{Solar,2,max} = \dot{m}_0\tau_2;$$

$$\dot{Q}_{Solar,3,max} = \dot{m}_0\tau_3.$$

- For the P1, P2, S1 and S2 operated with the VT-HL strategy:

$$\dot{Q}_{Solar,1,max} = \dot{m}_0\tau_1 + \dot{m}_A(r_2 + r_3);$$

$$\dot{Q}_{Solar,2,max} = \dot{m}_0(\tau_1+\tau_2) + (\dot{m}_A+\dot{m}_B)r_3 - \dot{Q}_{Solar,1,max};$$

$$\dot{Q}_{Solar,3,max} = \dot{m}_0(\tau_1+\tau_2+\tau_3) - \dot{Q}_{Solar,1,max} - \dot{Q}_{Solar,2,max}.$$

(3) For all four configurations operated with the VT-LH strategy and S1 configuration operated with the CT strategy, the extraction steam is displaced in the order below from low to high temperature (from point C to point A in Fig. 1). The $\dot{Q}_{Solar,i,max}$ for each FWH is calculated first. Then,

- if $\dot{Q}_{Solar} \leqslant \dot{Q}_{Solar,3,max}$, $\dot{Q}_{Solar}$ can only partly displace extraction steam C in Fig. 1.
- if $\dot{Q}_{Solar,3,max} < \dot{Q}_{Solar} \leqslant (\dot{Q}_{Solar,2,max} + \dot{Q}_{Solar,3,max})$, the solar heat can fully displace extraction steam C and partly displace extraction steam B in Fig. 1.
- if $(\dot{Q}_{Solar,2,max} + \dot{Q}_{Solar,3,max}) < \dot{Q}_{Solar} \leqslant \left(\dot{Q}_{Solar,1,max} + \dot{Q}_{Solar,2,max} + \dot{Q}_{Solar,3,max}\right)$, the solar heat is sufficient to displace extraction steam C and B fully and partly displace extraction steam A in Fig. 1.
- if $\left(\dot{Q}_{Solar,1,max} + \dot{Q}_{Solar,2,max} + \dot{Q}_{Solar,3,max}\right) < \dot{Q}_{Solar}$, the solar heat is sufficient to displace all of extraction steam C, B and A fully. It is assumed that the surplus HTF will be dumped if there is no storage system.

Then [Y] is calculated from Eq. (2).

The $\dot{Q}_{Solar,i,max}$ is given as:

$$\dot{Q}_{Solar,3,max} = \dot{m}_0\tau_3 - (\dot{m}_A+\dot{m}_B)r_3;$$

$$\dot{Q}_{Solar,2,max} = \dot{m}_0(\tau_2+\tau_3) - \dot{m}_A(r_2+r_3) - \dot{Q}_{Solar,3,max};$$

$$\dot{Q}_{Solar,1,max} = \dot{m}_0(\tau_1+\tau_2+\tau_3) - \dot{Q}_{Solar,2,max} - \dot{Q}_{Solar,3,max}.$$

3.2.3. Calculation of the plant's power output

After the matrix $[Y]$ has been calculated by Eq. (2), which yields the mass flow rates of the extraction steam, the power output from the turbine can be calculated.

The power output from the steam turbine in a power plant is given by,

$$W = \sum_{i=0}^{8} \dot{m}_i(h_i - h'_i); \tag{6}$$

where W (kW) is the power output from the steam turbine, $\dot{m}_i$ (kg/s) is the flow rate of each stage through each stage of the steam turbine, h_i (kJ/kg) is the specific enthalpy of the steam at the inlet of the turbine stage and h'_i (kJ/kg) is the specific enthalpy of the steam at the outlet of the turbine stage. Eq. (6) can also be written as:

$$W = \dot{m}_0 \sum_{i=0}^{8}\left(1 - \sum_{i=0}^{8} y_i\right)(h_i - h'_i). \tag{7}$$

When matrix [Y] is known from Eq. (2), the power output from the plant can be calculated with Eq. (7).

3.3. Solar field sub-model

The solar power used for displacement purpose ($\dot{Q}_{solar}$, kJ/s) is calculated as the solar radiation absorbed ($\dot{Q}_{solar,abs}$, kJ/s) less the heat losses ($\dot{Q}_{solar,loss}$, kJ/s) of the solar field, which is given by,

$$\dot{Q}_{solar} = \dot{Q}_{solar,abs} - \dot{Q}_{solar,loss}, \tag{8}$$

Then, the mass flow rate of the HTF produced by a solar field is calculated by,

$$\dot{Q}_{solar} = \dot{m}_{HTF} C_F (T_{solar,In} - T_{solar,Out}), \tag{9}$$

where $\dot{m}_{HTF}$ (kg/s) is the flow rate of the HTF produced by a solar field; C_F (kJ/kg °C) is the specific heat capacity of the HTF; and $T_{solar,In}$ and $T_{solar,Out}$ (°C) are the HTF temperature inlet and the outlet solar field.

In the present paper, it is assumed that a parabolic trough solar collector is used in the solar field. The $\dot{Q}_{solar,abs}$ is given by,

$$\dot{Q}_{solar,abs} = \eta_{op} K_\theta F_e \dot{Q}_{solar,on}, \tag{10}$$

and

$$\dot{Q}_{solar,on} = I_N cos\theta_i \eta_{Row,shading} \eta_{End,shading} A_{Solar}, \tag{11}$$

where $\dot{Q}_{solar,on}$ (kJ/s) is the Direct Normal Insulation (DNI) projected on the collector area; η_{op} is the optical efficiency of the solar collector; K_θ is the incidence angle modifier; F_e is the mirror cleanliness of the collectors; I_N (W/m^2) is the DNI radiation; θ_i is the solar radiation incidence angle [5]; $\eta_{Row,shading}$ is the row shadowing of the parallel rows; $\eta_{End,shading}$ is the edge shading effect (longitudinal shading) of the collectors; and A_{Solar} (m^2) is the aperture area of the solar field.

The heat losses of the solar field are calculated by using the experimental equations. In the present paper, the N-S tracking mode LS-2 parabolic trough solar collector is used as a case study. The key parameters and the heat losses equations of the LS-2 parabolic trough solar collector are shown in Table 2.

Table 2
Key parameters of LS-2 parabolic trough solar collector.

Parameters	Equation	Reference
Optical efficiency (η_{op})	75%	Mittelman and Epstein [13]
Incidence angle modifier (K_θ)	$1 + \frac{0.000884\theta_i}{\cos\theta_i} - \frac{0.00005369}{\cos\theta_i}$	Dudley et al. [4]
Mirror cleanliness (F_e)	97%	Mittelman and Epstein [13]
Row shadowing of parallel rows ($\eta_{Row,shading}$)	$l_f \cos\theta_z / W \cos\theta_i$ [1]	Stuetzle [23]
Edge shading effect ($\eta_{End,shading}$)	$1 - \left(1 + \frac{W^2}{48f^2}\right)\left(\frac{f}{l}\right)\tan\theta_i$ [2]	Goswami and Kreith [7]
$Q_{Solar,loss,collector}$ (collector heat loss)	$b_1 K_\theta Q_{solar,abs} + (b_2 + b_3\Delta T)\Delta T A_{Solar})\Delta t$ [3]	Dudley et al. [4]
$Q_{Solar,loss,pipe}$ (pipes heat loss)	$\left(\left(0.01693 \cdot \Delta T - 0.0001683 \cdot \Delta T^2 + 6.78 \times 10^{-7} \cdot \Delta T^3\right) A_{Solar}\right)\Delta t$	Patnode [17]

[1] l_f (m) is the distance between the focal line of two parallel rows; W (m) is the collector aperture width.
[2] l (m) is the collector length; and f (m) is the focal length of the collector.
[3] b1 = 0.00007276; b2 = 0.00496 kW/m^2 °C; b3 = 0.000691 kW/m^2; K_θ is the incidence angle modifier; ΔT is the difference between the average solar field temperature and the ambient air temperature.

3.4. Evaluation criteria

In order to evaluate the performance of an SAPG plant, some criteria are used to evaluate the performance of an SAPG plant operated for power boosting purposes.

(1) Instantaneous solar power output:

$$W_{Solar} = W_{Total} - W_{Ref}, \tag{12}$$

where W_{Total} (kW) is the total power output of the SAPG plant (in power boosting mode) after solar input, and W_{Ref} (kW) is the power output of the reference plant without solar input.

(2) Instantaneous solar share:

$$x_{Solar\ share} = \frac{W_{Solar}}{W_{Total}}, \tag{13}$$

(3) Instantaneous solar thermal to power efficiency:

$$\eta_{Solar} = \frac{w_{Solar}}{\dot{Q}_{Solar} + \dot{Q}_{Boiler}}, \tag{14}$$

where $\dot{Q}_{Solar}$ (kW) is the solar thermal power used for displacement purposes, and $\dot{Q}_{Boiler}$ (kW) is the changes to the boiler reheating load after the solar input. The η_{Solar} is actually the instantaneous solar useful thermal energy to power efficiency, without considering the solar field's efficiency.

(4) Annual solar share:

$$x_{Annual\ share} = \frac{\sum w_{Solar}\Delta t}{\sum w_{Total}\Delta t}, \tag{15}$$

where $\sum w_{Solar}\Delta t$ is the annual electricity produced by the solar energy, and $\sum w_{Total}\Delta t$ is the annual total electricity produced by the power plant.

(5) Annual net solar to power efficiency:

$$\eta_{Net\ solar} = \frac{\sum w_{Solar}\Delta t}{\sum \dot{Q}_{solar,on}\Delta t}, \tag{16}$$

where $\sum \dot{Q}_{solar,on}\Delta t$ is the annual DNI projected on the solar field. Therefore, the $\eta_{Net\ solar}$ includes the solar field's efficiency.

4. Case study

In the present study, an SAPG plant, modified from a 300 MW power plant, is used to compare the plant's performance across twelve combinations.

4.1. SAPG plant

The reference Regenerative Rankine Cycle (RRC) power plant shown in Fig. 1 is used for the case study. The key parameters of the reference RRC power plant are given in Table 3. Solar thermal energy is used to displace extraction steam at points A, B and C in Fig. 1 for power boosting purposes.

As the feedwater inlet temperature of the boiler is 269 °C, the HTF inlet temperature of the SP is assumed to be 279 °C. Also, the HTF outlet temperature of the SP is assumed to be 10 °C higher than the feedwater temperature for heat transfer.

4.2. Solar input

In the instantaneous simulation, the same amount of solar power is input into the SAPG plant. It is assumed that 10, 30, 50, 70, 90 and 108.2 MW of solar heat are transferred into the feedwater.

In the annual simulation, it is assumed that 200–600 sets of LS-2 parabolic trough solar collectors were used to collect solar radiation. The solar field consists of several loops of solar collectors. Each loop has 10 sets of LS-2 solar collectors. The area of each loop is 2355 m^2 (471 m × 5 m). The distance between each collector loop is 15 m. The historical hourly solar radiation data from 2010 for Adelaide (34°S, 138°E, Australia) and from 1997 for Beijing (39°N, 116°E) were selected for the evaluation. The solar data were taken from the Australian Government Bureau of Meteorology [1] and the National Renewable Energy Laboratory [15]. The summary of the weather conditions for the investigated sites is given in Table 4.

5. Results and discussion

In the present study, the instantaneous and annual performances of an SAPG plant with twelve combinations are simulated. The instantaneous performance is simulated by using the same solar input, while the annual performance is simulated by using the same solar field area.

5.1. Instantaneous performance of the SAPG plant

Table 5 shows the instantaneous solar power output (W_{Solar}) and the instantaneous solar share ($x_{Solar\ share}$) of different scenarios with diverse solar inputs. Furthermore, Fig. 6 shows the instantaneous solar thermal to power efficiency (η_{Solar}) of twelve scenarios shown in Table 1 with various solar inputs. It can be seen that when the solar input is sufficient to displace the high temperature

Table 4
Summary of weather conditions for investigated sites.

Location	DNI annual total (kW h/m^2)	Maximum DNI (W/m^2)
Adelaide	1899.6	1078
Beijing	1347.8	858

Table 3
Key parameters of a 300 MW RRC power plant.

Item	Unit	FWH1	FWH2	FWH3	DEA	FWH5	FWH6	FWH7	FWH8
Extraction steam in each stage									
Extraction pressure	Bar	54.41	34.62	15.76	7.56	4.86	1.87	0.632	0.226
Extraction temperature	°C	374.9	313.2	430.4	326.3	276.5	174.9	85.9	61.6
FWH outlet temperature	°C	269	240.2	198.2	169.1	146.1	113.7	83.1	58.8
Drain steam temperature	°C	245.9	203.8	174.7	165.4	119.3	88.8	64.4	40.2
Extraction flow rate	kg/s	16.00	19.78	9.70	14.73	10.42	9.44	7.34	7.37
		Boiler	Reheater	HP turbine		IP turbine		LP turbine	
Boiler, steam turbine and condenser									
Outlet pressure	Bar	167	31.16	34.62		4.77		0.052	
Outlet temperature	°C	537	537	312.8		276.5		33.6	
Outlet flow rate	kg/s	241.5	205.8	225.6		170.9		146.8	

Table 5
Instantaneous solar power output (W_{Solar}) and instantaneous solar share ($x_{Solar\ share}$) of 12 scenarios in Table 1 as a function of solar power input.

Scenario no.	Criteria	Solar input (MW)					
		10	30	50	70	90	108.2
10	W_{Solar} (MW)	4.28	12.79	20.50	27.98	34.16	38.95
	$x_{Solar\ share}$ (%)	1.4	4.1	6.4	8.5	10.2	11.5
2, 5, 8, 11	W_{Solar} (MW)	4.17	12.46	20.22	27.58	34.16	38.95
	$x_{Solar\ share}$ (%)	1.4	4.0	6.3	8.4	10.2	11.5
1, 4	W_{Solar} (MW)	3.73	11.15	18.45	25.63	32.67	38.95
	$x_{Solar\ share}$ (%)	1.2	3.6	5.8	7.9	9.8	11.5
3, 6, 7, 9, 12	W_{Solar} (MW)	2.87	9.09	16.65	24.09	31.93	38.95
	$x_{Solar\ share}$ (%)	1.0	2.9	5.3	7.4	9.6	11.5

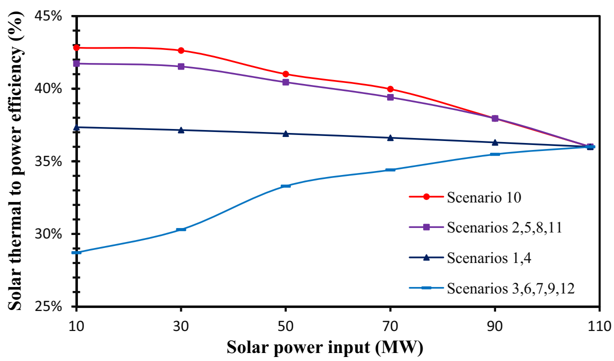

Fig. 6. Instantaneous solar thermal to electricity efficiencies (η_{Solar}) of 12 scenarios in Table 1 as a function of solar input.

extraction steam fully, all scenarios have the same level of performance, which is where 108.2 MW of solar power is input into the feedwater and the W_{Solar}, $x_{Solar\ share}$ and η_{Solar} are 38.95 MW, 11.5% and 36.0%, respectively.

Table 5 and Fig. 6 also show that when the extraction steam is partly displaced by the solar heat, the twelve scenarios fall into four distinguishable groups in terms of their instantaneous performance. The results show that for a given solar input, scenario 10 (i.e. the S2 configuration with CT strategy) has the best performance, followed by scenarios 2, 5, 8 and 11. Scenarios 1 and 4 have the third rank of performance, whilst scenarios 3, 6, 7, 9 and 12 have the poorest performance amongst twelve scenarios studied. The difference in performance across the twelve scenarios decreases with the incremental solar input until the extraction steam has been fully displaced.

In an SAPG plant, the technical benefit comes from the displaced extraction steam. The displacement of higher temperature extraction steam leads to a higher technical performance [27]. For scenarios 2, 5, 8, 10 and 11, the higher temperature extraction steam is prior displaced by the solar heat. Therefore, scenarios 2, 5, 8, 10 and 11 have a better technical performance than the other scenarios.

However, the variations of extraction steam responding to the solar input between scenario 10 and scenarios 2, 5, 8, 11 are different. In Fig. 7, it can be seen that the mass flow rate of higher temperature extraction steam for scenario 10 (Fig. 7(a)) declines more quickly than that of scenarios 2, 5, 8, 11 (Fig. 7(b)). The declined mass flow rate represents the displaced extraction steam. Thus, for a given solar input, more extraction steam with a higher temperature (and pressure) is displaced for scenario 10. Therefore, scenario 10 has the best performance.

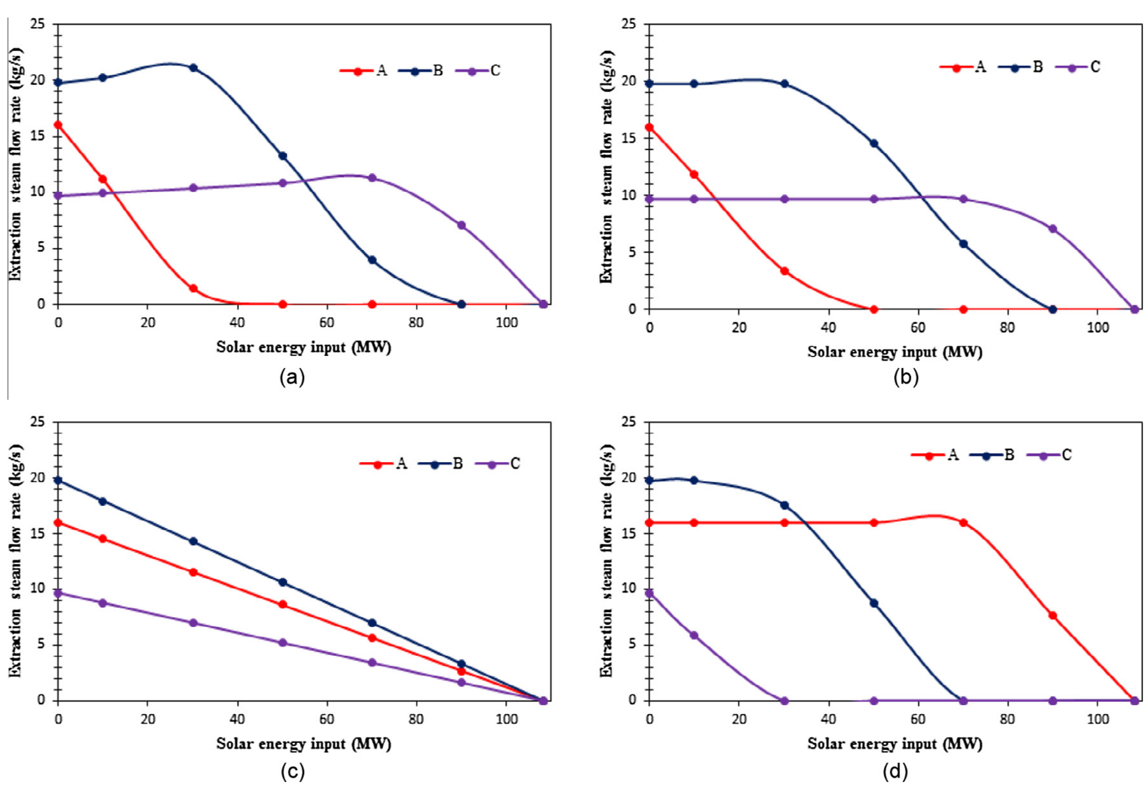

Fig. 7. Extraction steam flow rate variations at designed displaced extraction points in Fig. 1 (points A to C) of 12 scenarios in Table 1 as a function of solar power input for: (a) scenario 10; (b) scenarios 2, 5, 8, 11; (c) scenarios 1, 4; (d) scenarios 3, 6, 7, 9, 12.

5.2. Annual performance of the SAPG plant

The solar field's efficiency is influenced by the HTF inlet temperature of the solar field (i.e. the HTF outlet temperature of the SPs) which would be varied in some scenarios when the solar radiation changes. The comparison of the annual performance, based on the LS-2 parabolic trough solar collector area across twelve scenarios in Adelaide, Australia, and in Beijing, China, is shown in Figs. 8–10, respectively. It is shown that the twelve scenarios fall into six distinguishable groups in terms of their annual performance for these locations.

The results of Figs. 8–10 show that for a given solar collector area, scenarios 2, 5 and 8 (i.e. P1, P2 and S1 configurations with a VT-HL strategy) have the best annual performance, followed by scenario 10 (i.e. an S2 configuration with a CT strategy). Scenario 11 (i.e. an S2 configuration with a VT-HL strategy) has the third best annual performance, followed by scenarios 1 and 4 (i.e. a P1 and P2 configuration with a CT strategy). Scenarios 3, 6, 9 (i.e. P1, P2 and S1 configurations with a VT-LH strategy) and 7 (i.e. an S1 configuration with a CT strategy) have the fifth best annual performance, whilst scenario 12 has the poorest annual performance amongst the twelve scenarios studied. This order of performance is independent of the specific locations.

The results of the instantaneous performance, i.e. Fig. 6, differ from the results of the annual performance. Scenario 10 has the best instantaneous performance, whilst scenarios 2, 5 and 8 have the best annual performance. Scenarios 2, 5, 8 and 11 have the same instantaneous performance, whilst the annual performances of scenarios 2, 5 and 8 are higher than that of scenario 11. In Fig. 6, the instantaneous performances of scenarios 3, 6, 7, 9 and 12 are identical. However, the annual performances of scenarios 3, 6, 7 and 9 are higher than that of scenario 12. The reason is thought to lie in the variations of HTF outlet temperatures of the SP (point s2 in Fig. 5) for the S2 configuration. In scenarios 10, 11 and 12, the HTF outlet temperature of the SP, i.e. the temperature returned to the solar field, is normally higher than that for the other configurations. Therefore when considering the efficiency of the solar field, scenario 10 would no longer be the best in terms of annual performance, the annual performance of scenario 11 would be lower than that for scenarios 2, 5 and 8, and the annual performance of scenario 10 would be lower than that for scenarios 3, 6, 7 and 9.

From Figs. 9 and 10, it can be seen that the difference in annual solar power output per collector area and $\eta_{Net\ solar}$ between the combinations with the best annual performance (i.e. scenarios 2, 5 and 8) and the combination with the poorest annual performance (i.e. scenario 12) decrease with the incremental solar collector area. From Fig. 9(a) and Fig. 9(b), it can be seen that the annual solar power output per collector area (kW h/m^2) differences between scenarios 2, 5, 8 and scenario 12 range from 136.4 kW h/m^2 (47,100 m^2 solar collectors) to 65.2 kW h/m^2 (141,300 m^2 solar collectors) for Adelaide, and 92.4 kW h/m^2 (47,100 m^2 solar collectors) to 71.5 kW h/m^2 (141,300 m^2 solar collectors) for Beijing. Fig. 10(a) and Fig. 10(b), show that the $\eta_{Net\ solar}$ differences across scenarios 2, 5, 8 and 12 ranges from 9.1% (47,100 m^2 solar collectors) to 4.3% (141,300 m^2 solar collectors) for Adelaide, and 10.3% (47,100 m^2 solar collectors) to 7.9% (141,300 m^2 solar collectors) for Beijing. The results of Fig. 6 show that a higher solar input leads to lower differences in the instantaneous solar thermal to power efficiency. The larger solar collector area means more solar thermal energy is used for displacement purposes. Therefore, the differences in annual solar power output

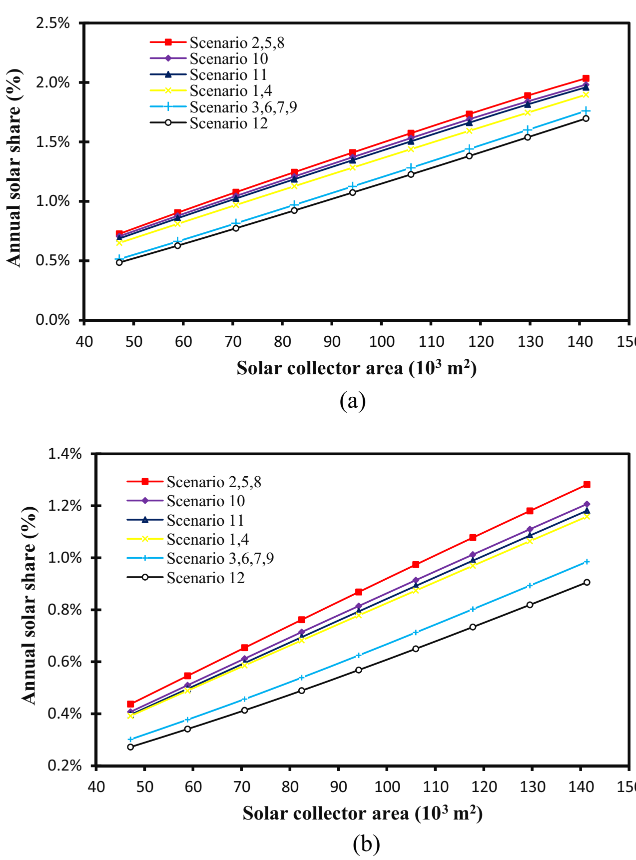

Fig. 8. Annual solar share as a function of the LS-2 parabolic trough solar collector area for 12 scenarios: (a) in Adelaide; (b) in Beijing.

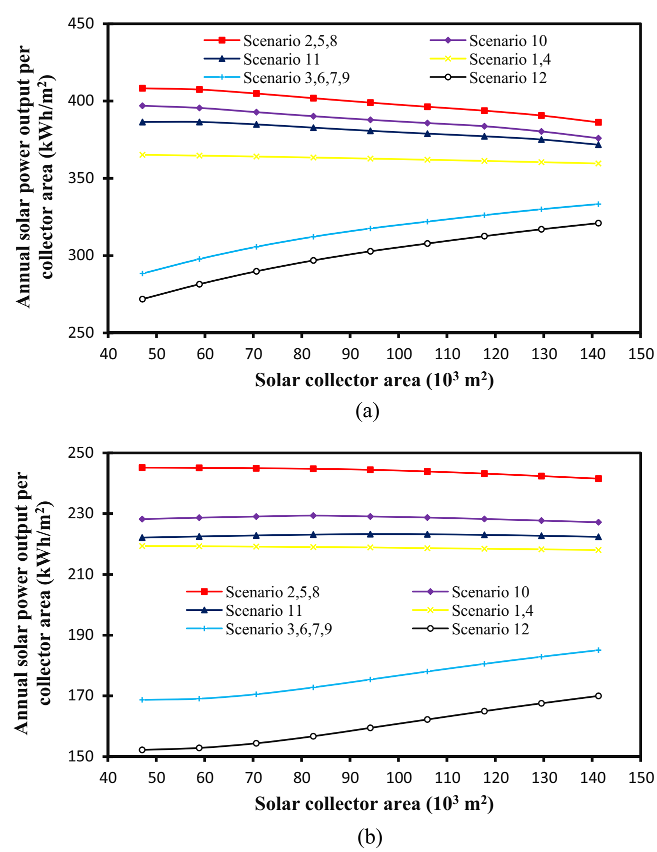

Fig. 9. Annual solar power output per collector area as a function of the LS-2 parabolic trough solar collector area for 12 scenarios: (a) in Adelaide; (b) in Beijing.

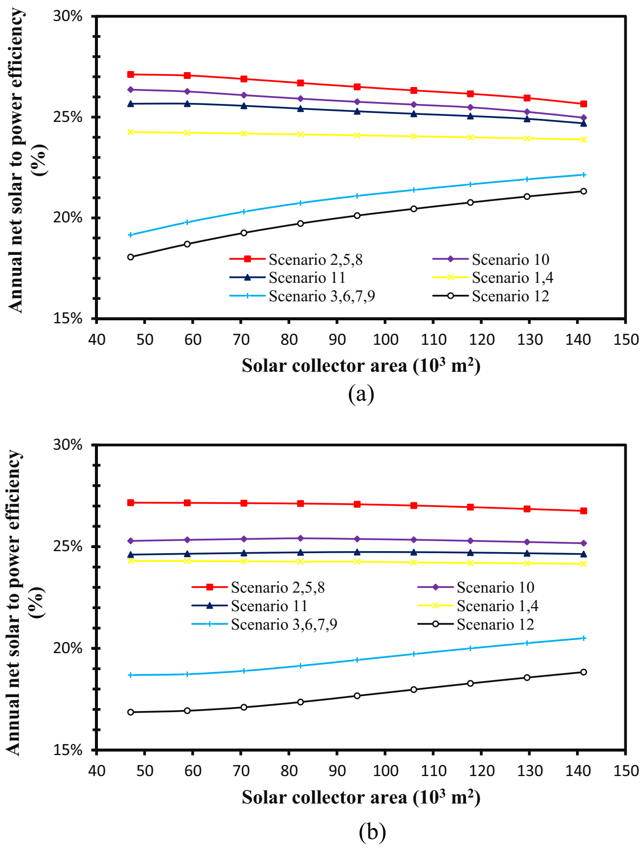

Fig. 10. Annual net solar to power efficiency as a function of the LS-2 parabolic trough solar collector area for 12 scenarios: (a) in Adelaide; (b) in Beijing.

per collector area and the $\eta_{Net\ solar}$ across different scenarios decreases with the incremental solar collector area.

6. Conclusions

In an SAPG plant, there are four possible configurations of solar preheater (SP), and also three typical SP operation strategies. Therefore, an SAPG plant has twelve potential "configuration-operation" combinations. An SAPG plant, modified from a typical 300 MW power plant, in which high pressure extraction steam was assumed to be displaced by the solar heat, is used as a case study to compare the plant's performance across all the "configuration-operation" combinations, i.e. the total of twelve scenarios/-combinations, when the plant is run in power boosting mode. The study draws the following conclusions.

With the same solar heat input, it has been found that:

- The SAPG plant's instantaneous performance would be identical for all scenarios if all the high pressure extraction steam to the FWHs were fully displaced by solar heat; it is necessary to input 108.2 MW solar thermal energy to displace all the high pressure extraction steam to the FWHs fully. Correspondingly, the instantaneous solar power output, the instantaneous solar share and instantaneous solar thermal to power efficiency are 38.95 MW, 11.5% and 36%, respectively;
- When the high pressure extraction steam is partly displaced, the S2 configuration adopting the CT strategy, i.e. scenario 10 in Table 1, has the highest technical performance.

By using the annual hourly solar radiation data in Adelaide and Beijing, with the same solar collector area, the results show that:

- The P1, P2 and S1 configurations adopting the VT-HL strategy are the combinations best designed to achieve the highest levels of annual solar share, annual solar power output per collector area and annual net solar thermal to power efficiency.
- The differences in annual solar power output per collector area and annual net solar to power efficiency across different combinations decrease with each increment to the solar collector area.
- The S2 configuration has a higher HTF outlet temperature of SP than the other configurations, implying its efficiency in terms of the solar field would be lower.

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Principal Author

Name of Principal Author (Candidate)	Jiyun Qin
Contribution to the Paper	Performed the literature review, wrote the manuscript. Developed the pseudo-dynamic model required for concentrating and non-concentrating solar collectors. Responsible for submission process.
Overall percentage (%)	60
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature	Date 6/11/2017

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Associate Professor Eric Hu
Contribution to the Paper	Supervised the work done. Provided suggestions and ideas to improve modelling approach. Provided assistance with addressing comments from reviews.
Signature	Date 7/11/17

Name of Co-Author	Professor Graham J. Nathan
Contribution to the Paper	Supervised the work done. Provided suggestions and recommendations to improve modelling approach. Assisted with editing the manuscript.
Signature	Date 7/11/17

Name of Co-Author	Dr. Lei Chen
Contribution to the Paper	Supervised the work done. Assisted with editing the manuscript.
Signature	Date 7/11/17

4 Concentrating or non-concentrating solar collectors for Solar Aided Power Generation

Jiyun Qin, Eric Hu, Graham J. Nathan, Lei Chen

School of Mechanical Engineering, The University of Adelaide, Adelaide, Adelaide, SA 5005, Australia.

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Concentrating or non-concentrating solar collectors for solar Aided Power Generation?

Jiyun Qin, Eric Hu*, Graham J. Nathan, Lei Chen

School of Mechanical Engineering, The University of Adelaide, Adelaide, SA 5005, Australia

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ABSTRACT

The preheating of the feedwater in a Regenerative Rankine Cycle power plant with solar thermal energy, termed Solar Aided Power Generation, is an efficient method to use low to medium temperature solar thermal energy. Here, we compared the use of medium temperature (200–300 °C) energy from concentrating solar collectors (e.g. parabolic trough collectors) to displace the extraction steam to high temperature/pressure feedwater heaters with that from low temperature (100–200 °C) non-concentrating solar collectors (e.g. evacuated tube collectors) to displace the extraction steam to low temperature/pressure feedwater heaters of the power plant. In this paper, the in terms of net land based solar to power efficiency and annual solar power output per collector capital cost of a Solar Aided Power Generation using concentrating and non-concentrating solar collectors has been comparted using the annual hourly solar radiation data in three locations (Singapore; Multan, Pakistan and St. Petersburg, Russia). It was found that such a power system using non-concentrating solar collectors is superior to concentrating collectors in terms of net land based solar to power efficiency. In some low latitude locations e.g. Singapore, using non-concentrating solar collectors even have advantages of lower solar power output per collector capital cost over using the concentrating solar collectors in an SAPG plant.

1. Introduction

Due to the environmental effects of the conventional fossil-fired power plants, the utilisation of renewable energy (e.g., solar energy) is attracting growing attention [1]. Although solar thermal energy has the advantages of being clean and having low greenhouse emissions, and has a trajectory of cost reduction, solar thermal power presently suffers from high costs where no carbon price has been established [2]. On the other hand, conventional fossil-fired power plants are the backbone of current electricity production. Therefore, integrating solar thermal energy with combustion power plant can be an attractive option [2]. It has been found that hybrid power systems has lower Levelized Cost of Electricity (LCOE) than stand-alone solar power plants [3]. There are two operations in integrating solar thermal energy into a Rankine power plant. One is to integrate the solar heat into the boiler and the other is to preheat the feedwater to the boiler [4,5]. The second operation has the advantages of being easy to control and lower capital costs, which the former has advantage of a higher solar share [4].

Solar Aided Power Generation (SAPG) plant uses solar thermal energy to preheat the feedwater of a Regenerative Rankine Cycle (RRC) power plant [6]. In this technology, the heat of the extraction steam from the steam turbine is displaced by the solar thermal energy to generate additional power in the steam turbine. This means that the thermodynamic benefit of an SAPG plant comes from the displaced high quality heat of the extraction steam [7,8]. Therefore, an SAPG plant can achieve higher solar thermal to power efficiency and thermo-economic benefits than a stand-alone solar power plant [9,10] and also reduce the exergy losses of an RRC power plant [11,12].

The utilisation of medium temperature (200–300 °C) concentrating solar collectors (e.g., parabolic trough collectors) to displace the extraction steam to high temperature/pressure feedwater heaters (FWHs) of an RRC power plant is the most common target for an SAPG plant. However, the system can be configured with the solar thermal energy displace the heat of the extraction steam at various alternative temperature stages. It has been found that the displacement of the extraction steam at higher temperature stages leads to higher solar thermal to power efficiency than at a lower temperature stage [13,14]. For an SAPG plant operated for fuel saving purposes, displacement of the extraction steam at a higher temperature stage also leads to more fossil fuel savings [9]. Considering the impact of overloading the steam turbine, with the same solar thermal input, displacement of the extraction steam to all high pressure/temperature FWHs can achieve highest solar share and solar thermal to power efficiency [15,16]. Therefore, most previous studies about SAPG plants are based on the assumption that

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

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Nomenclature

$C_{Initial}$	initial capital cost of the solar collectors, $
W_{Solar}	power output from the solar thermal energy in a time interval, kW
$\dot{Q}_{Land}$	solar radiation (global horizontal radiation) falling on the land of the solar field in a time interval, kW
x	annual solar power output per collector capital cost, kWh/$
η_{Net}	net solar to power efficiency, %
Δt	time interval (i.e. 1 h)

Abbreviation

DEA	Deaerator
ET	Evacuated tube
FWHs	Feedwater heaters
HTF	Heat transfer fluid
HPFWH	High temperature/pressure FWHs
LPFWH	Low temperature/pressure FWHs
LCOE	Levelized Cost of Electricity
PT	Parabolic trough
RRC	Regenerative Rankine Cycle
SAPG	Solar Aided Power Generation
SP	Solar Preheater

high pressure/temperature FWHs are displaced by the solar thermal energy [17–22]. As the feedwater outlet temperature of the high pressure/temperature FWHs is about 250–300 °C, medium temperature (200–300 °C) concentrating solar collectors (e.g. parabolic trough collectors) are often used to produce the heat transfer fluid (HTF) [17–22]. However, in these studies, only parabolic trough (PT) collectors are analysed as solar collectors to provide the HTF at a required temperature. The layout of collectors over a given piece of land has not been considered.

In terms of net land based view, an SAPG plant using low temperature (100–200 °C) non-concentrating solar collectors (e.g. evacuated tube collectors) may have net land based technical and economic advantages over using medium temperature (200–300 °C) concentrating solar collectors (e.g., parabolic trough collectors). In an SAPG plant, low temperature (100–200 °C) non-concentrating solar collectors (e.g., evacuated tube collectors) can only be used to displace the extraction steam to low pressure/temperature FWHs. The solar thermal to power efficiencies of an SAPG plant using non-concentrating solar collectors is lower than using concentrating solar collectors due to the low HTF temperature for the displacement [23]. However, Zhou et al. found that using non-concentrating solar collectors (i.e., evacuated tube (ET) collectors) still has higher net land based solar thermal to power efficiencies over using concentrating solar collectors (i.e., parabolic trough (PT) collectors) [24]. One reason for this is that in a given piece of land, the area of the ET collectors could be installed is larger than the PT collectors. Therefore, the annual solar thermal

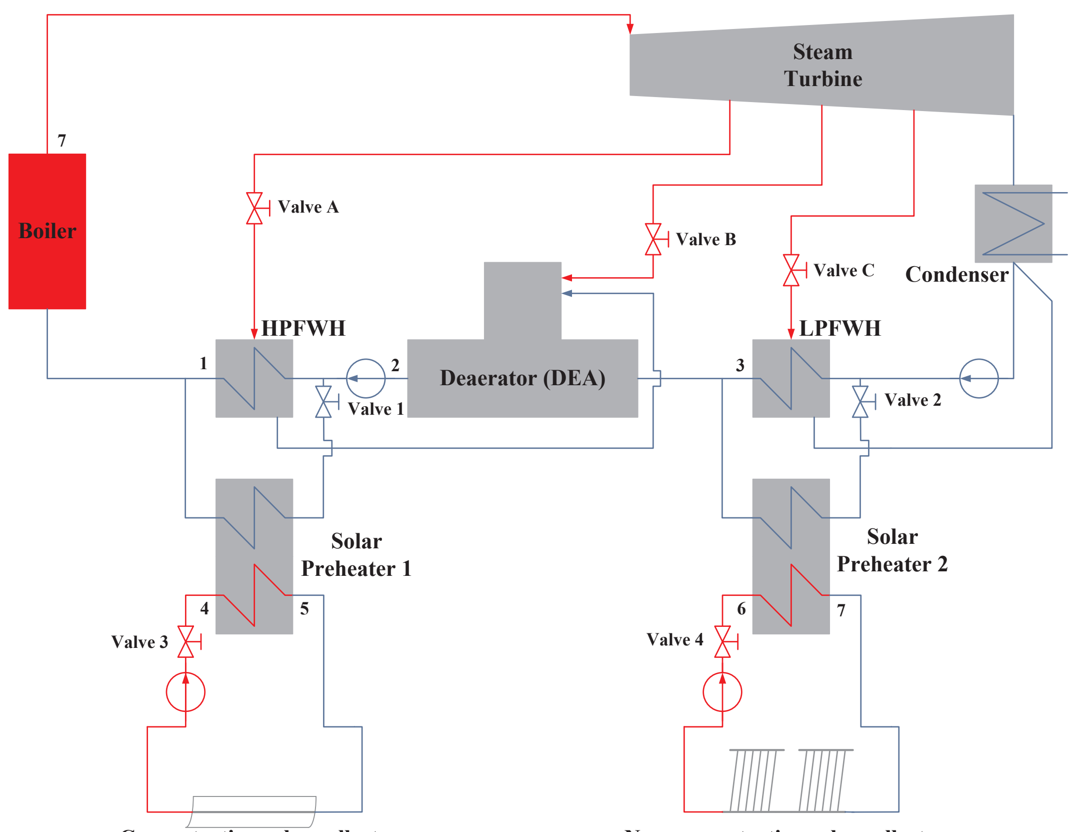

Fig. 1. Schematic diagram of a Solar Aided Power Generation (SAPG) plant. The medium temperature solar collector (i.e. concentrating solar collector is used to displace the extraction steam to high pressure/temperature FWHs, while the low temperature solar collector (i.e. non-concentrating solar collector) is used to displace the extraction steam to low the pressure/temperature FWHs.

energy produced by the ET collectors may be higher than the PT collectors. In addition, ET can collects both direct and diffuse solar radiation while the PT can collect direct solar radiation only. Therefore, under some conditions, an SAPG plant using ET collectors may be superior to using PT collectors. However, in the studies of Zhou et al., the annual solar radiation is only analysed in a single case (solar radiation data in Adelaide, AU) and the tilt angle of the ET collectors was fixed (34°), while the cost of the PT and ET collectors was not considered either.

Therefore the aim of this paper is to study more comprehensively the in terms of net land based technical and economic performance of an SAPG plant using non-concentrating solar collectors (e.g., evacuated tube collectors) and concentrating solar collectors (e.g., parabolic trough collectors) in different locations with different annual solar radiation. Specifically, this paper aims to identify the condition under which each option is best and each is worse.

2. Concentrating and non-concentrating collectors in a solar Aided power Generation plant

Fig. 1 presents a schematic diagram of a Solar Aided Power Generation (SAPG) plant for a Regenerative Rankine Cycle (RRC) power plant. In such a power system, the solar heat, which is typically transported by a heat transfer fluid (HTF), is used to preheat the feedwater of the power plant via a heat exchanger system, termed the Solar Preheater (SP) in Fig. 1. The feedwater of the power plant can be partly or fully preheated by the HTF, depending on the temperature and flow rate of the HTF, resulting in the flow rate of the extraction steam being decreased or displaced. This decreased/displaced extraction steam is then used to generate additional power through the steam turbine.

As shown in Fig. 1, the FWH system of an RRC power plant consists of the high temperature/pressure FWHs (HPFWH), a deaerator (DEA) and low temperature/pressure FWHs (LPFWH). The deaerator (DEA) of an RRC power plant is typically an open FWH to remove any oxygen from the feedwater, so it is difficult to displace with solar thermal energy. Hence, we consider only the case where extraction steam to the HPFWH or LPFWH is to be displaced by solar thermal energy. In practice, medium temperature (200–300 °C) solar thermal energy is typically used to displace the extraction steam to the HPFWHs, while low temperature (100–200 °C) solar thermal energy is used to displace the extraction steam to the LPFWHs. The high temperatures are applicable to concentrating solar collectors (e.g., parabolic trough collectors), the low temperatures could be provided by non-concentrating solar collectors (e.g., evacuated tube collectors), as shown in Fig. 1.

Although parabolic trough (PT) collectors have a higher thermal efficiency than evacuated tube (ET) collectors [25,26], the ET collectors offer potential to produce more annual solar thermal output per unit of land area than do PT collectors owing to their different geometry. Fig. 2 shows typical layouts of an N-S axis PT and ET collectors. The axis of the PT collector is arrayed in N-S direction, and PT collectors track the solar from east to west. The ET collectors is arrayed face the equator. Typically, due to the width of the PT collectors and the row distance for the PT collectors is higher than the ET collectors, on a given piece of

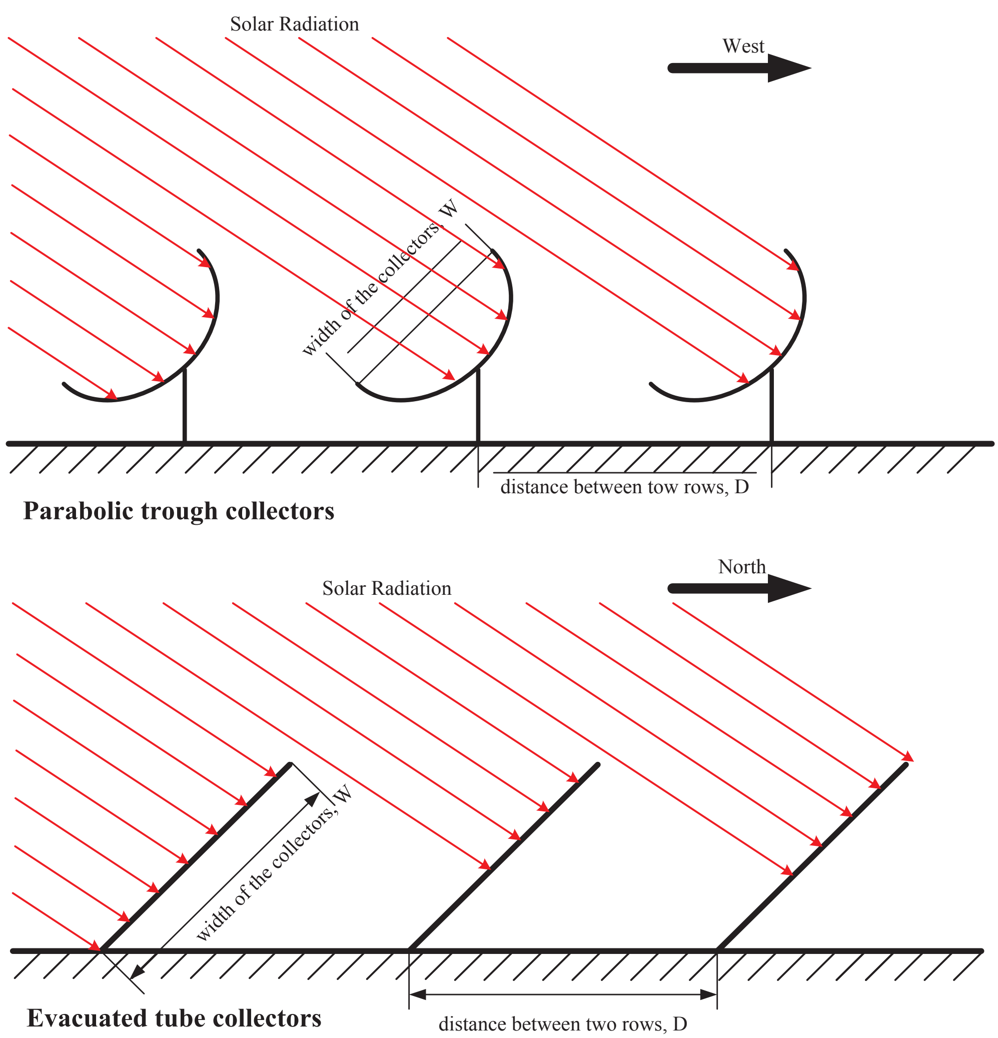

Fig. 2. Simplified layout of parabolic trough collectors and evacuated tube collectors on a given area of land.

land, the total collector area for ET collectors is larger than the PT collectors.

3. Methodology

To compare the technical and economic performance of an SAPG plant with the use of either concentrating or non-concentrating solar collectors, a pseudo-dynamic simulation model of an SAPG plant and simulation models for PT and ET collectors based on the TRNSYS software has been used.

3.1. Modelling of the SAPG plant

In this study, a pseudo-dynamic simulation model of by Qin et al. [27–30] is used to calculate the annual performance of an SAPG plant. In this pseudo-dynamic model, the annual technical performance of an SAPG plant is calculated as the sum of the SAPG's performance in a series of time intervals (e.g., 1 h). In each time interval, the technical performance of the SAPG plant is simulated by using the HTF flow rate from the modelling of the solar field.

3.2. Modelling of the solar field

The modelling of the solar field with parabolic trough (PT) and /or evacuated tube (ET) collectors was simulated with the TRNSYS with the STEC library [31]. Fig. 3 presents the solar field model for the PT and ET collectors which consists of weather data readings, processing components, a collector array shading component and a solar collector component.

In the simulation model, sub routine for "Solar resources" was used to provide the hourly solar radiation and calculate the hourly solar position (i.e. azimuth angle, zenith angle etc.) and incidence angle for different types of collectors. Solar radiation data was produced by Metronome for one typical year with 1-h steps, which is provided by the TRNSYS software. Sub routines for "Row shading for evacuated tube collectors" and "Row shading for parabolic trough collectors" are used to calculate the solar radiation after shading. By setting the number of rows, row distance, collector width, collector azimuth (for ET collectors), and tracking mode (for PT collectors). By using the data of solar radiation and solar position from "Solar resources" sub routine, hourly solar radiation after shading is calculated. Sub routines for "Evacuated tube collectors" and "Parabolic trough collectors" are used to calculate the HTF flow rate at required temperature. By setting the total collector area, required HTF temperature, and using data of solar position from "Solar resources" sub routine, solar radiation after shading from "Row shading for evacuated tube collectors" and "Row shading for parabolic trough collectors" sub routines, the HTF flow rate can be calculated.

3.3. Evaluation criteria

The following parameters were used to evaluate performance:

(1) Net solar to power efficiency (η_{Net}, %):

This criterion is defined as the annual power output from the solar thermal energy when the SAPG plant is run in power boosting mode, divided by the annual solar radiation falling onto the land area of the solar field (i.e., global horizontal radiation on land).

$$\eta_{Net} = \frac{\sum W_{Solar}\Delta t}{\sum \dot{Q}_{Land}\Delta t}, \quad (1)$$

where: W_{Solar} (kW) is the power output from the solar thermal energy in a time interval; $\dot{Q}_{Land}$ (kW) is the solar radiation (global horizontal radiation) falling on the land of the solar field in a time interval; and Δ_t is the time interval.

(2) Annual solar power output per collector capital cost (x, kWh/$):

This criterion is defined as the annual solar power output divided by the total initial capital cost of the solar collectors. The unit of x is kWh could be generated for per $ investment per year (kWh/$y)

$$x = \frac{\sum W_{Solar}\Delta t}{C_{Initial}} \quad (2)$$

where $C_{Initial}$ ($) is the initial capital cost of the solar collectors.

In the criteria of net solar to power efficiency and the annual solar power output per collector capital cost, the power output from the solar thermal energy (W_{Solar}) is calculated by subtracting the power output of the power plant without solar thermal input from the total power output of the power plant after the solar thermal input minus

4. Case study

Technical and economic performance of a 300 MW subcritical SAPG plant was assessed with concentrating and non-concentrating solar collectors as case studies.

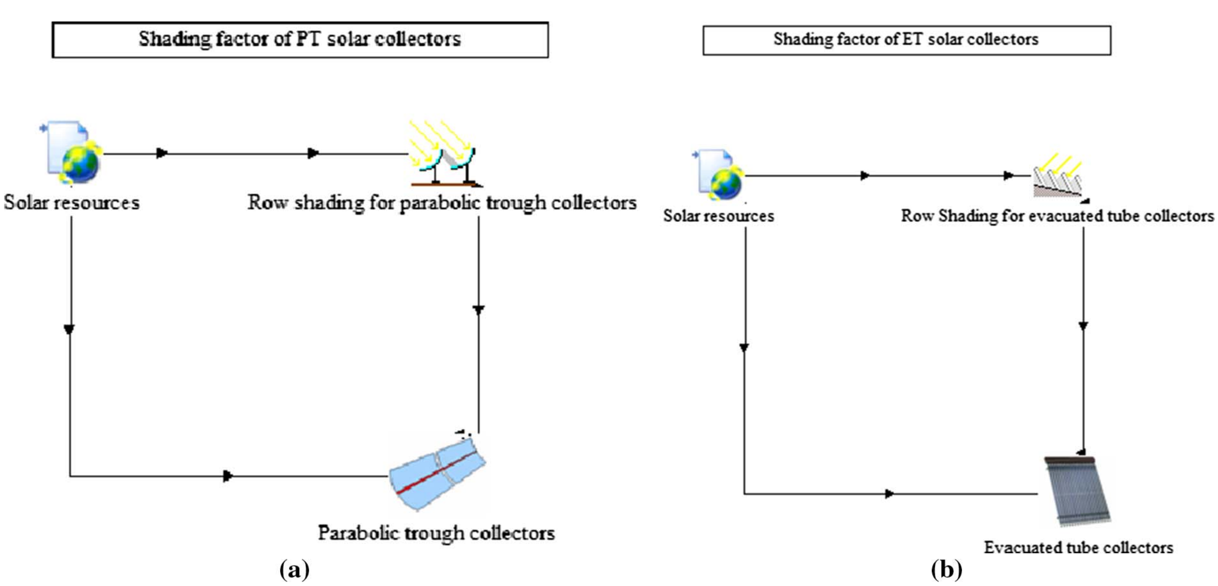

Fig. 3. Modelling of solar fields using TRNSYS with STEC library: (a) Parabolic trough solar field model; (b) Evacuated tube solar field model.

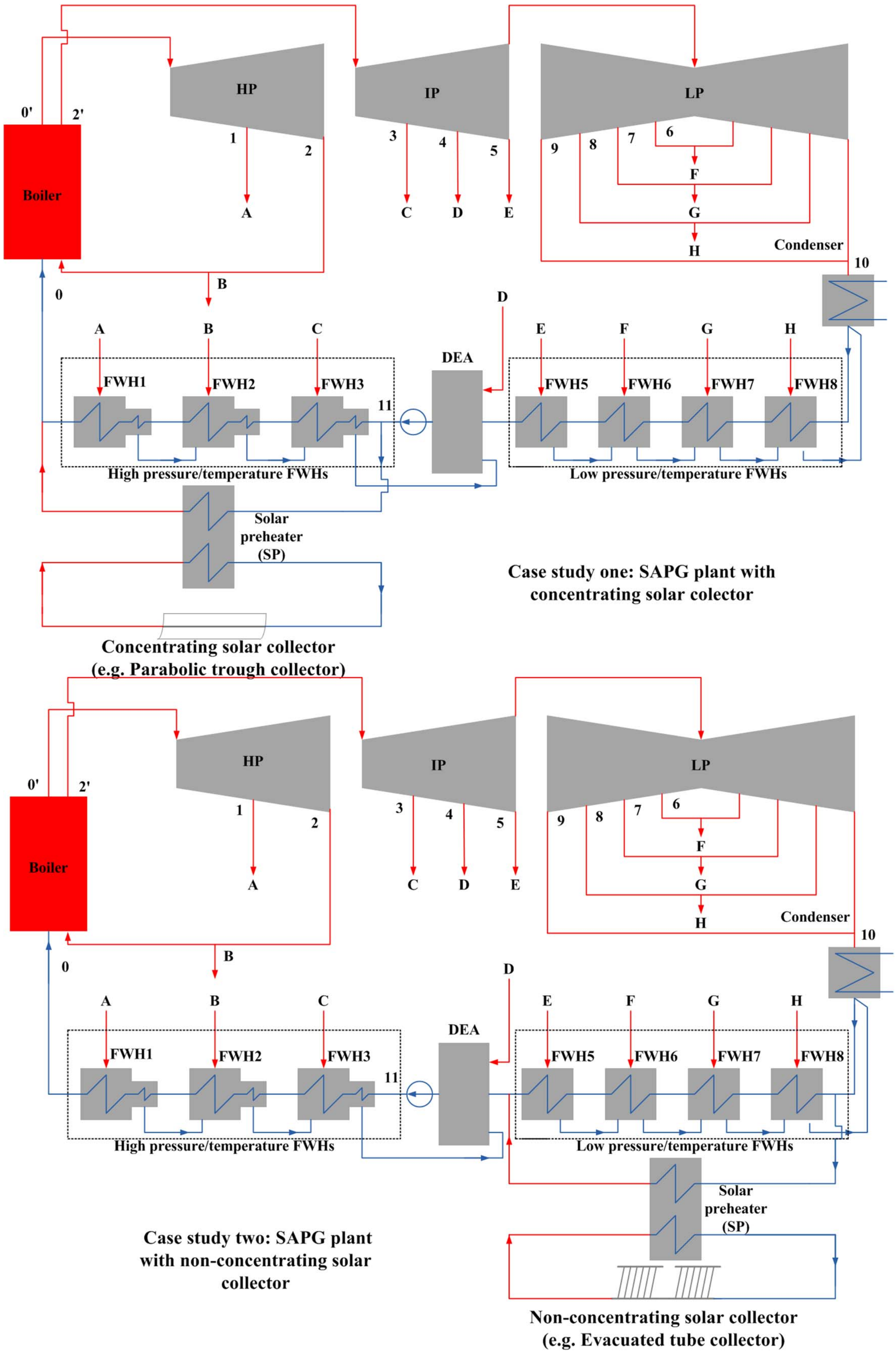

Fig. 4. A Solar Aided Power Generation (SAPG) Plant modified from a 300 MW subcritical power plant. Case study one: SAPG plant using concentrating solar collectors, Case study two: SAPG plant using non-concentrating solar collectors.

4.1. The SAPG plant

Fig. 4 presents a schematic diagram of the 300 MW subcritical regenerative Rankine cycle (RRC) SAPG plant, for which the solar thermal input can be provided with either concentrating or non-concentrating solar collectors. In present paper, there are two case studies. Case study one is the SAPG plant with concentrating (i.e. PT) solar collectors, and solar thermal energy is used to displace extraction steam to all high pressure/temperature FWHs. Case study two is the SAPG plant with non-concentrating (i.e. ET) solar collectors, and solar thermal energy is used to displace extraction steam to all low pressure/temperature FWHs. The key parameters of this 300 MW RRC power plant are given in Table 1. In present study, the flow rate of extraction steam is adjusted according to the available resource following the constant temperature strategy described by Qin et al. [27–29].

As shown in Table 1, the outlet temperature from the high temperature/pressure FWHs (point 0 in Fig. 4) is 269 °C, while that from the low temperature/pressure FWHs (point 7 in Fig. 4) is 146 °C. An assumption is made that a 10 °C temperature difference is required between the HTF and feedwater for heat exchange. Therefore, the required HTF outlet temperatures are 279 °C for PT collectors and 156 °C for ET collectors.

4.2. Solar field of parabolic trough (PT) collectors and evacuated tube (ET) collectors

The PT collectors are assumed to be the N-S tracking configuration of LS-2 PT collectors reported previously [32], whose key performance is presented in Table 2. The ET collectors are assumed to be reported previously [26], oriented towards the equator. Table 3 presents the parameters of the ET collectors used in the case study.

Considering the length, width and distance of PT and ET collectors, it is assumed that the available land area 180,000 m^2 (300 m × 600 m). The land price in this study has not been considered. The PT and ET collectors with different layouts are installed on the given land and generate the HTF at the required temperature for the SAPG plant. The layouts of the PT and ET collectors are shown in Fig. 5.

For the present study, the distance between each row for the LS-2 PT collectors is systematically varied over the three cases of 10 m, 15 m, and 20 m, while that for the ET collectors is systematically varied between 2 m, 3 m, and 4 m. This results in the six scenarios for the aperture area for the PT and ET collectors, as given in Table 4.

4.3. Solar and weather resources

In order to make a detailed comparison of an SAPG plant using PT and ET collectors, three different locations are selected for evaluation. The three selected locations are Singapore (1 °N, Singapore), Multan (30 °N, Pakistan), and St. Petersburg (60 °N, Russia), respectively. The solar radiation data of this three locations was obtained from the Metronome database of TRNSYS software [31]. The hourly data for

Table 2
Parameters of the LS-2 parabolic trough collectors.

Parameters	Value	Unit	Reference
Length of single collector	47.1	m	[32]
Trough aperture	5	m	[32]
Direct beam optical efficiency	0.75	–	[32]
Mirror cleanliness	0.97	–	[32]
Focal distance of the solar concentrator	1.49	m	[32]
Area of single collector	235.5	m^2	[32]
Absorber steel pipe outer diameter	70	mm	[32]
Envelop external diameter	115	mm	[32]
Focal ratio of the collector	7	–	[32]

Table 3
Parameters of the evacuated tube collector panel.

Parameters	Value	Unit	Reference
Length of collector	2.039	m	[26]
Width of collector	1.910	m	[26]
Aperture area of collector	3.89	m	[26]
Receiver area of collector	2.253	m^2	[26]
Absorber area of collector	2.07	m^2	[26]

Direct Normal Insolation (DNI), global horizontal radiation, direct horizontal radiation, diffuse radiation, ambient temperature, and wind speed are obtained from the Metronome database.

Table 5 presents the summary of weather and solar resources at the three locations. Fig. 6 shows the proportion of the annual direct and diffuse radiation at these locations. As shown, the selected locations represent the different proportions of annual diffused radiation in the annual global radiations, from 40% to 60%.

5. Results and discussion

5.1. Net solar to power efficiency

Fig. 7 presents for each of the three sites the η_{Net} of an SAPG plant using parabolic trough collectors as a function of row distance. It can be seen that, for all three locations, an SAPG plant has the highest η_{Net} when the row distance is 10 m. This is caused by the highest aperture area of the PT collectors. At Singapore, Latitude = 1 °N, η_{Net} drops 47.6%. While, at Multan (Latitude = 30 °N) and St. Petersburg (Latitude = 60 °N), η_{Net} decreases 47.1% and 43.1%, respectively. It indicates that shadowing has greater impact at low latitude location.

Fig. 8 presents for each of the three sites the net solar to power efficiency (η_{Net}) of an SAPG plant using evacuated tube collectors as a function of different collector tilt angles. It can be seen that, for all three locations, the η_{Net} of the SAPG plant using ET solar collectors increases with a reduction in spacing. This is because an increase in total collector area increases the total amount of solar energy collected.

Table 1
The main system parameters (i.e., temperature, pressure, enthalpy and mass flow rate) of the 300 MW power plant and solar field shown in Fig. 4.

Points in Fig. 4	A	B	C	D	E	F	G	H
Temperature (°C)	374.9	312.8	430.4	326.3	276.5	174.9	85.9	61.6
Pressure (Bar)	54.41	34.62	15.76	7.56	4.86	1.87	0.632	0.226
Enthalpy (kJ/kg)	3124.6	3014.2	3321.0	3113.7	3016.6	2820.3	2632.1	2484.9
Flow rate (kg/s)	16.00	19.78	9.70	14.73	10.42	9.44	7.34	7.37
Points in Fig. 4	0	1	2	3	5	6	7	8
Temperature (°C)	269	537	312.8	537	33.6	33.6	146	169
Pressure (Bar)	196.18	167	34.62	31.16	0.052	0.052	–	–
Enthalpy (kJ/kg)	1177.3	3394.1	3014.2	3537.8	2326.6	140.7	616.1	727.0
Flow rate (kg/s)	241.5	241.5	205.8	205.8	149.5	193.6	193.6	241.5
Points in Fig. 4	9	10	11	12				
Temperature (°C)	279	179	156	44				

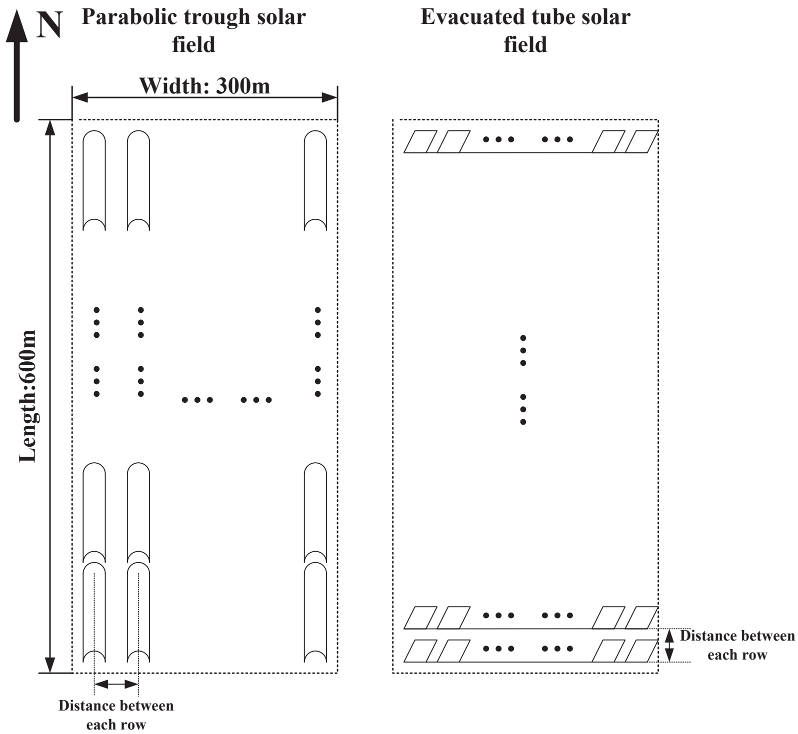

Fig. 5. The notation used to describe the alternative layouts for the parabolic trough and evacuated tube collectors, each on the same land area 300 m × 600 m.

Table 4
Scenarios for aperture area of the parabolic trough and evacuated tube collectors.

Scenario No.	Type of collector	Distance of each row (m)	collector area (m^2)
1	Parabolic trough	10	84,780
2	Parabolic trough	15	56,520
3	Parabolic trough	20	42,390
4	Evacuated tube	2	183,430
5	Evacuated tube	3	122,287
6	Evacuated tube	4	91,715

It can also be seen from Fig. 8 that, the optimum collector tilt angle depends on the number of rows and the location, as expected. At all three locations, the η_{Net} decreases with the incremental collector tilt angle for a row spacing of 2 m. That is, tilting the evacuated tube concentrators is counter-productive, since it introduces shading. That is, the maximum η_{Net} occurs for all SAPG cases investigated here with the minimum spacing of 2 m and a collector tilt angle of 5°.

It can also be seen from Fig. 8 that, for the case of larger row spacing of 3 m and 4 m, the optimum value of tilt angle depends on the latitude of the site. Without consideration of the shading effect, the optimum value of tilt angle is consistent with the latitude [33,34]. However, in this study, considering the shading effect, the optimum value is different. That is, for the case of Singapore (Latitude = 1 °N) η_{Net} is found decreases with any increase in collector tilt angle. However, at Multan (Latitude = 30 °N) and St. Petersburg (Latitude = 60 °N), the maximum η_{Net} occurs at tilt angle of 15–20° and 20–25°, respectively.

Table 6 summarizes for each of the three sites the optimal η_{Net} for PT and ET collectors. It can be seen that, the highest η_{Net} of the SAPG plant using ET collectors is 9% at Multan, while the highest η_{Net} of the SAPG plant using PT collectors is 6.3% also at Multan. This is because of the highest annual solar radiation at Multan. In addition, at Singapore, the highest η_{Net} of using ET collectors is 80.8% higher than that using PT collectors. However, at Multan and St. Petersburg, this advantages 42.9% and 8.6%, respectively. This means that the increase in the latitude would decrease the advantage of using ET collectors over that using PT collectors.

5.2. Annual solar power output per collector capital cost

The capital costs of the PT and ET collector fields include the initial unit capital cost, installation cost and operation and maintenance (O & M) cost. In this study, in order to simplify the simulation, only the initial unit capital cost of the collectors has been used for evaluating the economic performance of the PT and ET collectors. Typically, the unit capital cost of the PT collectors is higher than the ET collectors. In this study, the initial unit capital costs of the PT and ET collectors used is 295 \$/m^2 and 190 \$/m^2 respectively [35].

Figs. 9 and 10 present for each of the three sites the x of an SAPG plant using PT and ET collectors, respectively. It can be seen from Figs. 9 and 10 that, for all three locations, x of the SAPG plant using PT and ET collectors increases with an increases in spacing. This is because an increase in row distance decreases the row shading effects. This means that more solar thermal energy can be produced with unit area collectors, which leads to a higher x.

Table 7 presents the comparison for each of the three sites of the

Table 5
Summary of weather and solar resources for the investigated sites.

Sites	Location	Annual DNI (kW/m^2)	Annual direct radiation (kWh/m^2)	Annual diffuse radiation (kWh/m^2)	Annual global radiation (kWh/m^2)	Annual average temperature (°C)	Annual average wind velocity (m/s)
Singapore	1 °N 104 °E	893.74	636.29	986.38	1622.68	26.63	1.99
Multan	30 °N 71 °E	1597.09	993.42	783.85	1777.27	25.17	2.55
St. Petersburg	60 °N 30 °E	932.88	431.36	493.68	925.05	4.99	3.21

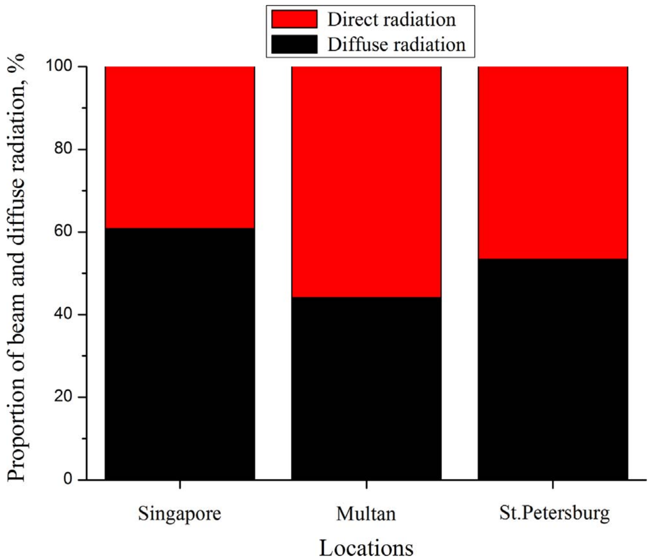

Fig. 6. Proportion of the annual direct and diffuse radiation for three sites shown in Table 2.

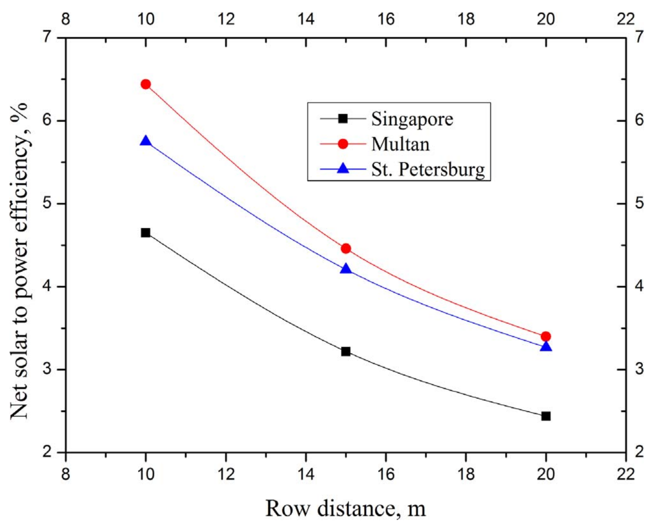

Fig. 7. Net solar to power efficiency (η_{Net}) of the SAPG plant using parabolic trough collectors with different row distances in three investigated locations shown in Table 2.

optimal x for the SAPG plant using PT and ET collectors. For the case of Singapore (Latitude = 1 °N), the maximum x is 0.96 kWh/\$y for using PT collectors, and 0.74 kWh/\$y for using ET collectors. For the case of Multan (Latitude = 30 °N), the maximum x is 1.16 kWh/\$y for using PT collectors, and 1.13 kWh/\$y for using ET collectors. The x for the SAPG plant using PT is higher than using the ET collectors at Singapore and Multan. However, for the case of St Petersburg (Latitude = 60 °N), the x for the SAPG plant using ET is higher than using the ET collectors. At St. Petersburg, the maximum x is 0.47 kWh/\$y for using PT collectors, and 0.56 kWh/\$y for using ET collectors. The results indicate that in the locations with higher latitudes, an SAPG plant using ET collectors has higher x.

In the x calculations above, only the capital costs for the collectors were considered. However, in practice, PT collectors would induce more costs e.g. operation and maintenance, as they require to track the sun. This would decrease the economic advantages of the SAPG plant using PT collectors further.

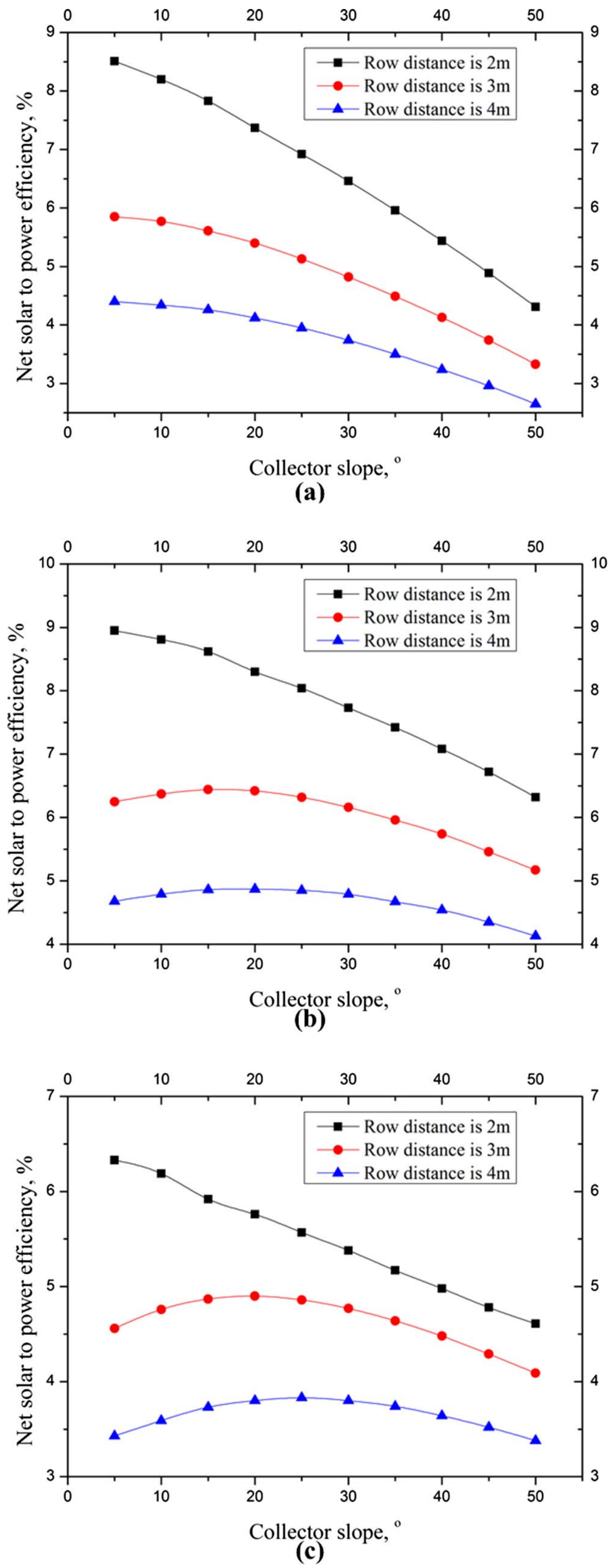

Fig. 8. Net solar to power efficiency (η_{Net}) of an SAPG plant using evacuated tube collectors with different row distances and tilt angles in three investigated locations (a) Singapore, (b) Multan, and (c) St. Petersburg.

Table 6
Comparison of the maximum η_{Net} for an SAPG plant using parabolic trough and evacuated tube collectors installed on 180,000 m² of land.

	Evacuated tube collectors			Parabolic trough collectors		
Row distance (m)	2 m	3 m	4 m	10 m	15 m	20 m
Collector area installed (m²)	183,430	122,287	91,715	84,780	56,520	42,390
Singapore (Singapore)	8.5%	5.9%	4.4%	4.7%	3.2%	2.4%
Multan (Pakistan)	9.0%	6.4%	4.9%	6.3%	4.5%	3.4%
St. Petersburg (Russia)	6.3%	4.9%	3.8%	5.8%	3.4%	3.3%

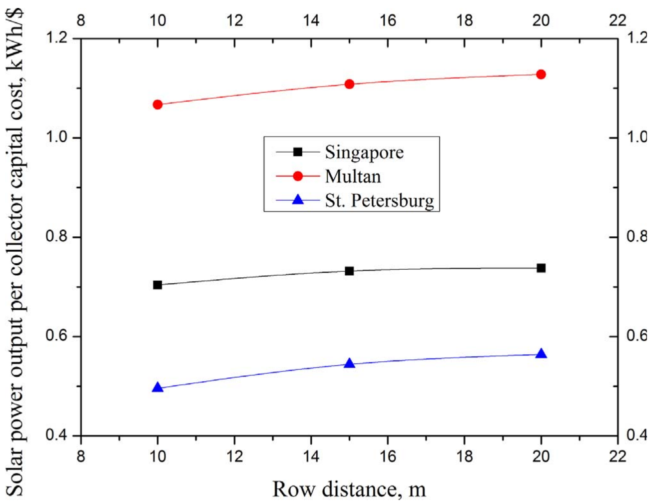

Fig. 9. Solar power output per collector capital cost (x) of an SAPG plant using parabolic trough collectors with different row distances in three investigated locations: (a) Singapore, (b) Multan, (c) St. Petersburg.

6. Conclusions

In a Solar Aided Power Generation (SAPG) plant, concentrating solar collectors (e.g., parabolic trough (PT) collectors) can be used to displaced the extraction steam to high pressure/temperature feedwater heaters (FWHs), while non-concentrating solar collectors (e.g., evacuated tube (ET) collectors) can be used to displace the extraction steam to low pressure/temperature FWHs. In this study, the PT collectors and ET collectors are assumed to be installed on a given piece land (300 m × 600 m) with different layouts to produce the solar thermal energy. The technical and economic performance of the SAPG plants using PT and ET collectors have been evaluated and compared. Annual solar radiation in three locations (Singapore, 1 °N, 104 °E, Singapore; Multan, 30 °N, 71 °E, Pakistan; and St. Petersburg, 60 °N, 30 °E, Russia) were selected for this case study.

The results draw the following conclusions:

- An SAPG plant using PT collectors and ET collectors has the highest net solar to power efficiencies (η_{Net}) when the row distance for the PT and ET collectors are 10 m and 2 m, respectively.
- The η_{Net} of the SAPG plant using ET collectors is higher than that using the PT collectors. However, the technical advantages of using

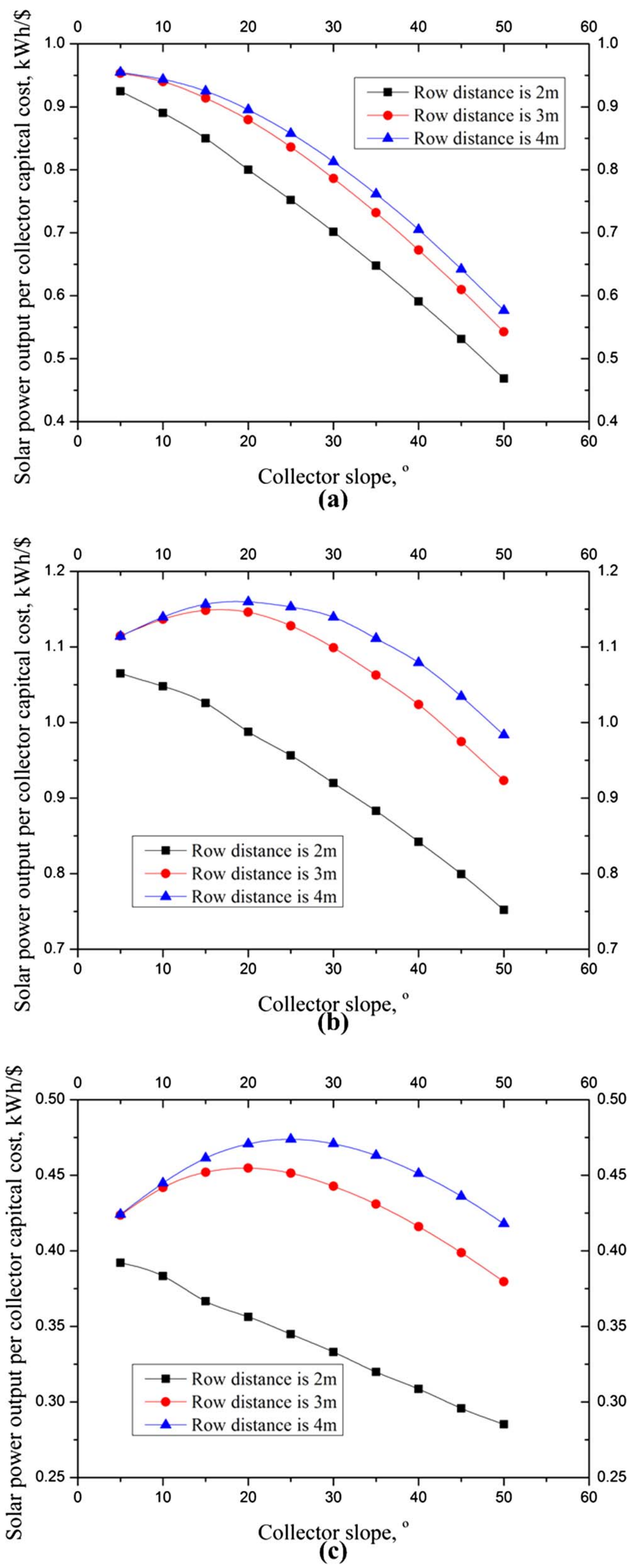

Fig. 10. Solar power output per collector initial capital cost (x) for an SAPG plant using evacuated tube collectors with different row distance and tilt angles in three investigated locations: (a) Singapore, (b) Multan, (c) St. Petersburg. The initial unit capital cost of the evacuated tube collectors is assumed to be 190 $/m².

Table 7
Comparison of the x of an SAPG plant using parabolic trough and evacuated tube collectors.

	Evacuated tube collectors			Parabolic trough collectors		
Row distance (m)	2	3	4	10	15	20
Collector area (m^2)	183,430	122,287	91,715	84,780	56,520	42,390
Singapore (Singapore)	0.93 kWh/$y	0.95 kWh/$y	0.96 kWh/$y	0.70 kWh/$y	0.73 kWh/$y	0.74 kWh/$y
Multan (Pakistan)	1.07 kWh/$y	1.15 kWh/$y	1.16 kWh/$y	1.07 kWh/$y	1.11 kWh/$y	1.13 kWh/$y
St. Petersburg (Russia)	0.39 kWh/$y	0.46 kWh/$y	0.47 kWh/$y	0.50 kWh/$y	0.54 kWh/$y	0.56 kWh/$y

ET collectors over using PT collectors decrease with the increase in the latitude.

- In the locations with lower latitudes (i.e. Singapore, Multan), an SAPG plant using ET collectors has economic advantages over using PT collectors. However, in the locations with higher latitudes (i.e. St. Petersburg), the result is contrary

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Principal Author

Name of Principal Author (Candidate)	Jiyun Qin
Contribution to the Paper	Performed the literature review, wrote the manuscript. Developed the pseudo-dynamic model required to simulate Solar Aided Power Generation operated in different non-displaced feedwater heater operation strategies. Took primary responsibility for responding to the reviewers.
Overall percentage (%)	60
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature	Date 20/6/2017

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Associate Professor Eric Hu
Contribution to the Paper	Supervised the work done. Provided assistance in developing the pseudo-dynamic. Assisted with editing and finalising the manuscript. Provided assistance with addressing comments from reviewers.
Signature	Date 20/6/2017

Name of Co-Author	Professor Graham J. Nathan
Contribution to the Paper	Supervised the work done. Provided suggestions and recommendations to improve modelling approach. Assisted with editing the manuscript.
Signature	Date 20/6/17

Please cut and paste additional co-author panels here as required.

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Jiyun Qin, Eric Hu, Graham J. Nathan

School of Mechanical Engineering, The University of Adelaide, Adelaide, Adelaide, SA 5005, Australia.

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Jiyun Qin, Eric Hu *, Graham J. Nathan

School of Mechanical Engineering, The University of Adelaide, Adelaide, SA 5005, Australia

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ABSTRACT

Solar Aided Power Generation is a technology in which low grade solar thermal energy is used to displace the high grade heat of the extraction steam in a regenerative Rankine cycle power plant for feedwater preheating purpose. The displaced extraction steam can then expand further in the steam turbine to generate power. In such a power plant, using the (concentrated) solar thermal energy to displace the extraction steam to high pressure/temperature feedwater heaters (i.e. displaced feedwater heaters) is the most popular arrangement. Namely the extraction steam to low pressure/temperature feedwater heaters (i.e. non-displaced feedwater heaters) is not displaced by the solar thermal energy. In a Solar Aided Power Generation plants, when solar radiation/input changes, the extraction steam to the displaced feedwater heaters requires to be adjusted according to the solar radiation. However, for the extraction steams to the non-displaced feedwater heaters, it can be either adjusted accordingly following so-called *constant temperature* strategy or unadjusted i.e. following so-called *constant mass flow rate* strategy, when solar radiation/input changes. The previous studies overlooked the operation of non-displaced feedwater heaters, which has also impact on the whole plant's performance. This paper aims to understand/reveal the impact of the two different operation strategies for non-displaced feedwater heaters on the plant's performance. In this paper, a 300 MW Rankine cycle power plant, in which the extraction steam to high pressure/temperature feedwater heaters is displaced by the solar thermal energy, is used as study case for this purpose. It was found that plant adopting the constant temperature strategy is generally better than that adopting the constant mass flow rate strategy. However, if rich solar energy is available, adopting the constant mass flow rate strategy can achieve better performance.

1. Introduction

In recent years, environmental issues around fossil fired power plants have led to solar thermal power plants attracting more attention. Different sunlight heating system has been evaluated [19]. However, solar thermal power plants have the disadvantage of higher costs when compared with lower cost fossil fired power plants. Therefore, a hybrid power system, integrating solar thermal energy into a conventional fossil fired power plant, has become an attractive option [12]. One hybrid power system uses solar thermal energy to preheat the feedwater of a regenerative Rankine cycle (an RRC) power plant [31]. Using this system, the extraction steam of the power plant, which is bled from the steam turbine to preheat the feedwater in a feedwater heater (FWH), can be displaced by the solar thermal energy. The displaced extraction steam is then expanded further in the steam turbine to generate power. This kind of power plant is known as a Solar Aided Power Generation (SAPG) plant [7,8]. The thermodynamic benefit of the SAPG plant comes from the displaced high quality (i.e. high temperature) extraction steam [26,27]. This technology has advantage of higher solar thermal to power efficiency than the solar alone power plant [30]. Also, the exergy losses of the RRC plant are decreased after the solar thermal input [4,5].

In an SAPG plant with multi-stages of extraction steam (i.e. with different temperature), the solar thermal energy is often used to displace part stages of extraction steam, not all the stages of extraction steam. It was found that solar thermal energy used to displace higher temperature extraction steam leads to greater solar thermal to power efficiency than that used to displace lower temperature extraction steam [28,29]. Zhao and Bai [32] also got the same results from an exergy perspective. In a typical RRC power plant, the FWHs include the high pressure/temperature FWHs, deaerator (DEA) and low pressure/temperature FWHs. Since the DEA is used for removing the oxygen from the feedwater, the extraction steam to the DEA is not displaced by the solar thermal

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

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Nomenclature

P_{solar}	annual power output from solar thermal energy, kW h
$\dot{Q}_{Boiler}$	variation of the re-heater load after the solar thermal input, kW
$\dot{Q}_{Solar}$	useful solar thermal power input into the power plant, kW
$\dot{Q}_{solar,on}$	solar thermal power falling on the solar collector, kW
W_{Ref}	power output from the reference RRC plant, kW
W_{Solar}	instantaneous solar power output, kW
W_{Total}	total electricity power output from the SAPG plant, kW
x_{Solar}	instantaneous solar share, %
$\eta_{Net\ solar}$	annual net solar-to-power efficiency, %
η_{Solar}	instantaneous solar thermal to power efficiency, %

Abbreviation

CT	constant temperature strategy
CM	constant mass flow rate strategy
DEA	deaerator
DNI	Direct Normal Insulation
FWH	feedwater heater
HTF	heat transfer fluid
LCOE	Levelized Cost of Electricity
RRC	regenerative Rankine cycle
SAPG	Solar Aided Power Generation
SP	solar preheater

energy. Some previous studied made a comparison between the displacement of the extraction steam to high pressure/temperature FWHs and low pressure/temperature FWHs. It was found that the displacement of extraction steam to low pressure/temperature FWHs has no significant effect on the performance of the SAPG plant [22]. Also, considering the overloading of the last turbine stages, the displacement of extraction steam to all high pressure/temperature FWHs is the best option for an SAPG plant [14]. Therefore, most subsequent studies about SAPG plants assumed that solar thermal energy is only used to displace the extraction steam to high pressure/temperature FWHs (i.e. displaced FWHs). This means that the extraction steam to low pressure/temperature FWHs (i.e. non-displaced FWHs) is not displaced by the solar thermal energy.

In an SAPG plant, when the solar radiation/input changes, the extraction steam should be adjusted responding to the variations of solar thermal input. Under the condition of only extraction steam to high pressure/temperature FWHs is displaced by the solar thermal energy, these extraction steam should be decreased (i.e. displaced) according to the solar thermal input. However, for the extraction steam to low pressure/temperature FWHs (i.e. non-displaced FWHs), which is not displaced by the solar thermal energy, these extraction steam can also be adjusted according to the solar thermal input. This is termed as non-displaced FWH operation strategy.

The impact of the non-displaced FWH operation strategies on the SAPG plant's performance has been overlooked by previous studies. Most of previous studies did not clearly defined the non-displaced FWH operation strategies that they are adopted. Based on the assumption that only extraction steam to high pressure/temperature FWHs has been displaced, Bakos and Tsechelidou [2] assessed the energy production cost and payback time of an SAPG plant, Pierce et al. [15] compared the cost of the SAPG plant with the solar alone power plant, Peng et al. [16–18] evaluated the SAPG plant under off-design condition of the power plant, and Zhu et al. [35,36] evaluated the solar contribution of the SAPG plant from exergy perspective. Zhao et al. [33,34] used a different criteria to optimise the SAPG plant modified from different capacity. Zhou et al. [37] used evaluated the SAPG plant with different solar collectors. Zhai et al. [38,39] optimised the solar contribution by adjusting the solar thermal fluid. Recently, Feng et al. [3] evaluated the thermodynamic-economic performance of the SAPG plant. However, these studies without mentioning the operation of the non-displaced feedwater heaters. Some other studies are based on a non-displaced FWH operation strategy that remains the feedwater outlet temperature of the non-displaced FWHs unchanged. Based on this strategy, Hou et al. [9,10,11] evaluated an SAPG plant, which is modified from a 300 MW power plant, with different collector areas to achieve the lowest Levelized Cost of Electricity (LCOE). Also, Wu et al. [23,24,25] evaluated an SAPG plant with a storage system. However, there are still some other previous studies based on the non-displaced FWH operation strategy that remains the extraction steam flow rates to non-displaced FWH unchanged [28,29]. Qin and Hu [20] evaluated the SAPG plant based on this strategy. It is obvious that most of previous studies have not clearly define their non-displaced FWH operation strategy. For an SAPG plant, the technical benefit comes from the extraction steam [26,27]. Although the extraction steam to non-displaced FWHs is not displaced by the solar thermal energy, their operation strategies still can impact the SAPG plant's performance. SAPG plant adopting different non-displaced FWH operation strategies would lead different technical performance. However, the impact of the non-displaced FWH operation strategy is lack of study. The comparison of different non-displaced FWH operation strategies is a gap in the extant studies.

The present paper aims to understand/reveal the impact of the non-displaced FWH operation strategies on the SAPG plant's performance in terms of the instantaneous and annual solar power output, solar share and solar efficiency.

2. Operation of non-displaced FWH in an SAPG plant

In an SAPG plant, the solar thermal energy carried by the heat transfer fluid (HTF) is used to displace some extraction steam through a heat exchanger (a solar preheater, or SP) to preheat feedwater. The SP facilitates heat transfer process between the HTF and feedwater of power plant.

2.1. Displaced FWH and non-displaced FWH

In an SAPG plant, the feedwater heaters of which the extraction steam is displaced (by solar heat) are termed as *Displaced feedwater heaters*. Other feedwater heaters of which the extraction steam is not displaced are termed as *Non-displaced feedwater heaters*. Fig. 1 presents a simplified SAPG plant, in which the solar thermal energy is used to displace the extraction steam to high pressure/temperature FWHs while the extraction steam to the DEA and low pressure/temperature FWHs is not displaced (by the solar thermal energy).

2.2. Non-displaced FWH operation strategies

In an SAPG plant as shown in Fig. 1, the mass flow rates of the extraction steam to displaced FWHs (i.e. extraction steam at points

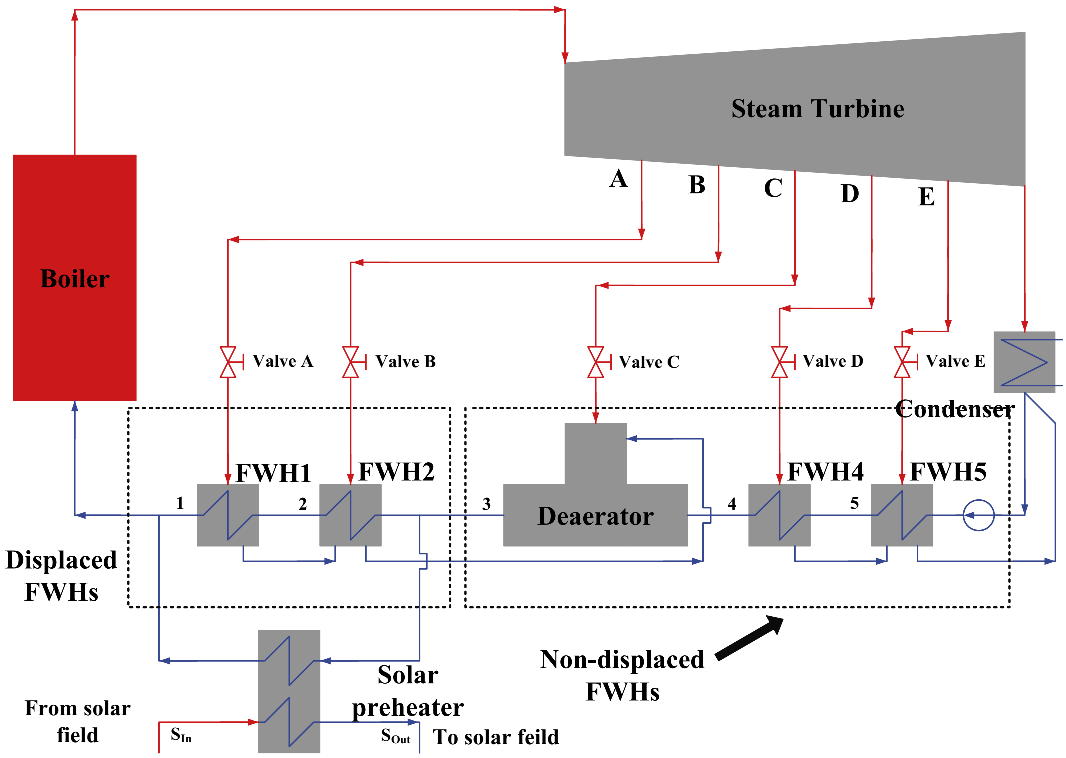

Fig. 1. Schematic diagram of a Solar Aided Power Generation (SAPG) plant, in which solar thermal energy is used to displaced extraction steam to high temperature feedwater heaters (i.e. FWH1 and FWH2).

A and B) have to be adjusted when solar radiation/input changes, in order to maintain the temperature of feedwater entering boiler unchanged. However, the extraction steam flow rates to non-displaced FWHs (i.e. extraction steam at points C to E), can either be adjusted accordingly following so-called *constant temperature* (CT) strategy or simply unadjusted following so-called *constant mass flow rate* (CM) strategy, when solar radiation/input changes.

In other words, when solar radiation/input changes,

- The CT strategy requires adjusting the mass flow rates of extraction steam to non-displaced FWHs (i.e. extraction steam at points C to E in Fig. 1) to maintain the feedwater outlet temperature of each non-displaced FWHs (i.e. DEA, FWH4 and FWH5 in Fig. 1) unchanged;
- The CM strategy, however, does not requires the mass flow rates of extraction steam to non-displaced FWHs (i.e. extraction steam at points C to E in Fig. 1) to be adjusted or changed when solar input and feedwater flow rate (through the FWHs) change. Namely, the CM strategy does not require to adjust the extraction flow rates (to the non-displaced FWHs) at all by allowing the feedwater outlet temperature of each non-displaced FWHs (i.e. DEA, FWH4 and FWH5 in Fig. 1) to vary.

When solar radiation/input into an SAPG plant changes, adjusting extraction steam flow to the non-displaced FWHs (i.e. adopting CT strategy) or not (i.e. adopting CM strategy) would have an impact on plant's performance.

3. SAPG plant's performance simulation model

To study the impact of the different strategies on the plant's performance, an improved simulation model has been developed based on an earlier model of Qin et al. [21]. The simulation model consists of an SAPG plant sub-model and a solar field sub-model.

3.1. SAPG plant and solar field sub-models

The SAPG plant sub-model developed is able to conduct steady state and pseudo-dynamic simulations. The steady state simulation calculates the instantaneous performance of the SAPG plant with given solar power input. The pseudo-dynamic simulation calculates the annual performance of the SAPG plant with hourly solar thermal input. The solar field sub-model could calculate hourly HTF flow rate at given exiting temperature by using the hourly solar radiation data. The details of the two sub-models could be found in Qin et al. [21].

3.2. Evaluation criteria

To assess the performance of an SAPG plant, the following criteria are used in this study:

(1) Instantaneous solar power output (W_{Solar}, kW):

$$W_{Solar} = W_{Total} - W_{Ref}, \quad (1)$$

where W_{Total} (kW) is the total electricity power output from the SAPG plant, and W_{Ref} (kW) is the power output from the reference RRC plant.

(2) Instantaneous solar share (x_{Solar}, %):

The instantaneous solar share is the ratio of the instantaneous solar power output to the total power output of SAPG plant, which can be presented as:

$$x_{Solar} = \frac{W_{Solar}}{W_{Total}}. \quad (2)$$

(3) Instantaneous solar thermal to power efficiency (η_{Solar}, %):

$$\eta_{Solar} = \frac{W_{Solar}}{\dot{Q}_{Solar} + \Delta\dot{Q}_{Boiler}}. \quad (3)$$

where $\dot{Q}_{Solar}$ (kW) is the useful solar thermal power input into the power plant, and $\Delta\dot{Q}_{Boiler}$ (kW) is the variation of the re-heater load due to the solar thermal input.

(4) Annual solar power output (P_{solar}, kW h):

The annual solar power output is the annual total power generated by the solar thermal energy, which can be presented as:

$$P_{solar} = \sum W_{Solar}\Delta t, \tag{4}$$

(5) Annual net solar-to-power efficiency ($\eta_{Net\ solar}$, %):

$$\eta_{Net\ solar} = \frac{P_{solar}}{\sum \dot{Q}_{solar,on}\Delta t}, \tag{5}$$

where $\sum \dot{Q}_{solar,on}\Delta t$ (kW h) is the sum of the annual solar thermal energy falling on the solar collector.

4. Case study

An SAPG plant, modified based on a conventional 300 MW sub-critical RRC power plant, is used as the study case.

4.1. SAPG plant

The schematic diagram of the power plant is shown in Fig. 2. The key parameters of the power plant are given in Table 1. It was assumed the solar thermal energy is used to displace the extraction steam at points A to C. Namely, the FWH1 to FWH 3 are displaced FWHs, while, the DEA, FWH5 to FWH8 are non-displaced FWHs. respectively.

There are also different strategies for adjusting the extraction steam to displaced FWHs (points A to C in Fig. 2) when solar input changes [21]. In present study, it is also assumed that the extraction steams at points A to C were adjusted to maintain the feedwater outlet temperature of FWH1 to FWH3 unchanged.

As a temperature difference of 10 °C assumed to be required between the HTF and the feedwater for heat transfer, the HTF inlet temperature of the SP is 279 °C. However, the HTF outlet temperature of the SP or inlet temperature of solar field depends on the non-displaced FWH operation strategy. In the study, if the CT strategy (to non-displaced FWHs) was adopted, the HTF outlet temperature of the SP would be 179 °C; while, the HTF outlet temperature of the SP would vary with the variations in solar radiation, if CM strategy was adopted.

4.2. Solar field and solar resource

As the HTF outlet temperature of solar field is 279 °C, a medium temperature solar collectors is needed. Therefore, the solar field in this study was assumed to consist of LS-2 parabolic trough solar collectors. Each set of LS-2 solar collectors is 47.1 m in length and 5 m in width [6], with an aperture area of 235.5 m^2. The distance between each row of collector is 15 m [6].

The hourly solar radiation data (Direct Normal Insulation, DNI) for a year for three locations are used for the simulation. The selected locations are Alice Springs (23°S, 133°E, Australia), Adelaide (34°S, 138°E, Australia), and Beijing (39°N, 116°E, China) which represents high, medium and low solar resource region respectively. The solar radiation data for Adelaide and Alice Springs were taken from the Australian Government Bureau of Meteorology [1] and for Beijing, the data was taken from the National Renewable Energy Laboratory [13]. Table 2 shows a summary of the solar radiation in the three locations.

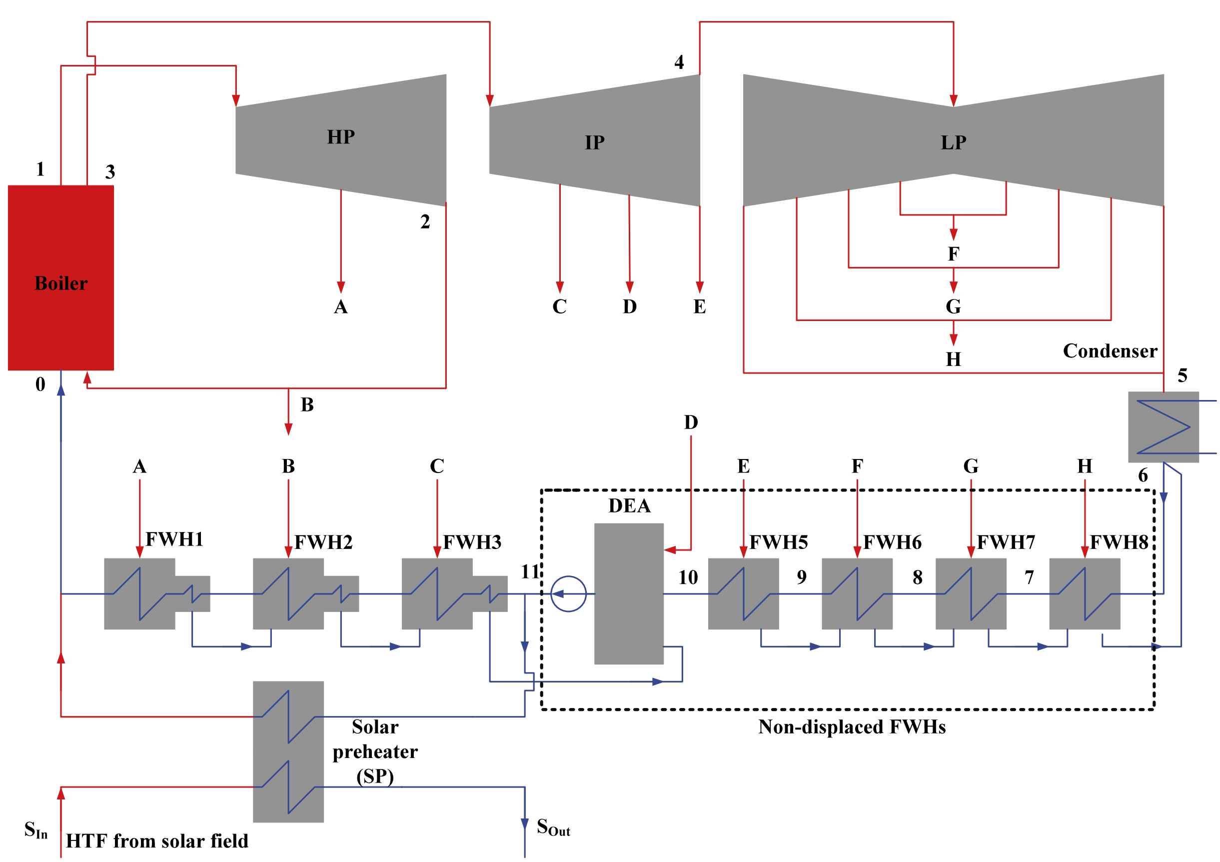

Fig. 2. Schematic diagram of a Solar Aided Power Generation (SAPG) plant, modified from a 300 MW regenerative Rankine cycle (RRC) power plant.

Table 1
Key parameters of the 300 MW power plant in Fig. 1.

Points in Fig. 2	A	B	C	D	E	F	G	H
Temperature (°C)	374.9	312.8	430.4	326.3	276.5	174.9	85.9	61.6
Pressure (Bar)	54.41	34.62	15.76	7.56	4.86	1.87	0.632	0.226
Flow rate (kg/s)	16.00	19.78	9.70	14.73	10.42	9.44	7.34	7.37
Points in Fig. 2	0	1	2	3	4	5	11	
Temperature (°C)	269	537	312.8	537	276.5	33.6	169	
Pressure (Bar)	196.18	167	34.62	31.16	4.77	0.052	–	
Flow rate (kg/s)	241.5	241.5	225.6	205.8	170.9	146.8	241.5	

Table 2
Summary of solar radiation for investigated sites.

Location	DNI annual total (kW h/m^2)	Maximum DNI (W/m^2)	Average sunny hours per day (h)	
Alice Springs	2857.6	1079	9.9	High annual solar radiation
Adelaide	1899.6	1078	8.1	Medium annual solar radiation
Beijing	1347.8	858	8.6	Low annual solar radiation

5. Results and discussion

In order to demonstrate the performance of the SAPG plant adopting CT and CM operation strategies for non-displaced FWHs, the instantaneous and annual performance of the CT and CM strategy have been simulated.

5.1. Instantaneous performance of the SAPG plant adopting CT and CM non-displaced FWH operation strategies

Figs. 3 and 4 present the instantaneous solar share (x_{Solar}), instantaneous solar power output (W_{Solar}) and the instantaneous solar thermal to power efficiency (η_{Solar}) of the SAPG plant with different non-displaced FWHs operation strategies with various useful solar thermal power input, respectively. It can be seen that the CT strategy has higher x_{Solar}, W_{Solar} and η_{Solar} than the CM strategy until useful solar thermal input is higher than about 130 MW in the study case. Also, Figs. 3 and 4 show that when the useful solar thermal input is higher than 108.2 MW for CT strategy and 142.1 MW for CM strategy, the x_{Solar} and W_{Solar} of two strategies remain unchanged and η_{Solar} start to drop significantly with the increment in solar thermal input. The reason is caused by the maximum solar thermal input for an SAPG plant, which means the maximum solar thermal energy input the plant can take, i.e. the extraction steam's flow rates to all displaced FWHs become nil. It can be seen when the solar thermal input achieve the maximum solar thermal input (108.2 MW for CT strategy, and 142.1 MW for CM strategy), the x_{Solar} and W_{Solar} achieve the maximum solar share ($x_{Solar,max}$) and maximum solar power output ($W_{Solar,max}$). Also, $x_{Solar,max}$ and $W_{Solar,max}$ for CT strategy is higher than the CM strategy. It implies CM strategy is able to generate more power from solar energy if required and rich solar energy available.

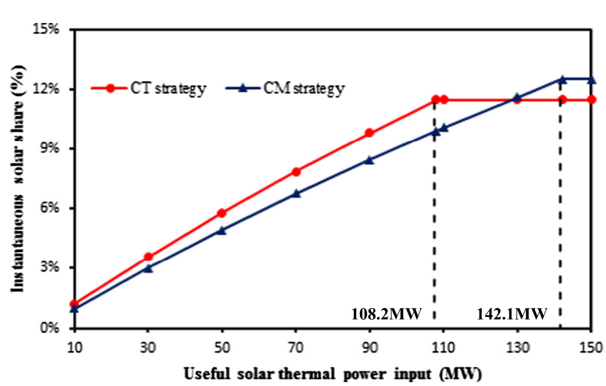

Fig. 3. Instantaneous solar share (x_{Solar}) of the SAPG plant with CT and CM non-displaced FWH operation strategies as a function of useful solar thermal power input.

In order to understand the findings in Figs. 3 and 4 better, the simulation results of the extraction steam flow rates and the feedwater outlet temperature of non-displaced FWHs (point 11 in Fig. 2) with different solar thermal power input in two operation strategies are given in Figs. 5–7, respectively.

In an SAPG plant, the solar energy does not generate power directly, instead displaces the extraction steams to the displaced FWHs. Therefore, more reduction of extraction steam flows to the displaced FWHs, more power generated by solar energy equivalently. As shown in Fig. 7, with the same solar thermal input, more reduction of extraction flows to the displaced FWHs could be achieved with CT strategy than that with CM strategy. This leads to the higher technical performance for the CT strategy than that for the CM strategy. The reason is that the reduced extraction steam flow rates to the displaced FWHs increase the feedwater flow rate entering the non-displaced FWHs (point 6 in Fig. 2). However, due to the different strategies to adjust the extraction steam's flow rates to non-displaced FWHs (shown in Fig. 5), the feedwater outlet temperatures of non-displaced FWHs (point 11 in Fig. 2) for CT and CM strategies are different (show in Fig. 6). Meanwhile, the displaced FWHs are required to supply feedwater at unchanged (design) temperature all the time. Therefore, with the same solar input, more extraction steam to the displaced FWHs required for CM strategy than the CT strategy as shown in Fig. 7. This means that more extraction steam has been displaced for the CT strategy than the CM strategy, which leads to higher technical performance for the CT strategy.

In addition, because the temperature of feedwater entering the displaced FWHs (point 11 in Fig. 2) is lower with CM strategy than that with CT strategy, it requires more solar thermal energy to fully displace the extraction steams to displaced FWHs for the CM strategy. Namely, with CM strategy, an SAPG plant could take more solar thermal energy than that with CT strategy, which means that CM strategy has higher maximum solar thermal input. In this study, 108.2 MW useful solar thermal power is required for the CT strategy to fully displace the extraction steam to displaced FWHs, while for the CM strategy, 142.1 MW is required.

It is also noted that, when the extraction steam to displaced FWHs has been fully displaced, the SAPG plant with CM strategy

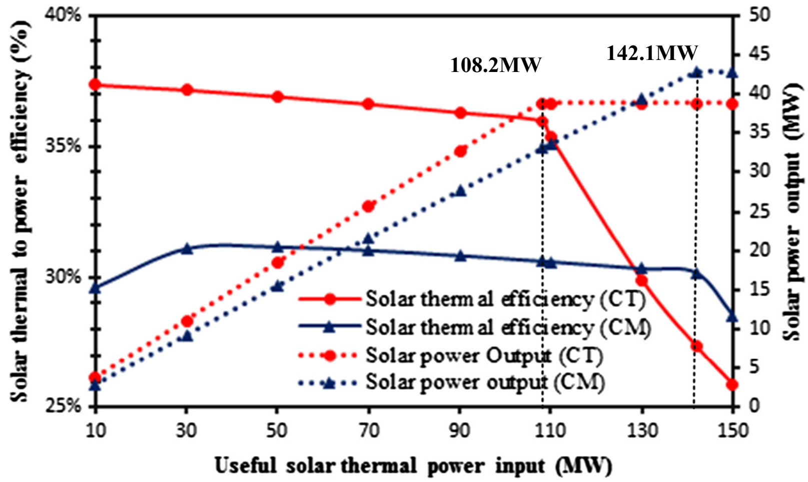

Fig. 4. Instantaneous solar thermal to power efficiency ($\eta_{Solar,CT}$) and instantaneous solar power output (W_{Solar}) of the SAPG plant with CT and CM non-displaced FWH operation strategies as a function of useful solar thermal power input.

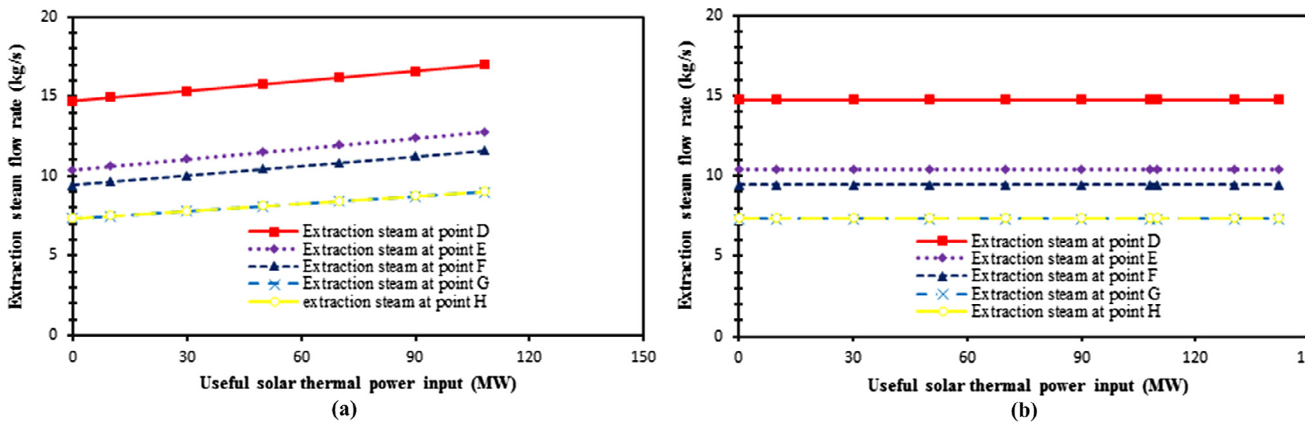

Fig. 5. Variations of extraction steam flow rate to the non-displaced FWHs (points D to G in Fig. 2) for the SAPG plant adopting the CT and CM non-displaced FWH operation strategy: (a) CT strategy; (b) CM strategy.

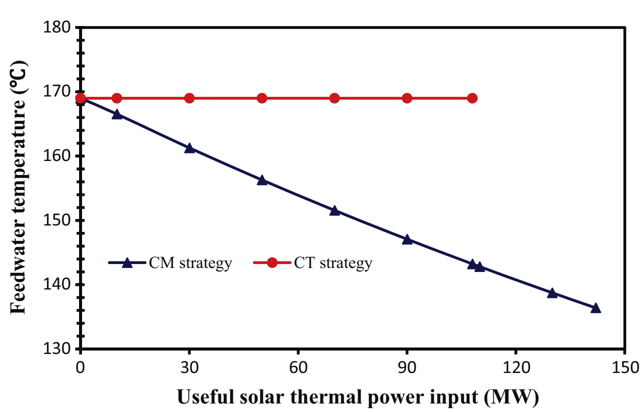

Fig. 6. Feedwater outlet temperature of the non-displaced FWHs (point 11 in Fig. 2) for the SAPG plant adopting the CT and CM strategies.

has higher maximum solar power output ($W_{Solar,max}$) and maximum solar share ($x_{Solar,max}$) than with the CT strategy. The reason is that when the extraction steam to displaced FWHs has been fully displaced, all the displaced extraction steam is expanded further in the steam turbine to generate power for the CM strategy. However, for the CT strategy, some of the displaced extraction steam is used to preheat the feedwater of power plant. Namely, partly displaced extraction steam is expanded further in the steam turbine. Therefore, the SAPG plant with CM strategy has higher $W_{Solar,max}$ and $x_{Solar,max}$ than that with CT strategy, as shown in Figs. 3 and 4. However, to achieve $W_{Solar,max}$ and $x_{Solar,max}$, CT and CM strategies require different maximum solar thermal input.

5.2. Annual performance of the SAPG plant adopting CT and CM non-displaced FWH operation strategies

Figs. 8–10 present the annual performance of an SAPG plant with CT and CM strategies as a function of the solar collector aperture area in the three locations. It can be seen that generally the CT strategy is superior to the CM strategy in terms of annual performance, unless the SAPG plant has oversized solar field and is located in high solar resource areas.

From Fig. 8, it can be seen that the $P_{solar,CM}$ is higher than $P_{solar,CT}$ only when the solar collector area is larger than about 270,000 m^2 in Alice Springs, and 330,000 m^2 in Adelaide. The reason is thought to be that when solar radiation and solar collector area is high available solar thermal energy could be higher than the maximum solar thermal input for two strategies. Namely, in good and medium solar resource regions and with the solar field areas larger than these values, solar energy available would be more than the maximum solar thermal input. As CM strategy has higher

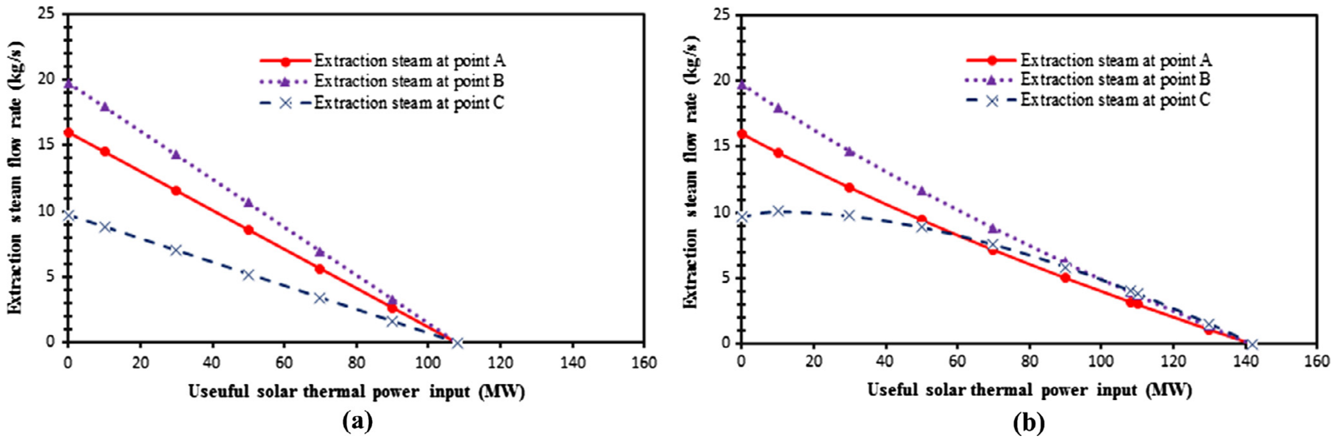

Fig. 7. Variations of extraction steam flow rate to the displaced FWHs (points A to C in Fig. 2) for the SAPG plant adopting the CT and CM non-displaced FWH operation strategy: (a) CT strategy; (b) CM strategy.

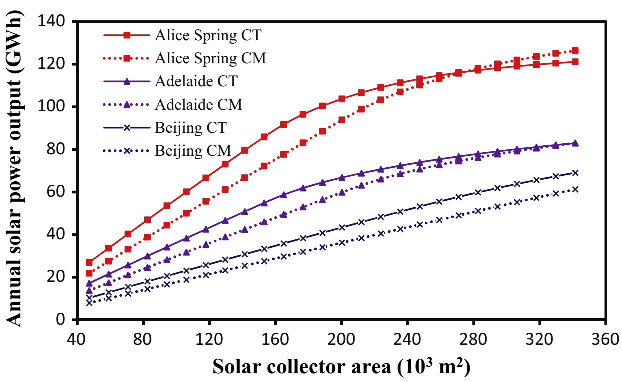

Fig. 8. Annual solar power output (P_{solar}) of the SAPG plant adopting CT and CM strategies in three locations, as a function of the solar collector aperture area.

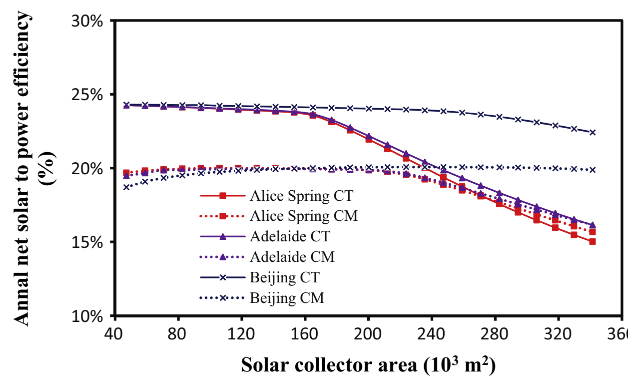

Fig. 10. Annual net solar-to-power efficiency ($\eta_{Net\ solar}$) with CT and CM strategies in three locations, as a function of the solar collector area.

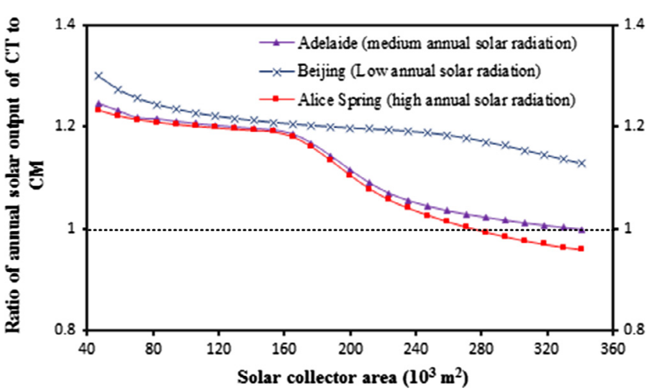

Fig. 9. Ratio of the annual solar power output of the CT strategy to the CM strategy ($P_{solar,CT}/P_{solar,CM}$), as a function of the solar collector aperture area.

$W_{Solar,max}$, therefore, plant performance with CM strategy has higher P_{solar}.

The results in Fig. 8 have been interpreted into the ratio of the annual solar power output of the CT strategy to CM strategy ($P_{solar,CT}/P_{solar,CM}$) as a function of solar collector area, as shown in Fig. 9. The ratio values greater than 1 indicates the annual solar power output of CT strategy is higher than that of CM strategy. As shown in Fig. 9, the technical advantages of the CT strategy decreases with the incremental solar collector area. However, in Beijing with lowest annual solar radiation, the ratio decreases more slowly than in Alice Springs and Adelaide with higher annual solar radiation.

Fig. 10 presents the annual net solar to power efficiency ($\eta_{Net\ solar}$) of the SAPG plant adopting the CT and CM strategies, respectively. It can be seen that generally the $\eta_{Netsolar,CT}$ is higher than the $\eta_{Netsolar,CM}$. However, if the solar collectors' areas larger than the 140,000 m^2, the $\eta_{Netsolar,CT}$ decreases with the increase of the collector areas in Alice Springs and Adelaide. In Beijing with lowest annual solar radiation, $\eta_{Netsolar,CT}$ decreases more slowly than that in Adelaide and Alice Springs with higher annual solar radiation.

6. Conclusions

In a Solar Aided Power Generation (SAPG) plant, the solar thermal energy is used to displace extraction steam to some, normally high pressure/temperature, FWHs (termed as displaced FWHs). For the extraction steam to other, i.e. low temperature FWHs (termed as non-displaced FWHs), which is not displaced by the solar thermal energy, there is *constant temperature* (CT) or *constant mass flow rate* (CM) strategy to operate when solar radiation/input changes. The study investigated the impact of the two strategies (to operate the non-displaced FWHs) on the overall performance of the SPAG plant operated in power boosting mode. The results draws following conclusions:

- When the extraction steam to displaced FWHs has been partly displaced, with the same useful solar thermal input, the SAPG plant adopting the CT strategy generally has higher instantaneous solar power output, instantaneous solar share and instantaneous useful solar thermal to power efficiency than the CM strategy has;
- When the extraction steam to displaced FWHs has been fully displaced, it requires more solar energy input to fully displace these extraction steams with CM strategy than that with CT strategy. Namely, the SAPG plant with CM strategy could take more useful solar energy/input than that with CT strategy. Under this condition, the maximum instantaneous solar share and solar power output with CM strategy is higher than that with CT strategy.
- The annual performance simulations for high (Alice Springs, Australia), medium (Adelaide, Australia) and low (Beijing, China) solar resource areas found generally, the SAPG plant with the CT strategy generates higher annual performance than that with CM strategy in all three locations. However, the difference decreases with the incremental solar thermal input (i.e. solar collector areas increase).
- The plant with CM strategy could achieve higher annual solar power output and annual net solar thermal to power efficiency if the solar field area is oversized and plant located in the high solar resources area.

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Principal Author

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Contribution to the Paper	Performed the literature review, wrote the manuscript. Developed the pseudo-dynamic model required for the mixed mode operation. Responsible for submission process.		
Overall percentage (%)	60		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Associate Professor Eric Hu		
Contribution to the Paper	Supervised the work done. Provided suggestions and ideas to improve concept of mixed mode operation. Provided assistance with addressing comments from reviews.		
Signature		Date	7/11/17

Name of Co-Author	Professor Graham J. Nathan		
Contribution to the Paper	Supervised the work done. Provided suggestions and recommendations to improve concept of mixed mode operation and Relative Profitability. Assisted with editing the manuscript.		
Signature		Date	7/11/17

Name of Co-Author	Dr. Lei Chen		
Contribution to the Paper	Supervised the work done. Assisted with editing the manuscript.		
Signature		Date	7/11/17

6 Mixed mode operation for the Solar Aided Power Generation

Jiyun Qin, Eric Hu, Graham J. Nathan, Lei Chen

School of Mechanical Engineering, The University of Adelaide, Adelaide, Adelaide, SA 5005, Australia.

Applied Thermal Engineering, submitted August 2017-Manuscript number: ATE_2017_4805.

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Jiyun Qin, Eric Hu*, Graham J. Nathan, Lei Chen

Key words: Solar Aided Power Generation, mixed mode of operation, single mode of operation, relative profitability, economic performance.

Corresponding Author: Eric Hu

Corresponding Author's Details

Phone number: +61 (0) 8 8313 0545

Email address: eric.hu@adelaide.edu.au

Address: The University of Adelaide, Australia 5005.

Mixed mode operation for the Solar Aided Power Generation

Jiyun Qin, Eric Hu*, Graham J. Nathan, Lei Chen

School of Mechanical Engineering, the University of Adelaide, Adelaide SA 5005 Australia

* Corresponding authors: eric.hu@adelaide.edu.au

Abstract

Integrating solar heat into a regenerative Rankine cycle power plant to displace the heat of the extraction steam is a highly efficient method to use solar thermal energy for power generation purpose. This technology is termed Solar Aided Power Generation. Such a power system can be operated for power boosting or fuel saving mode of operation. Here, we proposed a mixed mode of operation. In such a mixed mode of operation, the Solar Aided Power Generation is operated at a series of time intervals. In each time interval, such a power system is operated in one selected mode (i.e. either power boosting or fuel saving mode) with higher profitability. In this paper, the superiority of the mixed mode of operation over the single mode of operation (i.e. power boosting or fuel saving) has been demonstrated through two case studies. In these case studies, a Solar Aided Power Generation plant located in Australia and China where the market (and weather) conditions are significantly different, is assumed to operate in power boosting, fuel saving and mixed mode of operation. The results indicate that the mixed mode of operation could guarantee the best economics for such a power system over the single mode of operation in different markets. In Australia where the on-grid tariff fluctuate significantly, the annual profitability of the mixed mode of operation could be up to 12.1% higher than that of a single mode of operation. In China where is electricity market is controlled by the government and relatively flat, this economic advantage of mixed mode of operation over the single mode of operation decreases to only about 2.0%.

Key words: Solar Aided Power Generation, operation of plant, mixed mode of operation, single mode of operation, relative profitability.

Nomenclature

$C_{Capital}$	initial capital costs of the plant, $
$C_{E,i}$	electricity on-grid tariff (i.e. price achieved by the power plant selling electricity to the grid) at time interval i, $/kWh
C_{other}	Other annual operation costs of the SAPG plant including O&M and bank interest charge etc., $
$C_{F,i}$	fuel price at time interval i, $/MJ
$m_{f,i}$	fuel consumption of the boiler at time interval i, MJ/h
$\dot{Q}_{Solar,In,Max}$	maximum solar thermal input, kW
RP_i	relative profitability of the SAPG plant at time interval i, $
$W_{Total,i}$	total power output of the plant at time interval i, kW
Δt	time interval (i.e. 1 h)

Abbreviation

ARP	Annual Relative Profitability
DNI	Direct Normal Insolation (W/m^2)
FS	fuel saving
FWH	feedwater heater
HTF	heat transfer fluid
LCOE	Levelized cost of electricity
O&M	operating and maintenance
PB	power boosting
RP	Relative Profitability
RRC	regenerative Rankine cycle
SAPG	Solar Aided Power Generation
SP	Solar preheater

Subscript

i	i^{th} time interval

1. Introduction

Solar thermal power generation has the advantages of clean, low greenhouse emissions. However, solar thermal power also suffers from high costs and the variable nature of the resources [1]. As fossil-fired power plants are still the backbone of electricity production and have the advantage of lower costs but the disadvantage of high greenhouse emissions, integrating solar energy into fossil-fired power plants is attracting growing attention [2]. Solar Aided Power Generation (SAPG) is one of the integrating technologies in which the solar thermal energy is used to displace the heat of extraction steam (in regenerative Rankine cycle, RRC) to preheat the feedwater to the boiler [3]. The displaced extraction steam can therefore expand further in a steam turbine to generate power. Compared with a stand-alone solar power plant, the solar to power efficiency of an SAPG plant is not capped by the solar collector's temperature [4]. It was also found that this technology has the advantage of a lower capital cost than other integrating technologies [5]. Compared with a stand-alone power plant, the SAPG plant still has a higher thermo-economic benefit [6, 7].

An SAPG plant can be operated in two modes of operation: a power boosting (PB) mode and a fuel saving (FS) mode [8], as is shown in Fig. 1. The PB mode is defined as being where the additional power is generated without changing the steam flow rates of the boiler. The FS mode is defined as being when the power output of the plant is maintained by reducing the fuel consumption of the boiler. When the SAPG plant is operated in FS mode, the steam flow rates of the boiler should be adjusted i.e. reduced [9]. The benefit of the PB mode of operation is the increased power output, which has great potential when coupled with a high on-grid electricity tariff. The benefit of the FS mode of operation is the decreased fuel consumption, which has great potential for making savings in the face of rising fuel prices and the carbon tax [10]. It was found that with the same solar thermal input, the displacement of extraction steam at a higher temperature leads to higher technical benefits, i.e. to additional power output for the PB mode of operation and saved fuel consumption for the FS mode of operation [11, 12].

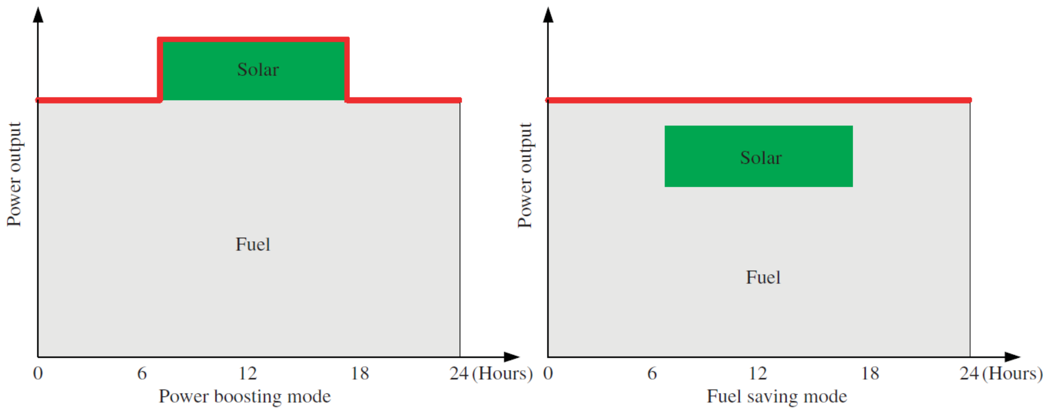

Fig. 1. The alternative daily "power boosting" and "fuel saving" modes operation for an SAPG plant [13].

When assessing the economic performance of an SPAG plant, most of the previous studies used the levelized cost of electricity (LCOE) as the economic criterion. It was found that, based on the PB mode of operation, there is a 5-7% increment in the LCOE for an SAPG plant over a stand-alone power plant [14]. It was also found that the carbon tax still has an impact on the LCOE of an SAPG plant operated in PB mode [15]. Also, the LCOE of an SAPG plant operated in FS mode is higher than that for the PB mode operation [16]. However, based on an SAPG plant operated in PB mode, Pierce et al. found that an SAPG plant is more cost effective than a stand-alone power plant due to the lower capital costs [17]. Based on an SAPG plant operated in FS mode, Hou et al. found that there is an optimal solar field area for an SAPG plant to achieve the lowest LCOE [18, 19]. Wu et al. and Zhou et al. also found that the optimal solar field area was influenced by the solar radiation, storage capacity and load of the power plant [20, 21]. For an SAPG operated in FS mode, it found that adjusting the solar thermal temperature and storage capacity can also help to achieve lowest LCOE for an SAPG plant [22, 23, 24]. Form previous studies, it was found that the measurements of SAPG plants always assume either PB or FS modes of operation for a whole year. Such an evaluation of LCOE and capital cost for the SAPG plant can help to optimise the design of the SAPG plant but cannot guide its operation.

As the SAPG plant is operated under variable electricity on-grid tariffs and fuel prices, an SAPG plant operated in PB or FS modes of operation for a whole year would achieve a different annual performance [25]. Once an SAPG plant has been built, mixing the PB and FS modes may achieve greater annual economic returns for the SAPG plant. However, as the previous studies are based on a single mode of operation, there is a gap in the knowledge as to how to switch between PB and FS modes to achieve greater annual economic returns. Also, in order to compare the economic profitability of an SAPG plant operated in both PB and FS mode, a new economic related criterion that links the electricity on-grid tariff and the fuel price together in order to evaluate the potential profitability of an SAPG plant, which can then be used to guide the actual operation of an SAPG plant, is required.

In the present paper, how to operate the SAPG plant to achieve maximum economic returns under different market conditions has been explored. A mixed mode of operation and a Relative Profitability (RP) criterion are proposed for guiding the operation of the SAPG plant to achieve the maximum economic benefit for the plant owner/operator. In particular, the economic returns of a mixed mode of operation and a single mode operation have been compared.

2. Operation and simulation model of a Solar Aided Power Generation plant

In a Solar Aided Power Generation (SAPG) plant, a mode of operation which mixes the Power Boosting (PB) and Fuel Saving (FS) modes may achieve greater annual economic benefit. However, the problem of how to guide the operation of such a mixed mode of operation is yet to be solved.

2.1. SAPG plant and its operation

An SAPG plant normally consists of a solar field, buffer tank sub-system, solar preheater (SP) sub-system and regenerative Rankine cycle (RRC) power plant, as shown in Fig. 2. The solar field is used to produce the heat transfer fluid (HTF) at a required temperature. The buffer-tank sub-system is used to supply the HTF at a steady flow rate to the SP at set time intervals. The SP sub-system is a heat exchanger system that facilities the heat transfer between the solar heat carried by the HTF and the feedwater of the boiler.

The operation of an SAPG plant requires control of the primary and extraction steam mass flow rates when the solar input changes, in order to ensure that the feedwater enters the boiler at a constant temperature. In PB mode, the primary steam (or feedwater) flow rate through the boiler (point 1, Fig. 2) remains unchanged and the extraction steam flow rates alone are adjusted when the solar input changes. In FS mode, all the primary and extraction steam rates need to be adjusted when the solar input changes. In practice, it is impossible to adjust the rates too frequently. Therefore, a reasonable time interval (e.g. 1

hour) is normally set. Thus, it is assumed the solar radiation/input and rates are unchanged with a set time interval, which would be facilitated practically by the buffer tank sub-system.

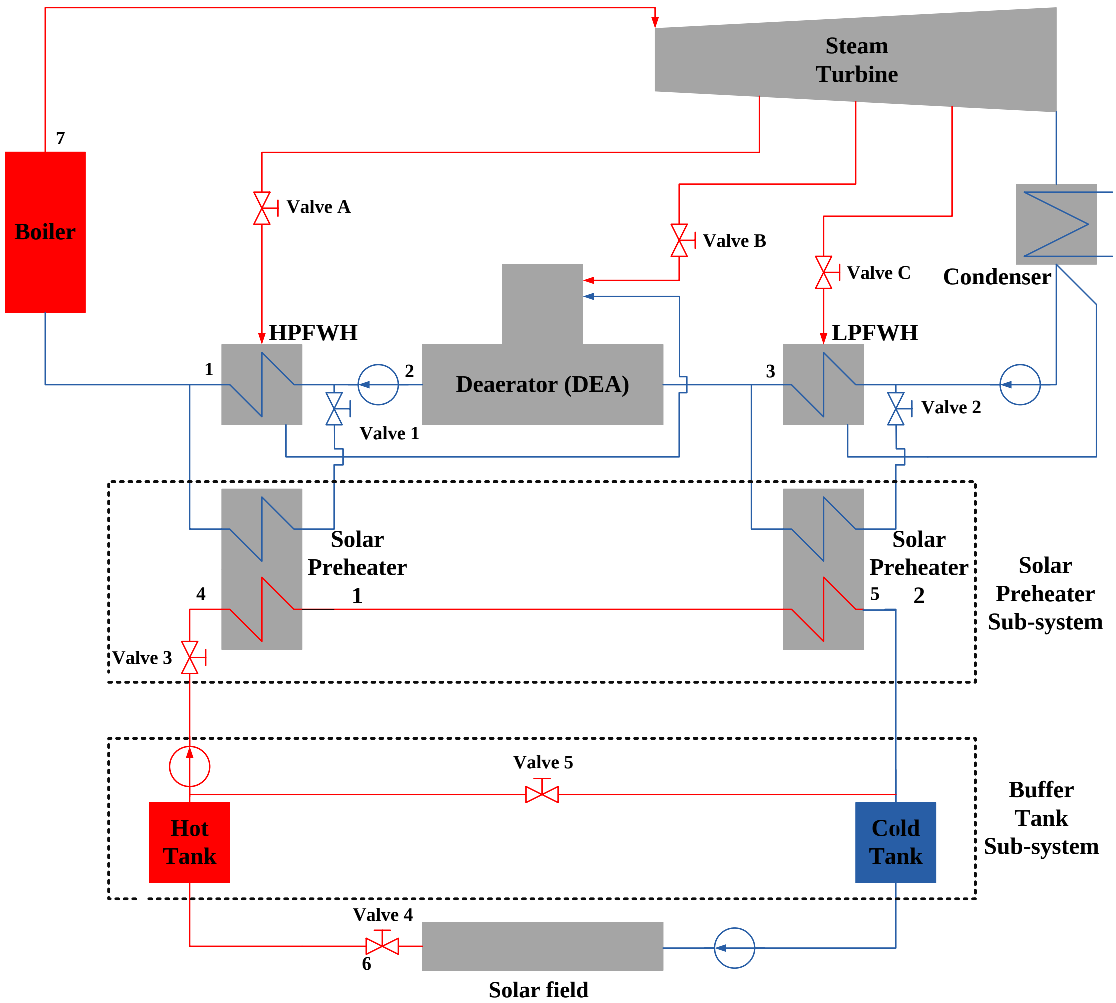

Fig. 2. Simplified schematic diagram of an SAPG plant for practical operation. The solar field is used to collect solar radiation, the buffer tank system is used to provide a stable HTF flow rate and the solar preheater is used to facilitate heat transfer between the HTF and the feedwater.

2.2. A Mixed mode of operation for an SAPG plant

In all previous studies, the SAPG plants were all assumed to be operated in either PB or FS mode for days, if not months. It is therefore expected that changing the plant's mode of operation on a time-interval basis according to the level of solar radiation, electricity on-grid tariff and fuel price, which change in every time interval, may maximize the annual economic benefit of an SAPG plant that had previously operated in a single mode all year round. This proposed mode of operation is termed (in this study) as a mixed mode of operation for an SAPG plant.

In such a mixed mode of operation, for each time interval (e.g. 1 hour) the economic performance of plants running in PB and FS modes are simulated respectively and whichever mode gives the better economic returns will be adopted to run the plant for the time interval. In order to assess and compare the economic returns for a time interval, a criterion termed the "Relative Profitability (RP)" is proposed. In the RP calculation, the electricity sale revenues, fuel costs and other costs, including operating and maintenance costs (O&M), can be considered. The Annual Relative Profitability (ARP) of a power plant is the sum of the RP in every time interval *i,* which is defined as:

$$ARP = \Sigma \mathrm{RP}_i - C_{other} = (\Sigma C_{E,i} W_{Total,i} \Delta t - \Sigma C_{F,i} m_{f,i} \Delta t) - C_{other}, \quad (1)$$

where:

RP_i ($) is the RP of the SAPG plant at time interval i;

$C_{E,i}$ ($/kWh) is the electricity on-grid tariff (i.e. the price at which the power plant is selling the electricity to the grid) in time interval i;

$W_{Total,i}$ (kW) is the total power output of the plant at time interval i;

Δt (h) is the time interval (i.e. 1 h);

$C_{F,i}$ ($/MJ) is the fuel price at time interval i;

$m_{f,i}$ (MJ/h) is the fuel consumption of the boiler at time interval i.

C_{other} ($) is the other annual operation costs of the SAPG plant, including O&M and bank interest charges etc., which are assumed to be dependent on the initial capital of the plant. C_{other} equals the initial capital costs, multiplied by a fraction factor f, accounting for the percentage of the other annual costs in relation to the initial capital costs, which means that $C_{other} = fC_{Capital}$.

The proposed mixed mode operation of an SAPG plant would make sure the plant runs in the mode (PB or FS) that produces a higher RP_i for every time interval (i.e. 1 hour). Mixed mode operation would therefore maximise the economic returns for the plant owners/operators, as demonstrated in the following case studies. However, to apply mixed mode operation, detailed information on the electricity and fuel markets must be known or estimated.

2.3. Simulation model for the mixed mode of operation

In this study, a validated pseudo-dynamic simulation model of by Qin et al. is used to simulation the performance of an SAPG plant [26, 27]. In this pseudo-dynamic model, the annual performance of an SAPG plant in different mode of operation is calculated as the sum of the SAPG's performance in series of time intervals (e.g. 1h). The simulation process for the SAPG plant in the mixed mode of operation is presented in Fig. 3.

The pseudo-dynamic simulation model for an SAPG plant consists of an RRC plant sub-model, and solar field sub-model. The RRC power plant sub-model can simulate the technical and economic performance of a power plant with given solar thermal input. The solar field sub-model is able to calculate the solar thermal output of parabolic trough (PT) collectors with given solar radiation, and geographical information.

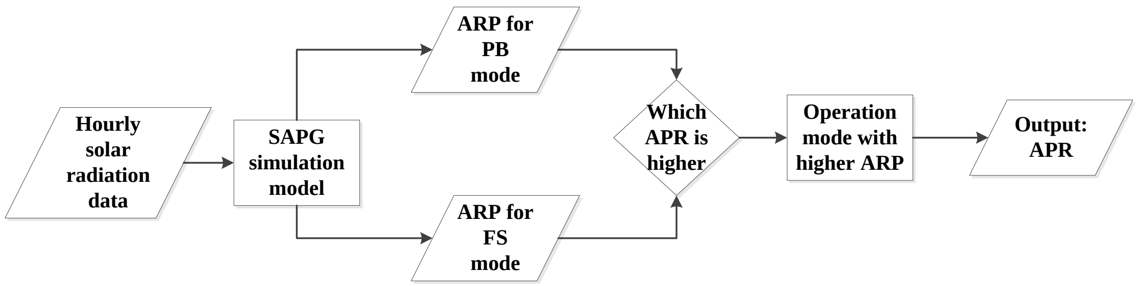

Fig. 3. Simulation process for the SAPG plant in the mixed mode of operation.

The RRC plant sub-model is based on the heat and mass balance of the RRC power plant. The input of the RRC power plant is the parameters (i.e. temperature, pressure) of the RRC power plant at key points. With the given solar thermal input, the mass flow rate of each point of the RRC power plant, the plant's output and boiler consumption can be calculated.

The solar field sub-model is still based on the heat and mass balance of PT solar collectors. The solar thermal output is calculated as the solar radiation absorbed less the heat losses of the solar field. The input of the solar field sub-model is the hourly solar radiation, geographical information and aperture area of PT solar collectors. The incident angle of PT collector is calculated based on the N-S tracking mode.

3. Case study

To demonstrate the superiority of the proposed mixed mode operation for SAPG plants, an SAPG plant modified from a 300MW coal fired power plant was assumed to be located in Adelaide (Australia) and Beijing (China), which has different electricity market conditions. The annual real electricity, fuel market and weather information has been used to evaluate the economic advantages of mixed mode operation.

3.1. Case study

The simplified heat and mass balance diagram of the plant is given in Fig. 4. As displacement of the extraction steam to high temperature FWHs (i.e. FWH 1 to FWH 3 in Fig. 4) is the best option for the SAPG plant [28], the solar thermal energy is used to displace the extraction steam to the FWHs in this study.

When solar radiation changes, the mass flow rate of the extraction steam is adjusted according to the level of solar radiation. In this case study, this flow rate of extraction steam is adjusted following the constant temperature strategy described by Qin et al. [26, 27], which the feedwater outlet temperature of each FWH unchanged. Hence, the HTF inlet temperature of the SP is assumed to be 279^{o}C, 10^{o}C higher than the feedwater outlet temperature for heat transfer.

The solar field used in the study case consists of a number of loops along the N-S axis orientation LS-2 parabolic trough solar collectors. Each loop has 10 sets of collectors.

The length of each set of collectors is 47.1m and the width is 5m [29]. Therefore, the aperture area of each set of collectors is 235.5 m^2.

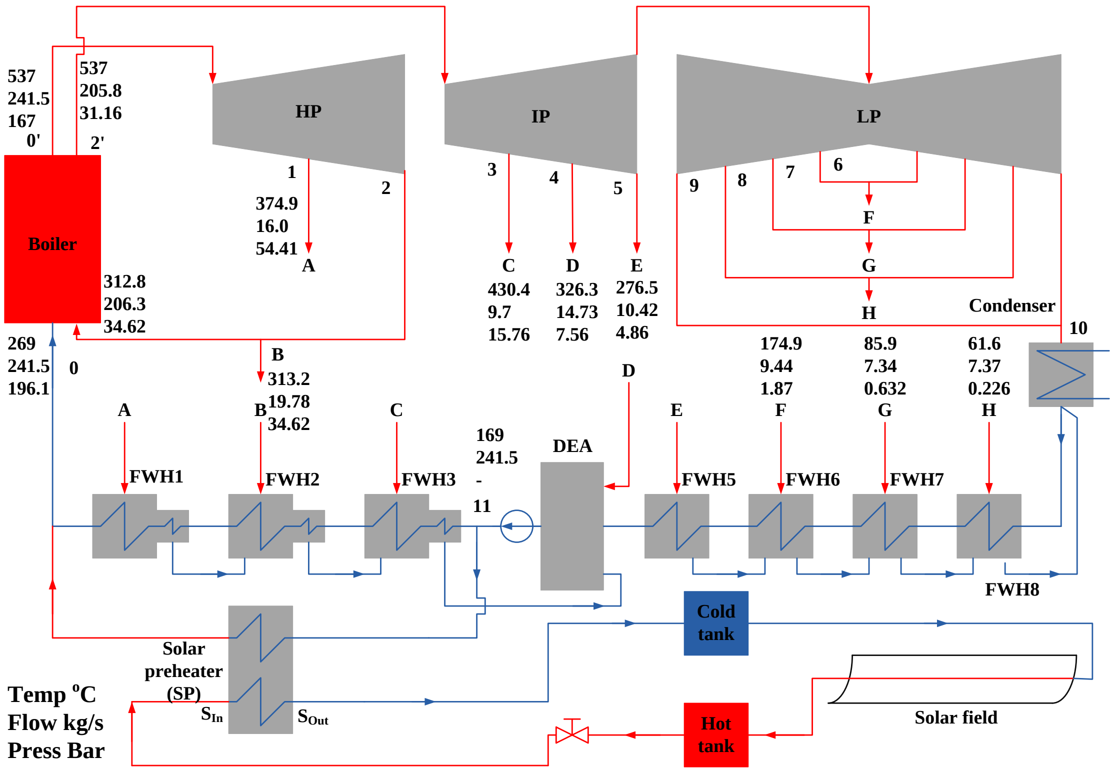

Fig. 4. Schematic heat and mass diagram of an SAPG plant modified from a typical 300 MW regenerative Rankine cycle power plant, in which high temperature extraction steam is displaced by the solar thermal energy.

In this study, the initial capital costs are estimated, based on the data from the National Renewable Energy Laboratory's report [30]. The initial cost of the power plant is 3,860 US$/kW. Thus, for a 300 MW power plant, the initial cost is about US$ 1,158 million.

3.2. Solar resources

The annual hourly solar radiation in Adelaide (34°S, 138°E) and Beijing (39°N, 116°E) are presented in Fig. 5 (a) and Fig. 5 (b), which are used as the case studies for this study.

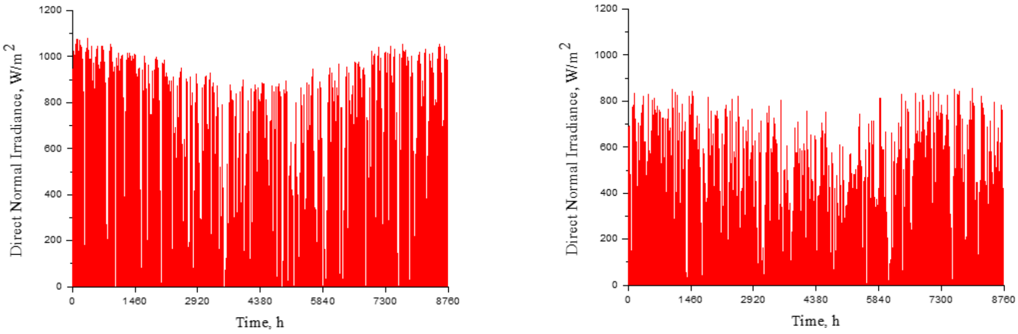

Fig. 5. Annual hourly Direct Normal Insolation (DNI): (a) Adelaide [31]; (b) Beijing [32].

In an SAPG plant, there is a concept of maximum solar thermal input ($\dot{Q}_{Solar,In,Max}$, kW), which is defined as when the solar thermal energy can fully displace the extraction steam. If the available solar thermal energy is greater than the maximum solar thermal input, the surplus solar thermal energy would be dumped. By using the model developed by Qin et al. [26, 27], it was found that the maximum solar thermal power inputs for the PB and FS modes are 108.2 MW and 92.9 MW, respectively, for the case study.

3.3. Fuel prices

In this study, it is assumed that the fuel (coal) price in Adelaide and Beijing are the same as that in the international market and, in each month, the fuel price remains unchanged. The monthly average coal prices from 2009 to 2014 are collected and presented in Fig. 6 [33]. It can be seen that 2011 has a relatively high coal price, while 2014 has a relative low coal price.

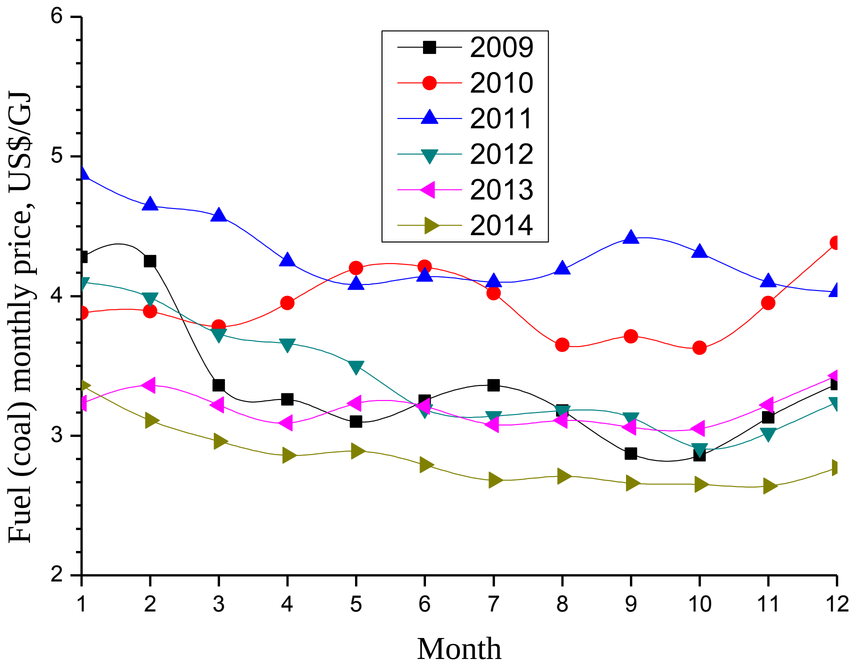

Fig. 6. Coal monthly average price (US$/GJ) from 2009 to 2014.

3.4. Electricity on-grid tariff

The electricity on-grid tariff is the wholesale price of the electricity sold to the grid by the power plant. In different countries or even cities, there are different policies to determine the electricity on-grid tariff. In this study, two different electricity market conditions have been used for the case study.

In Australia, all the electricity on-grid tariffs are traded in the electricity market through a biding price process, which is set at half hourly intervals. Each state in Australia then sets their own spot price. The half hourly electricity on-grid tariff data in Adelaide used in this study was taken from the Australian Energy Market Operator [34]. Fig. 7 (a) and Fig. 7 (b) show the annual electricity on-grid tariff in Adelaide in 2011 and 2014, respectively. As shown in Fig. 7, there is a great variation in the electricity tariff in Adelaide. There are even times when the electricity on-grid tariff is negative.

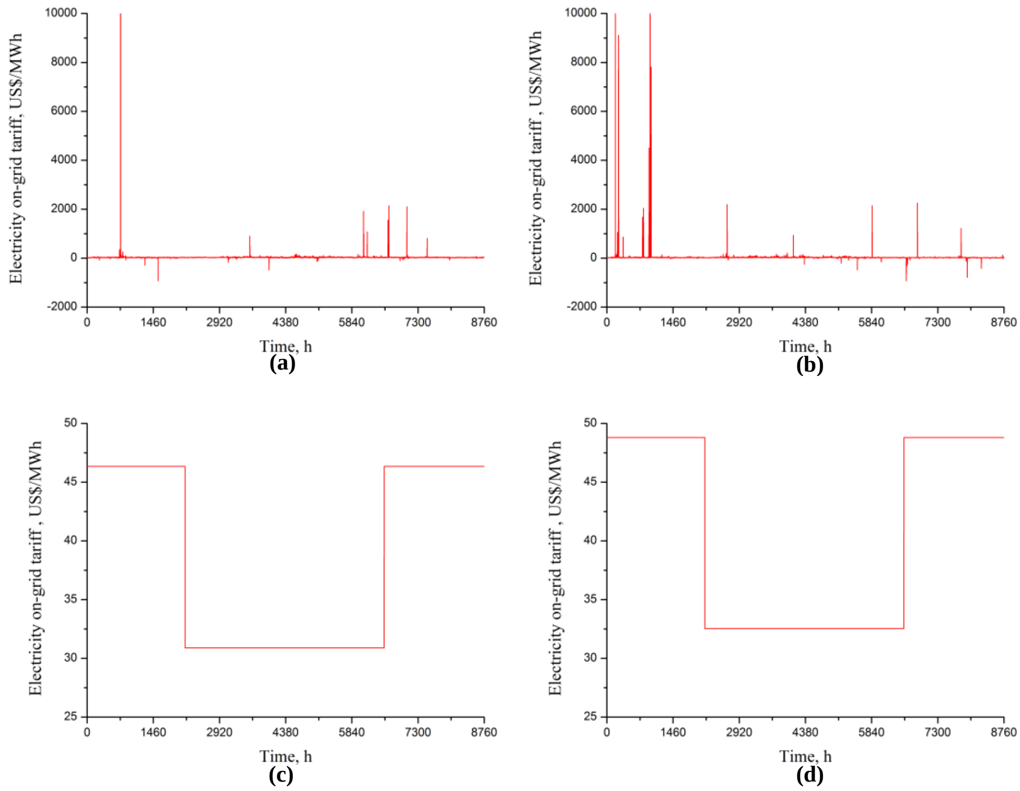

Fig. 7. Electricity on-grid tariff (US$/MWh): (a) Adelaide in 2011; (b) Adelaide in 2014; (c) Beijing in 2011; (d) Beijing in 2014.

Unlike Australia, in China, all power plants sell their electricity to the national grid. The electricity on-grid tariff only changes monthly. The electricity on-grid tariff for the fossil fired power plant and hydraulic power plant is about 300￥/MWh, while for the wind power plant is about 500￥/MWh [35]. In the present paper, the electricity on-grid tariff data used for Beijing is given in Fig. 7 (c) and Fig. 7 (d).

4. Results and discussion

In order to demonstrate the advantages of mixed mode operation over single mode operation, the annual Relative Profitability (ARP) of the SAPG plant operated in PB, FS and mixed modes has been compared.

4.1. Annual Relative Profitability of the different operational modes

In this section, the ARP of an SAPG plant operated in various modes in Adelaide and Beijing is calculated. As the other costs are the same for either PB or FS mode operation, it was assumed that the other cost is zero (i.e. f = 0).

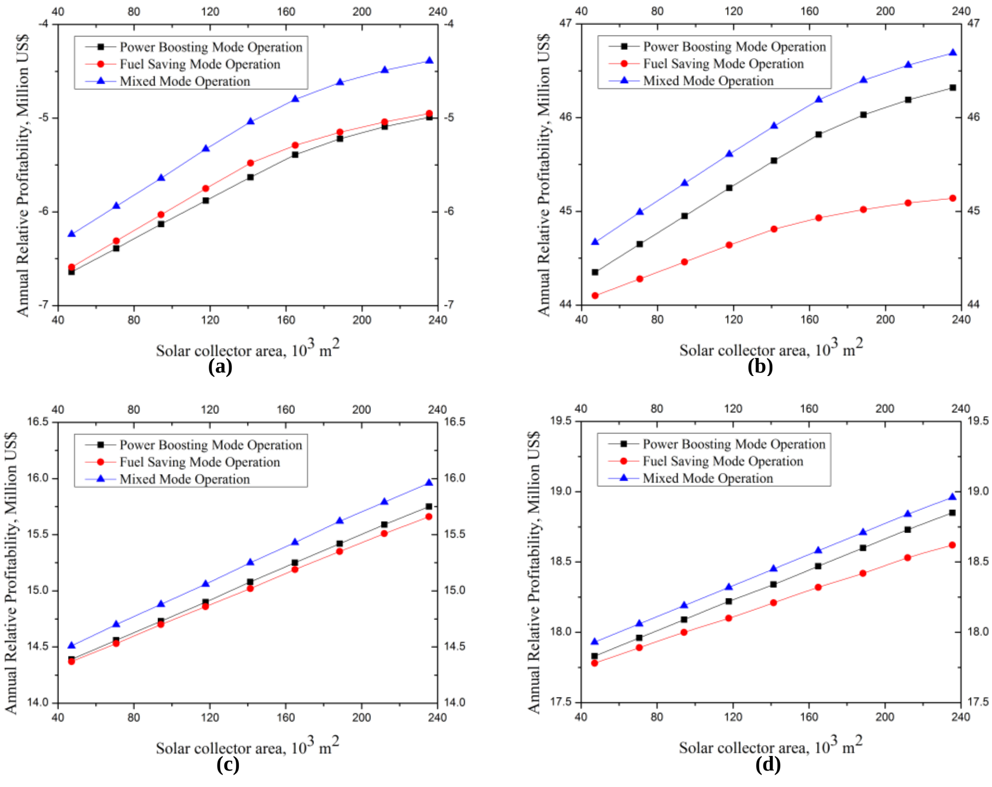

Fig. 8. Annual Relative Profitability (million US$) of the SAPG plant operated in Power Boosting, Fuel Saving and Mixed modes of operation: (a) Adelaide in 2011; (b) Adelaide in 2014; (c) Beijing in 2011; (d) Beijing in 2014.

Fig. 8 presents for each of the two sites the ARP of the SAPG plant with various solar collector areas. It can be seen from Fig. 8 that a mixed mode of operation would be better (i.e. showing reduced losses or increased profits) than a single mode operation in both years under Adelaide and Beijing conditions.

It is interesting to note for the case of Adelaide, when comparing two single mode operations, in the year when the fuel/coal price was high (in 2011), the FS mode was more favourable than the PB mode operation, and vice versa in the year when the fuel/coal price was low. It can be seen from Fig. 8(a) and Fig. 8(b) that for the case of Adelaide, the mixed mode of operation is up to 12.1% and 11.4% higher than the PB and FS mode of operation in 2011, and 0.8% and 3.4% higher than the PB and FS mode of operation in 2014.

It can be seen from Fig. 8(c) and Fig. 8(d) that for the case of Beijing, when comparing two single modes of operation, the PB mode was more favourable than the FS mode in both years studied in the Chinese case, which is different from that in the Australian case. The reason is thought to be that, in China, the electricity on-grid tariff was set by the government and was relatively high to prevent state-owned power companies/plants losing money, even when the true fuel costs varied. For the case of Beijing, the mixed mode of operation is up to 1.3% and 2.0% higher than the PB and FS modes of operation in 2011, while, 0.6% and 1.8% higher than the PB and FS modes of operation in 2014.

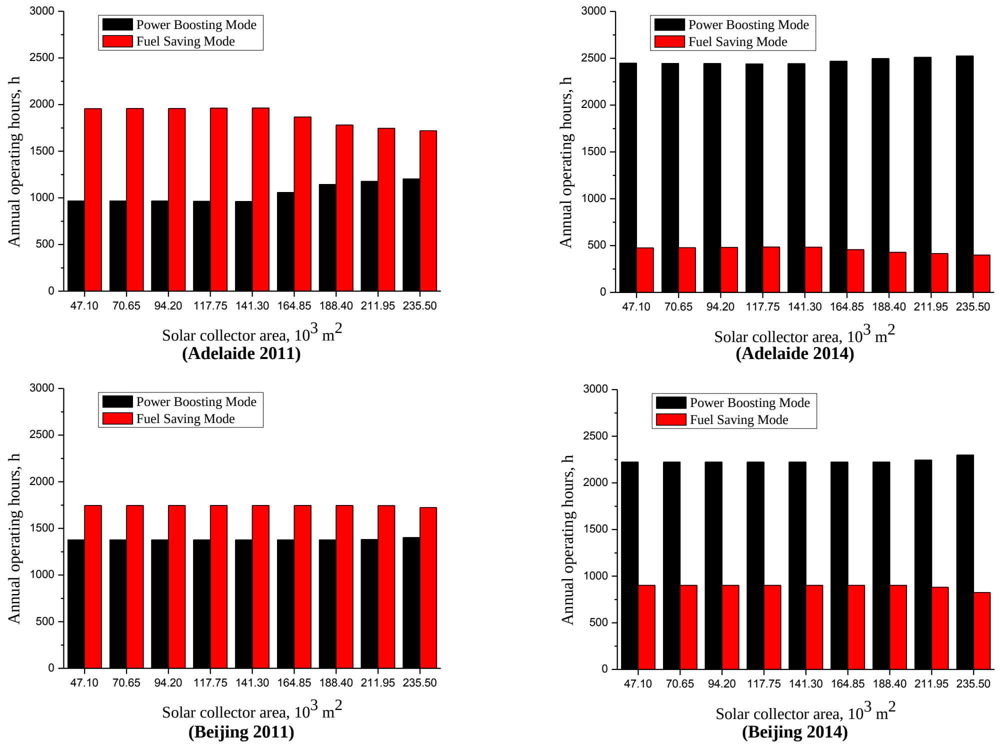

Fig. 9. Annual operating hours of the Power Boosting and Fuel Saving modes when the SAPG plant operated in mixed mode in Adelaide and Beijing.

Fig. 9 presents the annual operating hours of the PB and FS modes when the SAPG plant operated in a mixed mode of operation. As shown in Fig. 9, for the SAPG plant operated in a mixed mode of operation, the annual operating hours for the FS mode is higher than for the PB mode in both Adelaide and Beijing when the fuel/coal price was high (in 2011). However, it also can be seen that the annual operating hours for the PB mode are higher than those for the FS mode in both Adelaide and Beijing when the fuel/coal price was low (in 2014). The reason is thought to be that when the fuel/coal price was high, adopting FS would achieve a higher RP than adopting the PB mode.

4.2. Sensitivity analysis of the electricity on-grid tariff, fuel price and other costs on the ARP

In order to evaluate the influence of the electricity on-grid tariff, fuel price and other costs on the benefits of a mixed mode of operation over a single mode of operation in different locations (i.e. Adelaide and Beijing), a sensitivity analysis has been conducted in this section. It is assumed that the (hourly) electricity on-grid tariff and fuel price are increasing 1%, 2%, 3%, 4% and 5%, respectively. In the case of a negative on-grid tariff (as for some time intervals in Adelaide), the increases are not applied. Also, an assumption is also made that the other costs are 0%, 1%, 1.5% and 2% of the initial capital cost of the power plant (i.e. f is 1%, 1.5% and 2%). An SAPG plant with a solar field area of 211,950 m^2 (900 sets of LS-2 parabolic trough solar collectors), an electricity on-grid price and fuel price in 2014, and f of 0% are used as reference conditions. Under the reference conditions, the ARP_{Mixed} in Adelaide is 0.80% and 3.27% higher than the ARP_{PB} and ARP_{FS}, respectively, while the ARP_{Mixed} in Beijing is 0.59% and 1.68% higher than the ARP_{PB} and ARP_{FS}.

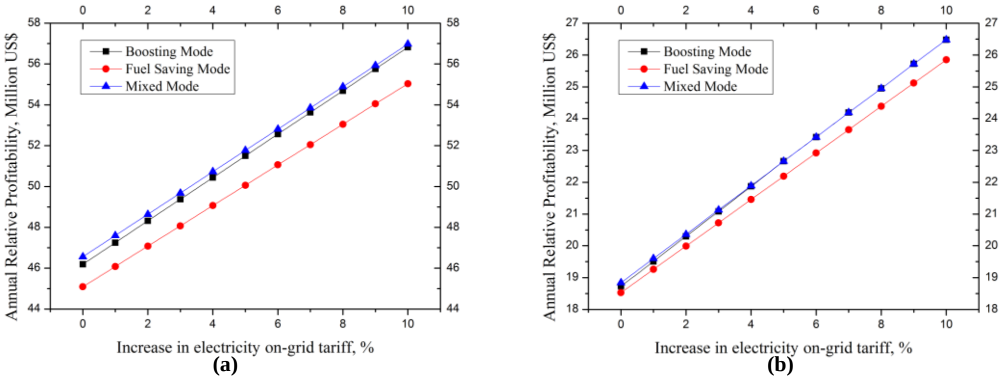

Fig. 10. Annual Relative Profitability (million US$) of an SAPG plant operated in Power Boosting, Fuel Saving and Mixed modes of operation with different electricity on-grid tariff increases: (a) Adelaide; (b) Beijing.

Fig. 10 presents the ARP of an SAPG plant operated in the PB, FS and Mixed modes of operation with an increase in the electricity on-grid tariff in both Adelaide and Beijing.

From Fig. 10 it can be seen that, as the electricity on-grid tariff increases, the ARP for every mode of operation are also increased, however, the mixed mode is still the best mode for operating the plant across the three modes. With the increase in the electricity on-grid tariff, the benefit of the mixed mode over the PB mode is gradually decreased. In Adelaide, this drops from 0.8% to 0.5% and in Beijing, from 0.6% to almost the same. The reason is that the PB mode of operation can take greater advantage of the higher electricity on-grid tariff. Also, as the electricity on-grid tariff increases, the operating hours for the PB mode in a mixed mode of operation are increased. It can be predicted that if the electricity on-grid tariff were high enough, the mixed mode could actually change to the PB mode.

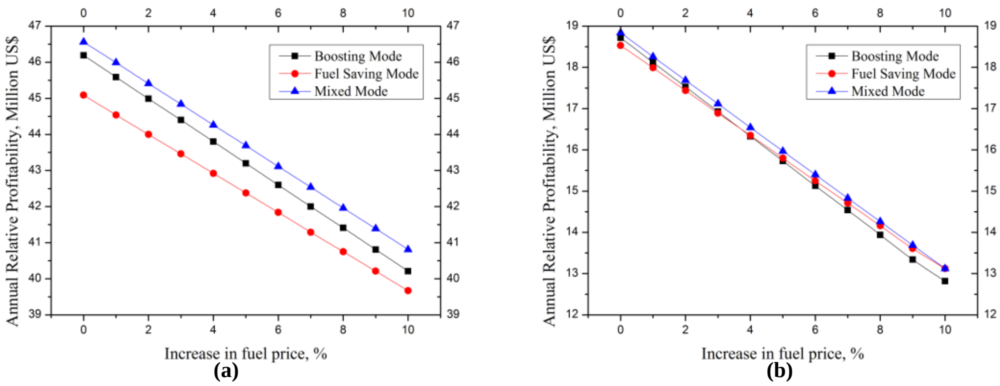

Fig. 11. Annual Relative Profitability (million US$) of an SAPG plant operated in the Power Boosting, Fuel Saving and Mixed modes of operation with different fuel price increases: (a) Adelaide; (b) Beijing.

Fig. 11 shows the ARP of an SAPG plant operated in the PB, FS and mixed modes of operation with different fuel price increases in both the Adelaide and Beijing cases. It can be seen that the ARP for every mode of operation are decreased with the increase in fuel price, although the ARP of the mixed mode is higher than for the other two modes. The advantage of the mixed mode of operation over the FS mode decreases with the increase in fuel price, from 3.4% to 3.1% in Adelaide, and from 1.8% to 1.1% in Beijing.

The reason is that the FS mode of operation can take better advantages of the higher fuel price, which is similar to the PB mode in the case of an electricity on-grid tariff increase. Meanwhile, the operating hours of the FS mode in a mixed mode of operation increase with the increase in fuel price. As shown in Fig. 11 (b), in the case of Beijing, ARP_{FS} equals ARP_{Mixed} when the fuel price increases 10% or more. This means that when the fuel price is high enough, a mixed mode of operation is actually the FS mode. It was also found that when the fuel price increases more than 5%, the ARP_{FS} is even higher than the ARP_{PB}.

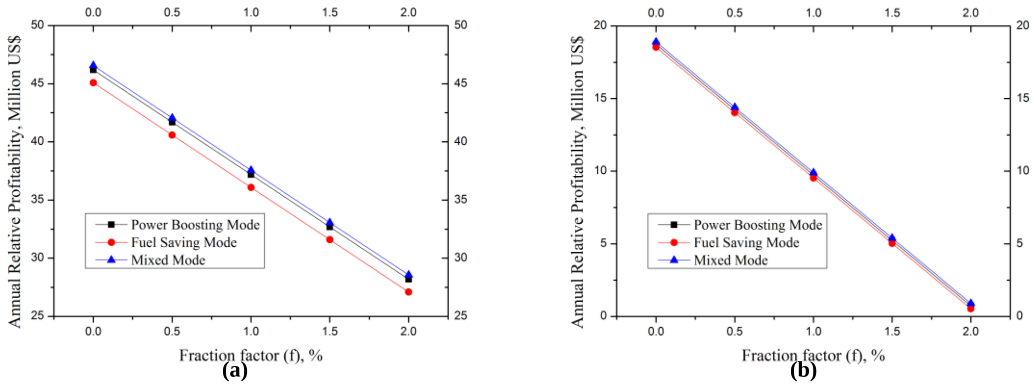

Fig. 12. Annual Relative Profitability (million US$) of an SAPG plant operated in the Power Boosting, Fuel Saving and Mixed modes of operation with other variable costs (fraction factor f) : (a) Adelaide; (b) Beijing.

Fig. 12 shows the ARP of an SAPG plant operated in PB, FS and Mixed modes of operation with other variable costs (fraction factor *f*) in Adelaide and Beijing. Similar to Fig. 12, the ARP for every mode of operation decreased with the increase in other costs. However, unlike Fig. 12, with the increase in the other costs, the ARP of the mixed mode of operation is always higher than that of other two. The reason is thought to be that the increase in the other costs would have no effect on the operating hours of PB and FS modes in the mixed mode of operation.

5. Conclusions

A Solar Aided Power Generation (SAPG) plant can be operated in either power boosting (PB) or fuel saving (FS) mode. Previous studies on an SAPG plant all assumed that the plant was operated in a single mode of operation for long periods of time; at least a season or a year. In order to optimise the operation of the plant and its economic benefits, the concept of mixed modes of operation is proposed. The mixed operation is such that the hourly operation mode (PB or FS) is determined by the hourly Relative Profitability (RP) calculated values. In the hourly RP calculation, the local electricity and fuel market conditions are taken into consideration to estimate/calculate the plant's hourly profitability in both PB and FS modes in order to determine the mode the plant should be operated in during that hour. The advantages of the mixed mode of operation are demonstrated through two case studies in this paper. The electricity on-grid tariff in Beijing and Adelaide and the monthly fuel price in the international market were used for the case studies. The results draw following conclusions:

- The mixed mode of operation is always superior economically over, or equal to, a single PB or FS mode of operation in the given electricity and fuel markets, especially in an electricity market that fluctuates significantly (i.e. in Adelaide, Australia). In Adelaide, the ARP of the mixed mode of operation is up to 12.1% and 11.4% higher than for the PB and FS modes, respectively. In Beijing, the ARP of the mixed mode of operation is up to 1.3% and 2.0% higher than the PB and FS modes, respectively. Also, it was found that the mixed mode of operation has more advantages than the PB and FS modes when the fuel price is relatively high.

- With the increase in the electricity on-grid tariff, the benefit of the mixed mode of operation over the PB mode is decreased. On the contrary, with an increase in fuel prices, the benefit of a mixed mode over an FS mode is decreased.
- With the increase of the other (operational) costs of the SAPG plant (including O&M, bank interest charges etc.), the benefit of the mixed mode of operation over the single mode of operation remains unchanged.

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7 Conclusions and recommendations for future work

This present thesis provides a new understanding of the impact of configuration/structure and operation strategies on the technical and economic performance of a Solar Aided Power Generation (SAPG) plant. 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 power system, 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. This displaced extraction steam is then expended further in the steam turbine.

The research and development of SAPG technology started in the 1990s. It was found that previous studies mainly focused on identifying the technical and economic advantages of the SAPG plant over other power generation technologies (i.e. solar alone power generation), designing and optimising the design of the SAPG plants. The detailed plant configuration, especially the arrangement to connect the solar field and the RRC power plant, and the operation of the SAPG plant have been overlooked. Therefore, the aim of this research is to advance the SAPG technology from the design and optimisation stages to the plant's operation stage.

The following are the main conclusions drawn from the study:

- In this research, four possible configurations for the SAPG plant to connect the solar field and the RRC power plant have been identified. Then, three operation strategies to adjust the displaced extraction steam in response to solar radiation changes have been proposed. Based on the proposed configurations and operation strategies, there are twelve 'configuration-operation' combinations. The technical performance of an SAPG plant with different combinations has been compared. It was found that the technical performance of the SAPG plant depends on the 'configuration-operation' combinations of the SAPG plant. When all the extraction steam to the displaced FWHs has been displaced by the solar thermal energy, the SAPG plant's technical performance would be identical for all 12 proposed combinations. However, when the steam was not 100% displaced, combinations 2, 5 and 8 (i.e. parallel or series configurations operated with high to low varying temperature strategies) would have the highest annual solar share, annual solar power output per collector area and solar thermal to power efficiency. In addition, the results indicate that the configurations also have impact on the solar field's efficiency.
- Generally speaking, using higher temperature solar heat from concentrating solar collectors to displace high temperature/pressure stages extraction steam would have a higher instantaneous solar to power efficiency than a lower temperature solar heat from non-concentrating collectors. However, when the SAPG plant's technical performance was assessed in terms of its net land based solar to power efficiency, the

conclusion was different. The study finds that non-concentrating solar collectors can and should be used in SAPG plants as they are superior to concentrating collectors in terms of the net land based solar to power efficiency. In some low latitude locations, SAPG plants using non-concentrating solar collectors have both technical and economic advantages over those using the concentrating solar collectors.

- In an SAPG plant, using the solar thermal energy to displace the extraction steam to high pressure/temperature feedwater heaters (i.e. displaced FWHs) is the most popular choice. As demonstrated in Chapter 3, operating the displaced FWHs when the solar input changes would have an impact on the plant's performance. However, in this research, it was found that operating the low pressure/temperature FWHs (i.e. non-displaced FWHs) also has impact on the SAPG plant's technical performance. It was found that an SAPG plant adopting the constant temperature (CT) strategy for each non-displaced FWH is generally more effective than adopting the constant mass flow (CM) strategy. However, if the SAPG plant were located in an area where rich solar resources were available, an SAPG plant adopting the CM strategy could achieve a better performance.
- A 'mixed mode' operation of an SAPG plant is proposed in this study for the first time. A mixed mode operation is based on a newly proposed economic criterion, 'Relative Profitability (RP)', in this study. This criterion links the plant's profitability with the operation mode under particular market conditions. In such a mixed operation mode, the SAPG plant is operated (i.e. the mass flows of extraction steam need to be adjusted when the solar input changes) at a series of time intervals. In each time interval, the SAPG plant is operated in one selected mode (i.e. either a power boosting or a fuel saving mode) with higher RP. The superiority of the mixed mode of operation over the single mode of operation (i.e. the PB or FS mode) has been

demonstrated through two case studies in Australia and China in this study. In Australia, where the on-grid tariff fluctuates significantly, the annual RP of the mixed mode of operation could be up to 12.1% higher than that of a single mode of operation. In China where the electricity market is controlled by the government and relatively flat, this economic advantage of the mixed mode over the single mode decreases to only about 2.0%. The results indicate that the mixed mode of operation could guarantee the best economics for an SAPG plant over the single mode of operation in different markets.

In light of this, the results obtained in this research have further advanced our understanding of the SAPG plant in the operation stages.

Gap 5, identified in Section 2.6, is not addressed in this study. In an SAPG plant, the RRC plant i.e. the boiler, steam turbine, condenser and FWH system, is actually operated in the off-design condition when the solar thermal energy is integrated into the plant. The simulation models of 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. A simulation model comprising off-design conditions for the boiler, steam turbine, condenser and FWH system could help to evaluate an SAPG plant's performance more accurately.

Another recommendation is to develop a model to simulate the daily start and shut down processes of an SAPG plant. In an SAPG plant, as there is no thermal storage, the plant is required to start when the sun rises and shut down when sun sets every day. These processes have never been simulated before and thus their impact on SAPG plant performance remain unknown. With this model, the true benefits of SAPG technology can be assessed more accurately.

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