Mechanism of Mid-Temperature Solar heat Hybridization with traditional fossil-fired power plant

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Abstract:

A higher solar-to-electricity conversion efficiency was one of the major advantages of the solar-fossil hybrid systems, compared to the solar-only power plants. In this paper, a new mechanism to reveal the reasons for the improved solar-to-electricity efficiency in a solar hybrid power plant was given. A correlation was built to describe the main influencing factors of its thermodynamic performances, including higher collector efficiency, higher turbine efficiency and upgraded energy-level of the mid-temperature solar heat. This proposed mechanism can be used to integrate solar hybridization system effectively. Studies were taken as the typical coal-fired power plant hybridized with solar heat, which was used to preheat the feed water before entering the boiler. And solar heat was integrated with the combined cycle to generate saturated or superheated steam. The results obtained here indicate that how to develop the mid-temperature solar hybridization technology can provide a promising direction to efficient utilization of low-grade solar heat, and provide the direction to enhance system performances of the solar hybrid power plants.

Keywords:

Mechanism, Solar Hybridization, Mid-Temperature, Solar-to-Electricity Efficiency. Fossil-fired power plant

1. Introduction

Today, solar thermal power plants based on parabolic troughs represent the only solar power plant technology tested on a commercial basis. Already commercially operated parabolic trough collector plants use thermal oil as heat transfer fluid, limited the upper temperature of main steam to 371°C [1]. In order to improve the solar-to-electric efficiency, possible alternatives allowing for higher operating temperatures are studied, such as molten salts [2] as well as the direct steam generation (DSG) [3]. The upper design temperature limit can be increased to 550 °C. However, solar heat utilizations at higher temperatures still face engineering challenges. High operating temperature of molten salt suffers from chemical decomposition and the rapidly increasing corrosion rates of piping materials [4]. DSG technology has the problem [5] of the absorber being circumferentially non-uniform heated with a two-phase flow leading to bent tube. Therefore, hybridizing solar heat at relatively lower temperature levels with the traditional fossil-fired power plants not only offers the possibility of converting middle-temperature solar heat into output power, but also appears to have an excellent near-term potential for market penetration.

In our previous paper, the thermodynamic and economic performances of a proposed solar-coal hybrid power plant have been studied. The relevant researches [6~10] have shown that the collected solar heat at around 300°C has a good match with the feed water back to the boiler. Utilizing the solar heat to replace the steam extractions to heat the feed water can increase the work output of the steam turbine. Going beyond Rankine cycle solar power plants, solar-fossil hybrid options using middle-temperature solar heat are possible with combined cycles. Integrated Solar Combined Cycle (ISCC) [11] systems combine a solar field and a gas-fired combined cycle power plant. The steam generated by the solar field is superheated in the heat recovery steam generator (HRSG) and expanded in the high-pressure steam turbines or is injected into the low-pressure steam turbines directly. Compared with solar-only power plant, the middle-temperature solar hybrid power plants have a more efficient solar-to-electricity conversion process and the lower capital cost. The solar-to-electricity efficiency is influenced by the energy level match between the collected solar heat and the thermodynamic cycle.

The objective of this paper are to describe the mechanism of middle-temperature solar thermodynamic processes from the viewpoint of the energy level, to identify the relationship between energy level upgrade of solar heat and work increment, to give the specific equation of net solar-to-electricity efficiency improvement and saved collector area by hybridizing solar heat with traditional fossil-fired power plants, and to give the provide the corret direction to enhance solar hybrid system performances.

2. Methodology

In the mid- and low-temperature solar hybrid processes, a conversion of low-grade solar heat into high-grade work is accomplished. This process is different from the direct conversion process from solar heat to output work in a conventional solar-only thermal power plant, where the quality of solar heat is decreased and the energy level is degraded. Conversely, the mid-temperature solar hybrid process is capable of raising the low quality of solar heat to a higher quality of work by the aid of the advanced thermal cycle. Hence, the integration of solar energy and traditional fossil-fired power generation system can be expected to increase the work output relative to the solar-only power generation process.

Here, the concept of the energy level as an important tool is utilized for understanding the mechanism of energy conversion and integrating mid- and low-temperature solar heat into traditional thermal cycle. The energy level A was proposed by Ishida[9~11], and was defined as the ratio of exergy change $\Delta\varepsilon$ to energy change ΔH, namely, $A=\Delta\varepsilon/\Delta H=1-T_0\Delta S/\Delta H$. Based on the first and second laws of thermodynamics, energy has three characteristic features: Direction, quantity, and quality. The direction is given by the sign of ΔH and/or ΔS, the quantity by the absolute value of ΔH, and the quality by the energy level, A. Hence, the energy level, as an intensive property, may be used to represent the degree of quality of the energy.

3. Mechanism of middle-temperature solar heat thermodynamic process

3.1 Options to hybrid middle-temperature solar heat with Rankine cycle

In the previous study, several schemes were suggested for hybridizing middle-temperature solar heat with the traditional Rankine cycle:

I. In the bottom Rankine cycle of the combined cycle power plant, high-pressure preheated feed water is evaporated and slightly superheated in the solar steam generator, and then returned to the heat recover steam generator (HRSG), finally superheated to the main steam temperature.

II. In the bottom Rankine cycle of the combined cycle power plant, low-pressure superheated steam is directly generated using solar heat, and then injected into the low-pressure steam turbine.

III. In the Rankine cycle of a coal-fired power plant, the feed water is preheated by the solar heat instead of the steam extractions, and then pumped into the boiler.

Option I and option II above are usually used in the integrated solar combined cycle system (ISCCs), where the collected solar heat is below 350°C. Option III is usually used in the solar-coal hybrid power generation system, where the collected solar heat is below 300°C. Fig. 1 shows the theoretical processes representing utilization of middle-temperature solar heat in a T-S diagram.

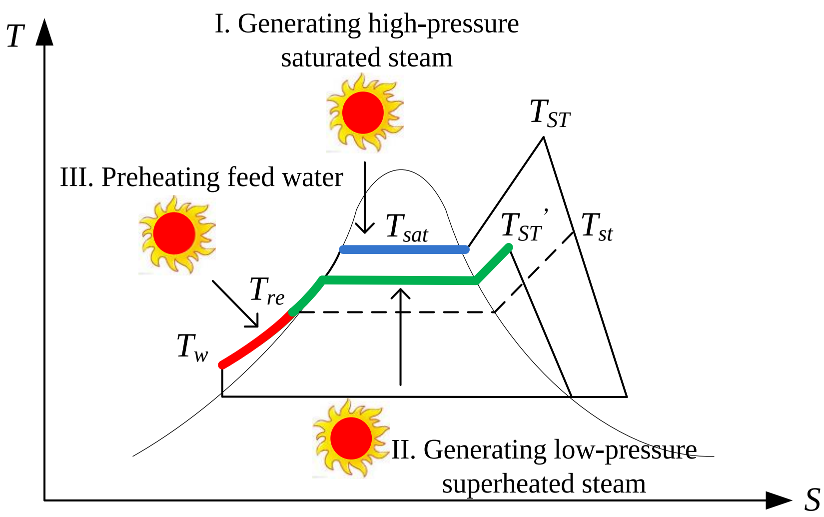

Fig. 1. Rankine cycle T-S diagram.

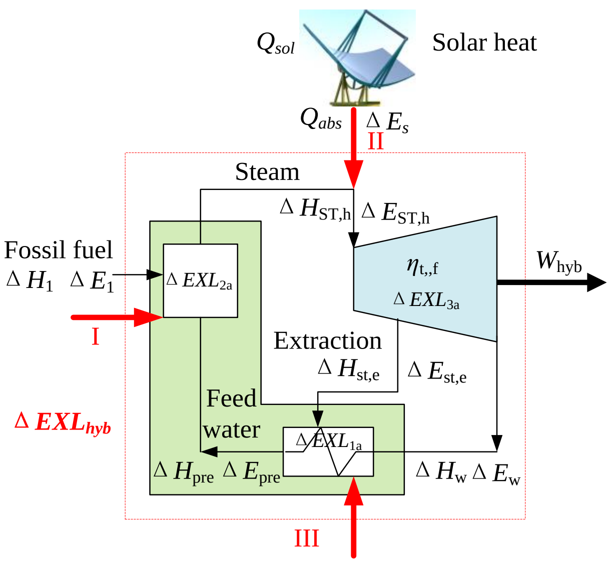

Fig. 2(a). Flowsheet of solar hybrid power generation processes

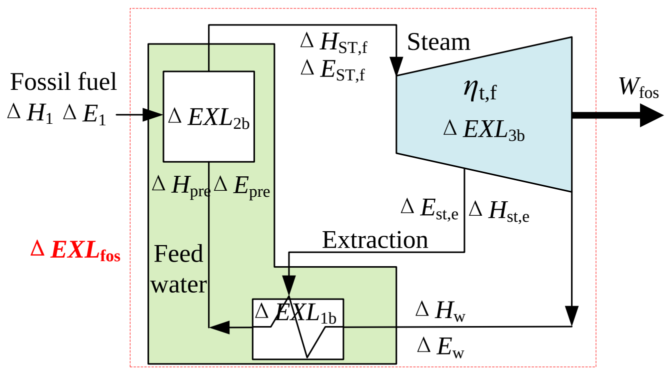

Fig. 2(b). Flowsheet of traditional fossil-fired power generation processes with non-solar heat

For the solar hybrid power generation system and the traditional fossil-fired power generation system, both of them compose a series of energy transformation processes: the feed water pre-heating process in the feed water heaters, the steam generation and superheating process in the boiler, and steam expanding process in the turbines. Figure 2(a) and 2(b) show the energy and exergy flow in the power generation processes, where ΔH, ΔE and ΔEXL represent energy, exergy and exergy destruction, respectively. Figure 2(a) shows the energy conversion processes by hybridizing solar heat with Rankine cycle. Figure 2(b) shows the energy conversion processes in the traditional fossil-fired power plant.

3.2 Relationship between Energy Level Upgrade of Solar Heat and Work Increment

For the middle-temperature solar hybrid system, the energy conservation of the feed water preheating, the steam generation and superheating processes, within the green area shown in Fig. 2(a), is given as:

$$\Delta H_{w} + \Delta H_{st,e} + \Delta H_{1} + Q_{abs} = \Delta H_{ST,h} \tag{1a}$$

Where ΔH_w is the enthalpy of the feed water. $\Delta H_{st,e}$ is the enthalpy of the steam extraction. ΔH_1 is the energy released by fossil fuel consumption. Q_{abs} is the absorbed solar heat. $\Delta H_{ST,h}$ is the enthalpy of the main steam of the solar hybrid power generation system.

For the non-hybridization fossil-fired power plant with the same fossil fuel (or gas exhaust) input, the energy conservation of the feed water preheating, the steam generation and superheating processes, within the green area in Fig. 2(b), is given as:

$$\Delta H_{w} + \Delta H_{st,e} + \Delta H_{1} = \Delta H_{ST,f} \tag{1b}$$

Where $\Delta H_{ST,f}$ is the enthalpy of the main steam of the non-hybridization fossil-fired power generation system.

Based on the exergy balance, the work output of solar hybrid system and the non-hybridization fossil-fired power plant can be expressed as, respectively:

$$W_{hyb} = \Delta E_1 + \Delta E_s - \sum \Delta EXL_{ia} \tag{2a}$$

$$W_{fos} = \Delta E_1 - \sum \Delta EXL_{ib} \tag{2b}$$

Where ΔE_s is the heat exergy of the absorbed solar heat and can be expressed as "$\Delta E_s = A_{abs} \cdot Q_{abs}$" based on the energy level, proposed by Ishida [12-14], as described in Appendix A. $\sum \Delta EXL$ is the total exergy destruction difference between the non-hybridization fossil-fired system and the solar hybrid system.

The incremental work output of the solar hybrid system contributed by solar heat can be calculated by subtracting Eq. (2b) from Eq. (2a).

$$\Delta W_{hyb} = W_{hyb} - W_{fos} = (\Delta E_1 + \Delta E_s - \sum \Delta EXL_{ia}) - (\Delta E_1 - \sum \Delta EXL_{ib}) = \Delta E_s + (\sum \Delta EXL_{ib} - \sum \Delta EXL_{ia}) \tag{3}$$

As can be found from Eq. (3), the incremental work output of the solar hybrid system is composed of the solar heat exergy and the reduced exergy destructions. Comparing with the non-hybridization fossil-fired system, the exergy destructions change of the solar hybrid system mainly happen in the solar-driven feed water preheating process, the steam generation process in the boiler and the steam expansion process in the turbine. To be specific, for Option I described in Fig. 2(a), the change of exergy destructions mainly occurs in the processes of the steam generation in the boiler and the steam expansion in the turbine. For Option II the change of exergy destructions mainly occurs in the process of the steam expansion in the turbine. For Option III the change of exergy destructions mainly occurs in the process of the feed water preheating and the steam expansion in the turbine. The exergy destruction changes can be mathematically expressed as follows, respectively:

Option I:

$$\sum\Delta EXL_{\mathrm{ib}}-\sum\Delta EXL_{\mathrm{ia}}=(\sum\Delta EXL_{\mathrm{2b}}-\sum\Delta EXL_{\mathrm{2a}})+(\sum\Delta EXL_{\mathrm{3b}}-\sum\Delta EXL_{\mathrm{3a}}) \quad (4a)$$

Option II:

$$\sum\Delta EXL_{\mathrm{ib}}-\sum\Delta EXL_{\mathrm{ia}}=\sum\Delta EXL_{\mathrm{3b}}-\sum\Delta EXL_{\mathrm{3a}} \quad (4b)$$

Option III:

$$\sum\Delta EXL_{\mathrm{ib}}-\sum\Delta EXL_{\mathrm{ia}}=(\sum\Delta EXL_{\mathrm{1b}}-\sum\Delta EXL_{\mathrm{1a}})+(\sum\Delta EXL_{\mathrm{3b}}-\sum\Delta EXL_{\mathrm{3a}}) \quad (4c)$$

In addition, the exergy destruction during the energy transformation process can also be derived based on the concept of energy level in Appendix A. According to its expression, exergy destruction can be given as "$\Delta EXL=\Delta H_{\mathrm{ed}}(A_{\mathrm{ed}}-A_{\mathrm{ea}})=\Delta H_{\mathrm{ea}}(A_{\mathrm{ed}}-A_{\mathrm{ea}})$", where ΔH_{ed} is the energy quantity of the energy donor which equals to that of energy acceptor based on energy conservation. A_{ed} and A_{ea} are the energy level of the energy donor and energy acceptor, respectively. Then when the energy level of the energy acceptor is fixed and the energy level of the energy donor is deceased from A_{ed1} to A_{ed2}, the exergy destruction of the energy transformation process can be "$\Delta EXL_2-\Delta EXL_1=\Delta H_{\mathrm{ea}}(A_{\mathrm{ed1}}-A_{\mathrm{ea}})-\Delta H_{\mathrm{ea}}(A_{\mathrm{ed2}}-A_{\mathrm{ea}})=\Delta H_{\mathrm{ea}}(A_{\mathrm{ed1}}-A_{\mathrm{ea2}})$".

In this study, "$\Delta EXL_{\mathrm{2b}}-\Delta EXL_{\mathrm{2a}}$" and "$\Delta EXL_{\mathrm{1b}}-\Delta EXL_{\mathrm{1a}}$" are the exergy destructions of steam generation process and feed water preheating process, respectively. If the energy level of the energy donor in the non-hybridization fossil-fired power generation system is A_{fos}, and the energy level of the energy donor in the solar hybrid system is A_{abs}, then the exergy destructions of "$\Delta EXL_{\mathrm{2b}}-\Delta EXL_{\mathrm{2a}}$" and "$\Delta EXL_{\mathrm{1b}}-\Delta EXL_{\mathrm{1a}}$" can be uniformly expressed as "$Q_{\mathrm{abs}}(A_{\mathrm{fos}}-A_{\mathrm{abs}})$", where Q_{abs} is the absorbed solar heat in the solar hybrid system.

ΔEXL_{3b} and ΔEXL_{3a} are the exergy destructions of steam expansion processes in the turbines after and before solar hybridization, respectively. During steam expansion processes in the turbines the exergy balance expressions of solar hybrid system and the non-hybridization fossil-fired power plant can be given as, respectively:

$$\Delta E_{\mathrm{ST,h}}=W_{\mathrm{hyb}}+\Delta EXL_{\mathrm{3a}}+\Delta EXL_{\mathrm{st,e}}+\Delta E_{w} \quad (5a)$$

$$\Delta E_{\mathrm{ST,f}}=W_{\mathrm{fos}}+\Delta EXL_{\mathrm{3b}}+\Delta EXL_{\mathrm{st,e}}+\Delta E_{w} \quad (5b)$$

Then subtract Eq. (5a) from Eq. (5b), "$\Delta EXL_{\mathrm{3b}}-\Delta EXL_{\mathrm{3a}}$" can be rewritten as:

$$\Delta EXL_{\mathrm{3b}}-\Delta EXL_{\mathrm{3a}}=(W_{\mathrm{hyb}}-W_{\mathrm{fos}})-(\Delta E_{\mathrm{ST,h}}-\Delta E_{\mathrm{ST,f}}) \quad (6)$$

Here, the turbine internal efficiency of η_{tur} is used for considering the irreversibility of the steam expanding process in the turbine. It is defined as: $\eta_{\mathrm{t}}=\Delta H_{\mathrm{actual}}/\Delta H_{\mathrm{ideal}}$. Where $\Delta H_{\mathrm{actual}}$ is the actual enthalpy drop which equals to the actual work output W. $\Delta H_{\mathrm{ideal}}$ is the isentropic enthalpy drop and equals to the process exergy change. Thus, the turbine internal efficiency of the coal-fired power plant is presented as "$\eta_{\mathrm{t,f}}=W_{\mathrm{hyb}}/(\Delta E_{\mathrm{ST,h}}-\Delta E_{\mathrm{st,e}}-\Delta E_{\mathrm{w}})=W_{\mathrm{fos}}/(\Delta E_{\mathrm{ST,f}}-\Delta E_{\mathrm{st,e}}-\Delta E_{\mathrm{w}})$". Then Eq.(6) can be written as:

$$\Delta EXL_{\mathrm{3b}}-\Delta EXL_{\mathrm{3a}}=(\Delta E_{\mathrm{ST,f}}-\Delta E_{\mathrm{ST,h}})\cdot(1-\eta_{\mathrm{t,f}}) \quad (7)$$

During steam generation process and the feed water preheating processes, the exergy balance expressions of solar hybrid system and the non-hybridization fossil-fired power plant can be given as, respectively:

$$\Delta E_{\mathrm{w}}+\Delta E_{\mathrm{st,e}}+\Delta E_{1}+\Delta E_{\mathrm{s}}-\Delta EXL_{\mathrm{1a}}-\Delta EXL_{\mathrm{2a}}=\Delta E_{\mathrm{ST,h}} \quad (8a)$$

$$\Delta E_{\mathrm{w}}+\Delta E_{\mathrm{st,e}}+\Delta E_{1}-\Delta EXL_{\mathrm{1b}}-\Delta EXL_{\mathrm{2b}}=\Delta E_{\mathrm{ST,f}} \quad (8b)$$

Subtracting Eq. (8a) from Eq. (8b), the following expression can be given:

$$\Delta E_{\mathrm{ST,f}}-\Delta E_{\mathrm{ST,h}}=-\Delta E_{\mathrm{s}}+\Delta EXL_{\mathrm{1a}}-\Delta EXL_{\mathrm{1b}}+\Delta EXL_{\mathrm{2a}}-\Delta EXL_{\mathrm{2b}} \quad (9)$$

Substituting Eq. (9) into Eq. (7), Eq. (10) can be obtained as follows:

$$\Delta EXL_{\mathrm{3b}}-\Delta EXL_{\mathrm{3a}}=(-\Delta E_{\mathrm{s}}+\Delta EXL_{\mathrm{1a}}-\Delta EXL_{\mathrm{1b}}+\Delta EXL_{\mathrm{2a}}-\Delta EXL_{\mathrm{2b}})\cdot(1-\eta_{\mathrm{t,f}})$$

$$=\left[-\Delta E_{\mathrm{s}}-Q_{\mathrm{abs}}\cdot\left(A_{\mathrm{fos}}-A_{\mathrm{abs}}\right)\right]\cdot(1-\eta_{\mathrm{t,f}}) \tag{10}$$

Then subtracting Eq. (10) into Eq. (3), and based on the expressions of "ΔEXL_{2b}-ΔEXL_{2a}" and "ΔEXL_{1b}-ΔEXL_{1a}" given before, the incremental work output of the solar hybrid system can be expressed as:

$$\Delta W_{\mathrm{hyb}}=\Delta E_{\mathrm{s}}+(\sum\Delta EXL_{\mathrm{ib}}-\sum\Delta EXL_{\mathrm{ib}})=\Delta E_{\mathrm{s}}\cdot\eta_{\mathrm{t,f}}+Q_{\mathrm{abs}}\cdot\left(A_{\mathrm{fos}}-A_{\mathrm{abs}}\right)\eta_{\mathrm{t,f}} \tag{11}$$

Eq. (11) explicitly states that the incremental work output from the input solar thermal energy is determined by two terms: term "$E_{\mathrm{s}}\cdot\eta_{\mathrm{tur\text{-}fos}}$", meaning the contribution from the amount of input solar heat exergy; term of "$Q_{\mathrm{abs}}\cdot(A_{\mathrm{fos}}-A_{\mathrm{abs}})\cdot\eta_{\mathrm{tur\text{-}fos}}$", contribution from the energy level upgrade of the middle-temperature solar heat when using solar heat to hybrid with the traditional fossil-fired power generation system.

Taking the solar-coal hybrid system for example, solar heat in the temperature range of 200~300°C is utilized to replace the steam extractions from the high and mid-pressure turbines. In this way, the energy level of solar heat A_{abs} is enhanced to that of the high-temperature and pressure steam extractions $A_{\mathrm{st,ext}}$. That means, the energy level of solar heat at medium temperature levels can be substantially improved from a low value of about 0.43 (corresponding to 250°C) to the high value of 0.50~0.60 (corresponding to 320°C~450°C). It is worth emphasizing that this energy-level improvement of solar heat is dependent on the reduction in the exergy destruction of feed water preheating and steam expanding processes.

3.3. Specific Equation of Net Solar-to-Electricity Efficiency Improvement and saved collector area

One of the benefits of upgrading the energy level of middle-temperature solar heat is to considerably improve its availability in the conversion process from solar heat to work. The net solar-to-electricity efficiency is utilized to evaluate how well middle-temperature solar heat is converted into work in a hybrid system, and is defined as Eq. (B2) in Appendix B. Then, the net solar-to-electricity efficiency of solar hybrid system can be expressed as follows, where ΔW_{hyb} is the net incremental work output given in Eq. (11), and η_{col} is the solar collector efficiency given as Eq. (B1).

$$\eta_{\mathrm{s\text{-}e,h}}=\frac{\Delta W_{\mathrm{hyb}}}{Q_{\mathrm{sol}}}=\frac{\Delta E_{\mathrm{s}}\cdot\eta_{\mathrm{t,f}}+Q_{\mathrm{abs}}\cdot\left(A_{\mathrm{fos}}-A_{\mathrm{abs}}\right)\eta_{\mathrm{t,f}}}{\dfrac{Q_{\mathrm{sol}}}{\eta_{\mathrm{col}}}}=\eta_{\mathrm{col}}\cdot A_{\mathrm{fos}}\cdot\eta_{\mathrm{t,f}} \tag{12}$$

The solar-to-electricity efficiency of a solar-only power plant can be simply expressed as:

$$\eta_{\mathrm{s\text{-}e,s}}=\eta_{\mathrm{col}}\cdot\eta_{\mathrm{c}}\cdot\eta_{\mathrm{t,s}}=\eta_{\mathrm{col}}\cdot(1-\frac{T_0}{T_{\mathrm{abs}}})\cdot\eta_{\mathrm{t,s}}=\eta_{\mathrm{col}}\cdot A_{\mathrm{abs}}\cdot\eta_{\mathrm{t,s}} \tag{13}$$

Where, η_{c} is the Carnot efficiency. T_{abs} and A_{abs} are the average collected temperature of the solar heat and its energy level in a solar-only power plant, respectively. $\eta_{\mathrm{t,s}}$ is its turbine internal efficiency.

Then, compared with the solar-only power plant, the relative improvement of the net solar-to-electricity efficiency in solar hybrid system can be given as:

$$\Delta\eta_{\mathrm{s\text{-}e,h}}=\frac{\eta_{\mathrm{s\text{-}e,h}}}{\eta_{\mathrm{s\text{-}e,s}}}=(1+\frac{A_{\mathrm{fos}}-A_{\mathrm{abs}}}{A_{\mathrm{abs}}})\cdot\frac{\eta_{\mathrm{t,f}}}{\eta_{\mathrm{t,s}}} \tag{14}$$

This relative improvement of solar-to-electricity efficiency can reflect whether the hybridization of solar energy into a fossil-fired power plant is worthy or not. Only if $\Delta\eta_{\mathrm{s\text{-}e,h}}>1$, it means that the conversion efficiency from solar heat to work is improved by the solar hybridization in the traditional fossil-fired system. It is determined by the differences of the energy level "A_{fos}-A_{abs}" and the turbine internal efficiency "$\eta_{\mathrm{t,f}}/\eta_{\mathrm{t,s}}$".

For the solar-coal hybrid system with option III shown in Fig. 2(a), the mid-temperature solar heat at around 300°C is applied, the replaced high-temperature and pressure extractions (before the deaerator) can directly become the work steams in solar-coal hybrid system. Its energy level A_{fos} is higher than the energy level of the absorbed solar heat of A_{abs}; Besides, the solar-coal system has the aid of relative large capacity units of a traditional coal-fired power plant. The steam can be converted through advanced steam turbine with relatively higher turbine internal efficiency $\eta_{\text{t,f}}$. While in the state-of-the-art solar-only thermal power plant, low-temperature and pressure main steam has to adopt the inefficient steam turbine with relatively lower turbine internal efficiency $\eta_{\text{t,s}}$. Thus, $\Delta\eta_{\text{s-e,h}} > 1$. This specific equation derived here is extremely important in disclosing the mechanism of system performance improvement via the solar-coal hybridization.

Another benefit of upgrading the energy level of middle-temperature solar heat is to reduce the solar collector area when generate the same work output compared with that of a solar-only plant. This solar heat utilization shows a potential for the low-cost solar power. The collector area per kW solar power can be expressed as:

$$s_{\text{hyb}} = \frac{S_{\text{hyb}}}{\Delta W_{\text{hyb}}} = \frac{Q_{\text{abs}} / (\eta_{\text{col}} \cdot DNI)}{\Delta E_{\text{s}} \cdot \eta_{\text{t,f}} + Q_{\text{abs}} \cdot \left(A_{\text{fos}} - A_{\text{abs}}\right)\eta_{\text{t,f}}} = \frac{1}{\eta_{\text{col}} \cdot A_{\text{fos}} \cdot \eta_{\text{t,f}} \cdot DNI} \quad (15)$$

Where, S_{hyb} is the collector area of the solar hybrid system.

Based on the definition of the solar-to-electricity efficiency, the solar work output in the solar-only power plant can be expressed as "$\Delta W_{\text{sol}}=DNI \cdot S_{\text{sol}} \cdot \eta_{\text{s-e}}$". Where, S_{sol} is the collector area of the solar-only system. Then the collector area per kW solar power of a solar-only power plant can be expressed as:

$$s_{\text{sol}} = \frac{S_{\text{sol}}}{\Delta W_{\text{sol}}} = \frac{S_{\text{sol}}}{DNI \cdot S_{\text{sol}} \cdot \eta_{\text{s-e,s}}} = \frac{S_{\text{sol}}}{DNI \cdot S_{\text{sol}} \cdot \eta_{\text{col}} \cdot A_{\text{abs}} \cdot \eta_{\text{t,s}}} = \frac{1}{\eta_{\text{col}} \cdot A_{\text{abs}} \cdot \eta_{\text{t,s}} \cdot DNI} \quad (16)$$

Based on Eq.(15), Eq.(16), Eq. (13) and Eq.(14), the relative saved solar collector area in the solar hybrid system compared with the solar-only power plant can be given as:

$$\Delta s_{\text{hyb}} = s_{\text{sol}} - s_{\text{hyb}} = \frac{1}{\eta_{\text{col}} \cdot A_{\text{abs}} \cdot \eta_{\text{t,s}} \cdot DNI} - \frac{1}{\eta_{\text{col}} \cdot A_{\text{fos}} \cdot \eta_{\text{t,s}} \cdot DNI} = \frac{1}{DNI \cdot \eta_{\text{s-e,s}}}(1 - \frac{1}{\Delta\eta_{\text{s-e,h}}}) \quad (17)$$

This relative saved solar collector area of ΔS_{hyb} can also be considered as an important performance index in the solar hybrid system. From Eq. (17), it can be found that ΔS_{hyb} relies on the relative efficiency improvement of $\Delta\eta_{\text{s-e,h}}$, for a fixed reference solar-only power plant and with a given design solar radiation. For solar-coal hybrid system with $\Delta\eta_{\text{s-e,h}} > 1$, its relative saved solar collector area of ΔS_{hyb} can also larger than zero.

4. Discussions

Analysis assumptions for the solar hybrid systems are shown in Table 1.

Table 1. Analysis assumptions

Ambient temperature (°C)	10
Wind speed (m/s)	5
Incidence angle (N-S axis orientation) (°C)	10
Collector optical efficiency (°C)	0.76
Turbine internal efficiency (high/mid/low-pressure turbine)	0.85/0.89/0.83

4.1. Incremental work output of the solar hybrid system

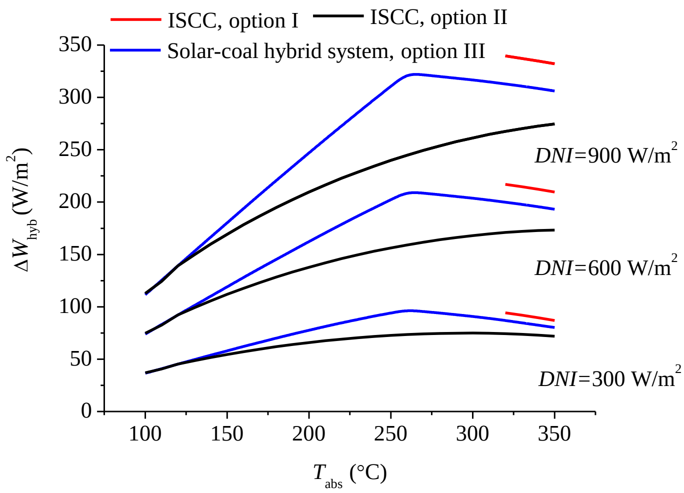

Fig. 3. Incremental work output of solar hybrid system

Figure 3 show how the incremental work output of the solar hybrid system varies as a function of the mean temperature of the absorbed solar heat T_{abs} and the solar radiation *DNI* with the three middle-temperature solar hybridization options. It can be found that below 320°C the solar-coal hybrid system shows a better performance than the ISCC system with solar heat generating low-pressure superheated steam (Option II). For solar heat above 320°C, ISCC system with solar heat generating high-pressure saturated steam (Option I) has the best thermodynamic performances.

It can also be found that the incremental work output first increases then decreases with the increase mean temperature of the absorbed solar heat for the solar-coal hybrid system. It is interesting to note that there exists an optimum range of the mean temperature of solar heat for the desired incremental work output. The range of 250–300℃ solar heat could lead to a higher incremental solar work output compared to other ranges of mean temperature of solar heat. For example, the incremental work output would be theoretically increased to 210 W/m^2, at the solar radiation of 600 W/m^2. It is because that with the increase mean temperature of solar heat, the higher-temperature steam extraction with higher energy level can be replaced by solar heat. That means the middle-temperature solar heat can be converted into work more effectively. It is worth nothing that the maximum values of the incremental work output decreased with the increase of the mean temperature of solar heat. This is due to the fact that the solar heat with a higher temperature will cause a mismatch of the energy levels between the supplied solar heat and that of the feed water preheating demand.

Notably, the incremental work output would be increased with higher solar radiation. In addition, the difference of incremental work output between the solar-coal hybrid system and ISCC system with hybridization option II will become larger at the higher DNI. This could be attributed to the fact that the increased DNI can provide sufficient solar heat, thereby allowing higher-temperature steam extraction to be replaced, leading to a higher energy level upgrade of the middle-temperature solar heat, which will affect the incremental work output.

4.2. Specific Equation of Net Solar-to-Electricity Efficiency Improvement and saved collector area

Figure 4(a) and 4(b) exhibit the profiles of the relative improved solar-to-electricity efficiency and the theoretical results of the solar collector area. The solid curves represent the theoretical values based on Eq. (15). Similarly, for the solar radiation of 600 W/m^2 the improved efficiency of the solar-coal hybrid system was demonstrated to have the optimum collector operating temperature of 250–300°C. The theoretical results showed an increase of 1.3–1.4 times upgrade than the solar-only power plant, when the solar radiation was at 600W/m^2. Above 320 °C the ISCC system with option I shows a better performance than the solar-coal system. Figure 4(a) also presents the lowest temperature of solar heat above which the solar hybrid system can have a higher efficiency than that of the solar-only power plant. For the solar-coal hybrid system, the lowest operating temperature is at round 200 °C.

Figure 4(b) presents the variation of the demanded collector area of solar hybrid systems in the case of different hybridization options at a given solar radiation of 600 W/m^2. Corresponding to the change of the efficiency, the collector area can also be saved compared with a solar-only power plant, such as SEGS VI with mean operating temperature of 350°C. This further proves that the excellent achievement of the energy level upgrade of middle-temperature solar heat can be obtained with the solar hybridization processes. Figure 4(b) presents that the collector area can be decreased to 5 m^2/kW almost reducing 25 percentage compared with the solar-only power plant, at solar radiation of 600 W/m^2 with an operating temperature of about 200-300 °C.

In general, this mechanism of the solar hybridization process reveals that a good interaction of mean temperature of the absorbed solar heat, the internal turbine efficiency and the energy level of the thermodynamic process in the Rankine cycle influence the upgrade of the energy level of the collected middle-temperature solar heat. More importantly, it provides the tremendous potential of upgrading the energy level of low quality solar heat. This feature cannot be obtained in the conventional energy transformation of heat transfer where the energy level of the range of solar thermal energy is usually degraded, rather than significantly upgraded. It also provides the substantial advantage of the efficient utilization of low quality solar thermal energy over the conventional approach of heat transfer. At the same time, it offers a new approach of synergetic conversion of solar thermal energy and the thermodynamic process.

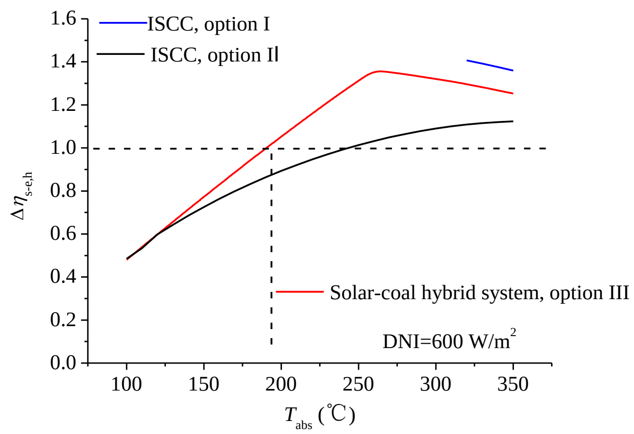

Fig. 4(a). Relative efficiency improvement of solar hybrid system

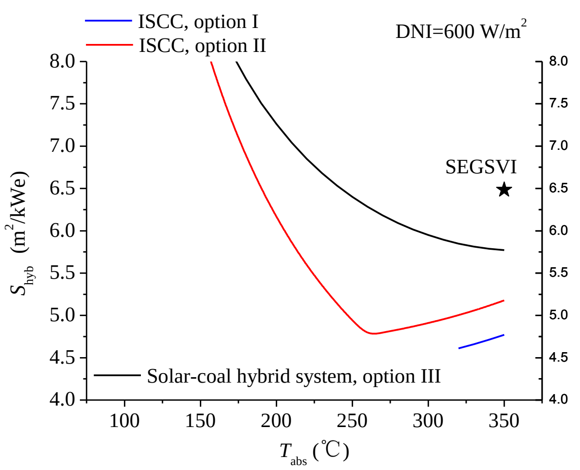

Fig. 4(b). Saved collector area of solar hybrid system

5. Conclusions

The approaches to utilizing mid and low-temperature solar heat hybridizing with fossil-fired power plant were investigated. The solar energy conversion mechanism, having the energy-level upgrade of solar heat at approximately 150-300℃ to the high-level work output, was disclosed by using the advanced thermodynamic method of the energy level. The equations for solar-to-electricity efficiency and saved solar collector area in the solar hybrid systems were identified.

Based on the mechanism, three solar hybrid systems were integrated for screening potentially viable mid- and low-temperature solar heat to generate electricity. Their thermodynamic performance was identified. For the solar-coal hybrid system with solar heat at around 250–300°C it was demonstrated that the net solar-to-electric efficiencies would be expected to be approximately 1.3-1.4 times upgrade compared to that of the state-of-the-art solar electricity generation system (SEGS VI). And the demanded solar collector area can be decreased to 5 m^2/kW almost reducing 25 percentage compared with the parabolic trough solar power plant. For solar heat above 320°C, the thermodynamic performance of the solar-coal hybrid system is deceased, while the ISCC system with solar heat generating high-pressure saturated steam still has a higher solar-to-electricity efficiency, 1.4 times higher than that of the solar-only power plant.

The results obtained here are very encouraging and support the development of the middle-temperature solar hybridization processes. The results also show that the proposed process provides the possibility of utilizing solar energy effectively with traditional fossil-fired power plants in the near future.

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Nomenclature

DNI= Direct normal irradiance (W/m^2)

η_{col} = Parabolic trough collector efficiency

η_{s-e}= Net solar-to-electricity conversion efficiency

η_{tur} = Turbine internal efficiency

η_{c}= Carnot efficiency

$\Delta\eta_{s-e}$= Improvement of the net solar-to-electricity efficiency in ISST compared to solar-only power plant

f_{ss}= Thermal solar share

S= Parabolic trough collector aperture area (m^2)

W = Work output (W)

ΔH, Q= Energy (W)

ΔE= Exergy (W)

ΔEXL= Exergy destruction (W)

A= Energy level

T_{col} = Average temperature of the collector (°C)

T_0 = Environmental temperature (°C)

Subscripts

w=Feed water

st,e= Steam extraction

ST=Main steam

1= Coal combustion fume

sol-only=Solar-only power plant

t=Turbine internal efficiency

sol= Solar radiation collected by mirrors

abs = Solar heat absorbed by fluid

actual= Actual irreversible expansion

ideal= Isentropic expansion

Appendix A. Energy level Definition

For an energy-transformation system, there exist an energy donor and an energy acceptor. Energy is released by the former and is accepted by the latter. For an energy donor and energy acceptor, we have:

$$\Delta H_{\mathrm{ed}} + \Delta H_{\mathrm{ea}} = 0 \tag{A1}$$

$$\Delta S_{\mathrm{ed}} + \Delta S_{\mathrm{ea}} \geq 0 \tag{A2}$$

Where the subscripts ed and ea represent, respectively, the energy donor and energy acceptor in the system.

Equation (A1) is a statement of energy conversation: the energy released by the energy-donating process ($-\Delta H_{ed}$) must be equal to the energy gained by the energy-accepting process (ΔH_{ed}); this is the first law of thermodynamics. On the other hand, Eq. (A2) is the second law of thermodynamics: the total entropy change in the whole system must be greater than or equal to zero.

The entropy has the dimension of energy/temperature. By intruding the environment temperature T_0, the exergy change can be defined as:

$$\Delta E = \Delta H - T_0 \cdot \Delta S \tag{A3}$$

The sum of the exergy change is:

$$\Delta E_{ed} + \Delta E_{ea} = (\Delta H_{\mathrm{ed}} + \Delta H_{\mathrm{ea}}) - T_0(\Delta S_{\mathrm{ed}} + \Delta S_{\mathrm{ea}}) = -T_0(\Delta S_{\mathrm{ed}} + \Delta S_{\mathrm{ea}}) \leq 0 \tag{A4}$$

Hence, - (ΔE_{ed}+ΔE_{ed}) is always positive and equals the exergy consumption caused by the energy transformation. Multiplying Eq. (A4) by -1, we find the exergy consumption:

$$-\Delta E_{ed} - \Delta E_{ea} = \Delta H_{ea}\left[-\left(\frac{\Delta E_{ed}}{\Delta H_{ea}}\right) - \left(\frac{\Delta E_{ea}}{\Delta H_{ea}}\right)\right] = \Delta H_{ea}\left[\left(\frac{\Delta E_{ed}}{\Delta H_{ed}}\right) - \left(\frac{\Delta E_{ea}}{\Delta H_{ea}}\right)\right] = \Delta H_{ea}(A_{\mathrm{ed}} - A_{\mathrm{ea}}) \geq 0 \tag{A5}$$

Where, energy level *A* is defined [9-11] as the ratio of exergy change ΔE to energy change ΔH.

$$A=\Delta E/\Delta H=1-T_0(\Delta S/\Delta H) \tag{A6}$$

Thus, the exergy change ΔE for any energy transformation may be given as $\Delta E = A\cdot\Delta H$. Then in Eq. (3) and (5b), $\Delta E_s=A_{abs}\cdot Q_{abs}$ and $\Delta E_{st,ext}=A_{st,ext}\cdot\Delta H_{st,ext}$. The exergy destruction may be given as $\Delta EXL=-\Delta E_{ed}-\Delta E_{ea} =\Delta H_{ed}(A_{ed}-A_{ea})$, where A_{ed} is the energy donor and A_{ea} is the energy acceptor.

For the transferred heat, its energy level A_T may be simplified to $A_T=1-T_0/T$ where T_0 is the environmental temperature and T is the temperature of the heat source. In this study, the energy level of middle-temperature solar heat may be evaluated based on the collector temperature and given as $A_{abs}=1-T_0/T_{col}$, where T_{col} is the average temperature of the collector and T_0 is the environmental temperature.

Appendix B. Definitions of solar collector efficiency and net solar-to-electricity efficiency

The collector efficiency, η_{col}, is normally defined as follows, according to Odeh et al **Erreur ! Source du renvoi introuvable.**. Where *DNI* is the solar direct normal irradiance and S_{aper} is the collector aperture area.

$$\eta_{col} = \frac{Q_{abs}}{DNI \cdot S_{aper}} = \frac{Q_{abs}}{Q_{sol}} \tag{B1}$$

Another important indicator of a solar hybrid power plant is the net solar-to-electricity efficiency, $\eta_{sol\text{-}to\text{-}elec}$, defined by Buck et al. **Erreur ! Source du renvoi introuvable.**, which is the conversion efficiency from solar energy to work.

$$\eta_{sol-to-elec} = \frac{\Delta W_{ISST}}{DNI \cdot S_{aper}} = \frac{W_{ISST} - W_{coal}}{Q_{sol}} \tag{B2}$$

Where W_{ISST} is the ISST system work output and W_{coal} is the work output of the non-hybridization system.

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