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Proposed Partial Repowering of a Coal-Fired Power Plant Using Low-Grade Solar Thermal Energy*

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Abstract

In this paper, a hybrid power-generation system with integration of solar heat at approximately 300 ºC was proposed for a coal-fired power plant. The system was investigated with the aid of energy-utilization diagram methodology (EUD methodology). In this research, instead of steam, low-grade solar heat was utilized to heat the feed water, leading to an improvement in the plant thermodynamic performance. The net annual solar-to-electric efficiency was recorded as over 15%. Solar feed-water heaters can operate in line with previously used feed-water heaters during the solar off-design period. A preliminary economic evaluation demonstrated that the increased capital cost of the solar collectors may be approximately $2,007/kWe. The promising results indicated that the proposed thermal cycle offers an approach that integrates mid-temperature solar heat to partially repower existing coal-fired power plants.

Keywords: *Mid-temperature solar energy; feed-water heater; exergy analysis; economic evaluation.*

1. Introduction

In recent years, the number of large-capacity electrical power-generating units has increased due to rapid industrial development and the rising need for additional electrical power in China. However, small-scale thermal-power units with low efficiency, which are technologically obsolete, still comprise a large proportion of electrical power generators, giving rise to high energy consumption and severe environmental pollution. Nevertheless, replacing all of these with large-capacity systems will lead to large costs and a waste of investment in fixed assets. Consequently, it is imperative to repower or at least partially repower or upgrade or upgrade these existing small power stations to reduce fuel costs and environmental impact.

Since the 1990s, more attention has been given to hybridizing solar energy with fossil power plants from the viewpoint of the sustainable development of solar thermal power plants in the near and medium terms (Steinfeld & Palumbo, 2001). At present, there are two basic approaches to hybridizing solar thermal energy with coal plants or natural gas-fueled plants: fuel saver and power booster (Gregory, 1998). In a “fuel-saver” plant, fuel input to the plant is reduced, while electricity output is constant. In this way, solar thermal energy may be utilized to produce steam in a conventional steam turbine with the coal Rankine cycle or to preheat the inlet air to a gas turbine in a combined cycle. For example, in a hybrid solar power station being constructed by the Israeli energy company AORA in Israel's Negev desert (www.greenprophet.com/2009/05/14/9008/aora-israel-solar-power/, Retrieved May 14, 2009), solar thermal energy is added to preheat the inlet air to around 800 ºC by pressurized air receivers in the solar tower plant in the gas turbine cycle; the maximum reduction in fuel consumption would be approximately 27%. In a “power-booster” plant, additional electricity is produced by oversizing the steam turbine of the pure Rankine cycle or the bottoming portion of a combined cycle under the condition of constant fuel input to the plant, such as PAESI (Allani, 1991; Kane & Favrat, 1999; Kane, Favrat, Ziegler & Allani, 2000) or ISSCS Nevada of USA (Pilkington solar international gmbh, 1996; Goswami, 1993). Based on efficient combined cycles with a better fuel conversion efficiency, electricity production costs can be reduced by as much as 42% compared with the present SEGS plants (Kolb, 1997). In both the fuel-saver and the power-booster plants, a promising economic potential exists that is greater than that for a solar-only plant with the same field size.

In Northwestern China, the installed capacity of coal-fired power plants by the end of 2006 increased to 26.62 GWe. Of these, small plants with a capacity of 200MWe or less accounted for 47.56% of capacity (12.66 GWe) and face the situation of being eliminated. Local governments have already planned to decommission quite a few of them, for example, 320-MWe small thermal power units were scheduled to be closed in Xinjiang area during 2006–2010. Simultaneously, it should be noted that the northwestern area, especially the Xinjiang region, is rich in solar energy with a large sunshine time of 2,550–3,500 hours and a high average solar radiation of 5,430–6,670 MJ/m^2 per year (www.chinabyte.com/449/7768949.shtml). It seems that there is a promising prospect for partial repowering these small-capacity plants with new technologies characterized by solar energy utilization in areas where there is adequate sunlight.

The objective of this paper is to propose a hybrid power-generation system with synergistic integration of solar heat at approximately 300 º C, identify the

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performance characteristics using the graphical exergy methodology, and identify the potential for further improvement in the thermodynamic performance of the system. Finally, a preliminary economical evaluation is performed.

2. System Description and Performance Evaluation

2.1. Description of the partially repowered system

A simplified diagram for a novel system employing solar thermal energy is given in Figure 1 and its state parameters are shown in Table 1. The solar-hybrid power plant includes a boiler system with reheating and regenerating processes; a power system consisting of high, intermediate, and low-pressure turbines; and a feed-water heater system partially repowered with solar energy.

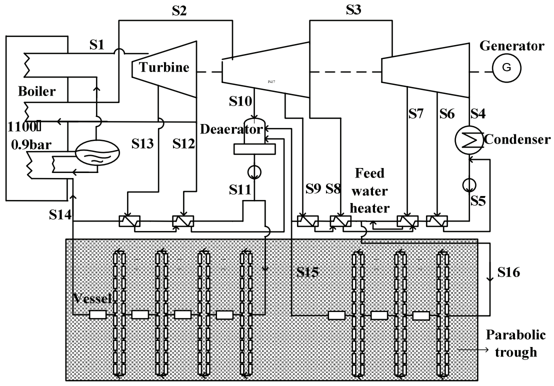

Figure 1. A simplified diagram for the solar- hybrid power plant.

Table 1. State parameters of the partially repowered system.

Items	T (℃)	P (bar)	Items	T (℃)	P (bar)
S1	535	132	S9	305	4
S2	535	22	S10	366	7
S3	242	2	S11	148	145
S4	32.5	0.049	S12	209	25
S5	33	15	S13	358	37
S6	53	0.144	S14	230	140
S7	113	1	S15	136	7
S8	242	2	S16	78	9

For this kind of solar-hybrid power plant, the net annual solar-to-electric efficiency based on the reference (Buck et al. 2002; Hong, Jin & Yang, 2006) was defined as follows:

$$\Delta\eta_{net} = \frac{W_{sol,cc} - W_{ref}}{IS} \times 100\% \tag{1}$$

where, $W_{sol,cc}$ is the output work of the repowered plant, W_{ref} represents the output work of the plant before being partially repowered, I refers to the annual average direct incident radiation, and S is the total area of the parabolic trough collectors.

The feed-water heating system consists of a deaerator, two low-pressure heaters, and two new solar feed-water heaters. The solar feed water heater before the deaerator is called the high-pressure solar feed-water heater, while the solar feed water heater located after the deaerator is called the low-pressure solar feed-water heater. Solar feed-water heaters are composed of a parabolic trough concentrator aligned on a north–south horizontal axis, with a concentration ratio of 30–70. The heaters also feature an evacuated absorber that concentrates the solar thermal energy to approximately 300 ºC. After flowing through the two non-solar low-pressure heaters, the temperature of the feed water rises to 80 º C. Subsequently, the water is pressured to 9 bars by a feed-water pump and then flows into the vacuum tube of the low-pressure solar feed-water heater. The solar heat at around 300 ºC substitutes for the extracted steam to heat the feed water to a temperature of 136 ºC. In the deaerator, the feed water is brought up to the saturation temperature of 140 ºC at a pressure of 3.6 bars. After that, the feed water is pumped to 140 bars and flows into the vacuum tube of the high-pressure solar feed-water heater, which heats the feed water to a temperature of 230 º C before it is fed into the economizer of the boiler.

In addition, the four low-pressure and high-pressure feed-water heaters in the existing plant are retained and operate in parallel with the solar feed-water heaters. In this way, the partially repowered power plant can operate at a fully rated output during periods of low solar radiation, such as during night time and overcast days. The two feed water circuits work independently of each other; in this manner, the proposed solar thermal power plant could operate continuously without an energy storage device, leading to cost reductions and system simplification. Thus, the problem of solar intermittency is expected to be overcome, enabling continuous power supply and increasing the reliability of the electrical grid.

2.2. Performance evaluation

The system simulations were built by using Advanced System for Process Engineering steady state simulation software (ASPEN PLUS). The thermodynamic properties of water or steam and gas were evaluated by the STEAM-TA, and Peng-Robinson equations, respectively, and the traditional coal-fired power plant (135 MWe) was selected as the reference plant. The main compositions of the selected coal used in this study are presented as follows: carbon, 51.28%; hydrogen, 3.7%; oxygen, 8.1%; nitrogen, 1.1%; and sculpture, 0.6%. In addition, its lower heating value is 19,984 kJ/kg. For simple comparison, it was assumed that the plant consumes the same quantity of coal before and after partial repowering. In this study, the annual average direct incident radiation was considered to be 610 W/m^2, and the number of full-load operating hours per year was estimated to be 3,037 hours, based on the atmospheric condition in the Xinjiang area in China. The ambient temperature and pressure were assumed to be 25 ºC and 1 bar. The solar collector efficiency was chosen to be 0.6 based on the reference given by Kribus, Krupkin, Yogev & Spirkl (1998). To keep the same inlet temperature of the boiler, the input solar energy was 68.2 MWe and the size of solar field was 0.19 km^2.

It can be clearly seen from Table 2 that the overall power output of the partially repowered system increased from 136.70 MWe to 153.77 MWe, almost 11.1% higher than that of the reference system. Furthermore, the coal consumption was reduced from 319.75 g (TCE)/kWh to 284.24 g (TCE)/kWh, reducing the TCE consumption by as much as 35.51 g/kWh.

Table 2. Thermodynamic performances in the reference and partially repowered systems.

Items	The reference system	The partially repowered system
Internal efficiency of turbine	0.85/0.91/0.74	0.85/0.91/0.74
Power output (MWe)	136.70	153.77
Generation efficiency (%)	38.30	43.08
TCE consumption (g/kWh)	319.75	284.24
Proportion of solar energy (%)	0	16.03
Net annual solar-to-electric efficiency (%)	0	15.03

More attractively, the net annual solar-to-electric efficiency of the proposed system is expected to reach up to 15.03%, which is a significant advantage over the efficiency of the state-of-the-art parabolic trough solar plants. For instance, compared to the cumulative 354-MWe capacity of SEGS plants in the Kramer Junction, California, the annual solar-to-electric efficiency of the plants would be 9.3–13.6% (SEGS I–XI) (Enermodal Engineering Limited, 1999) even with the sunlight concentrated by about 70–100 times and the operating temperatures at 307–391° C (SEGS I–XI).

Additionally, since the proposed plant has multiple inputs of both fossil energy and solar thermal energy in different energy grades, the exergy efficiency based on the second law of thermodynamics was utilized to estimate performance. The exergy efficiency can be defined as:

$$\eta_e = \frac{W}{\Delta\varepsilon_{coal} + IS(1-\frac{T_o}{T})} \tag{2}$$

Where, W is the work generated by the turbine; $\Delta\varepsilon_{coal}$ is the exergy of coal input to the system; I refers to the annual average direct incident radiation; S is the total area of the parabolic trough collectors; T_o is the ambient temperature, and T is the temperature at the surface of the receiver.

Table 3 shows that the exergy efficiency of the partially repowered system was estimated at 38.53% compared with the 37.25% for the traditional coal-fired plant, where the chemical exergy of coal is calculated from the correlations for solid fuels using the LHV, and mass fractions of carbon, hydrogen, oxygen and nitrogen in the fuel (Torao, 1980).

$$e = LHV\left(1.0064 + 0.1519\frac{H}{C} + 0.0616\frac{O}{C} + 0.0429\frac{N}{C}\right) \tag{3}$$

3. Graphical Exergy Presentations of the Reference System and the Proposed System

In a conventional exergy analysis, the magnitudes of exergy destruction in each process are usually obtained by obtaining the exergy difference between the output and the input, with less specific information on internal phenomena. Hence, this research adopted the energy-utilization diagram (EUD) methodology based on the graphical exergy analysis developed by Ishida and co-workers in 1982.

Table 3. Exergy destruction in the reference and partially repowered systems.

Items	The reference system		The partially repowered system	
	Exergy (kJ/kg-coal)	Ratio (%)	Exergy (kJ/kg-coal)	Ratio (%)
Coal	20,544	100	20,544	91.95
Solar	0	0	1,798	8.05
Sum of influx	20,544	100	22,342	100
Boiler subsystem	11,261		11,223	
Heat exchanger	1,439	7	1,500	6.72
Exhaust gas	684	3.33	689	3.08
Combustion	9,137	44.48	9,034	40.44
Power subsystem	1,630		2,510	
Steam turbine	1,075	5.23	1,366	6.11
Feed-water heaters	229	1.11	783	3.51
Condenser	253	1.23	325	1.45
Pump	23	0.11	25	0.05
Others	50	0.24	11	0.11
Net power	7,653	37.25	8,609	38.53
Sum of efflux	20,544	100	22,342	100

The EUD methodology is determined by plotting the energy level (A) versus the energy transformation quantity or enthalpy change (ΔH). The energy level (A) is equal to the exergy change ($\Delta\varepsilon$) divided by the enthalpy change (ΔH) (i.e., A = $\Delta\varepsilon/\Delta H$). For an energy transformation system, the energy is released by an energy donor and is accepted by the energy acceptor. The exergy destruction is represented as the specified area between the curves of energy donors and energy acceptors in the various thermal or chemical processes (Ishida & Kawamura, 1982; Jin & Ishida, 1997). In this study, the exergy destruction is discussed in following two subsystems: boiler and power.

3.1. Boiler subsystem

Figures 2 (a) and (b) show the exergy destruction for the combustion in the boiler, while Figs. 3 (a) and (b) show the exergy destruction caused by the convective heat transfer in the boiler.

For the steam turbine cycle with coal/air combustion, Figs. 2 (a) and (b) illustrate that the heat released by combustion is transferred and accepted by $A_{ea\ air}$, $A_{ea\ fuel}$ and $A_{ea\ steam}$, representing the processes of preheating the air, the coal, and the process of water evaporation, respectively. There is no difference in the exergy destruction of the combustion subsystem between the two systems because the boiler was not changed.

As shown in Figs. 3 (a) and 3 (b), the exergy destruction caused by the convective heat exchange between the curves A_{ed} and A_{ea} is identified by the areas labeled “1, 2, 3 and 4,” representing the process of heat exchange in an air preheater, an economizer, a reheater and a superheater, respectively. No significant exergy loss difference between the two systems exists in the figures.

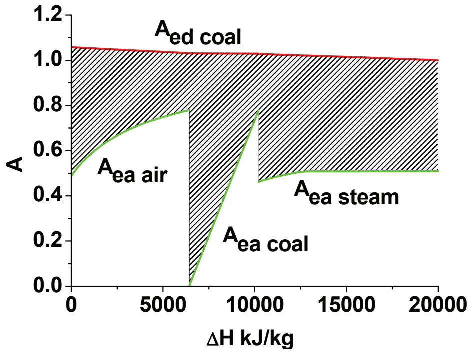

Figure 2 (a). Combustion subsystem for the reference system.

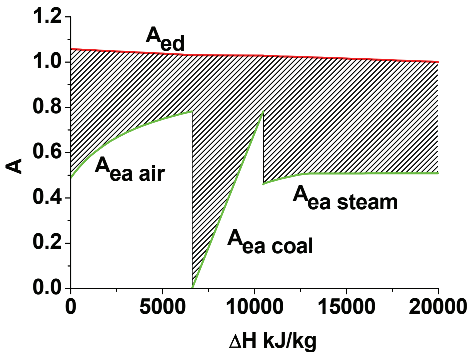

Figure 2 (b). Combustion subsystem for the partially repowered system.

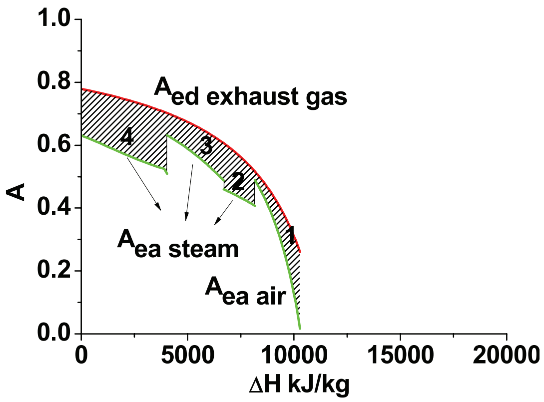

Figure 3 (a). Convective heat transfer in the reference system.

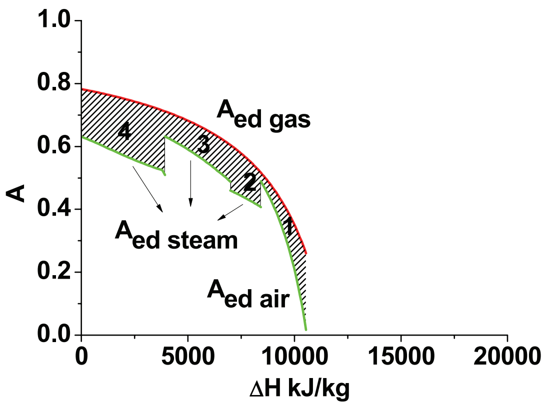

Figure 3 (b). Convective heat transfer in the partially repowered system.

3.2. Power subsystem

The degradation of energy level in the feed-water heating cycle is shown in Figs. 4 (a) and (b). Power generation and its exergy destruction are illustrated in Figures 5 (a) and (b).

For the reference system, the degree of exergy destruction during the process of heating the feed water is illustrated as the area between the varying energy level, A_{ed}, contributed by the turbine extraction steam with different temperatures and the feed water, $A_{ea\ water}$ (from 78 to 230 ^{o}C) (Fig. 4 (a)). In the diagram, lines 1 and 2 represent the energy level of steam with temperatures of 52 and 85 ^{o}C, respectively, extracted from the low-pressure turbine; lines 3 and 4 represent the energy level of steam with temperatures of 125 and 304 ^{o}C, respectively, from the mid-pressure turbine; and lines 5 and 6 represent the energy level of steam with temperatures of 279 and 355 ^{o}C, respectively, from the high-pressure turbine. The total area is 229 kJ/kg-fuel (1.11%). Figure 4 (b) shows the partially repowered system, and steam from the low-pressure turbine remains in the feed-water heating cycle, as shown by lines 1 and 2; meanwhile, the low-grade solar energy (300 ^{o}C) – instead of steam from turbine extraction – becomes the energy donor to heat the feed water (79–230 ^{o}C). This gives rise to the exergy destruction of 783 kJ/kg-fuel (3.51%) for the $A_{ed\ solar}$ of the solar energy. Exergy destruction in the partially repowered system was identified to be greater than that observed in the reference system due to the presence of a heat source with a constant temperature of 300 ^{o}C.

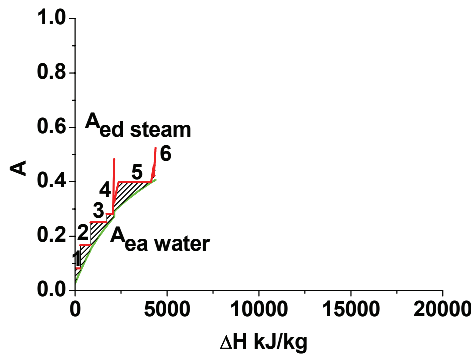

Figure 4 (a). Feed-water heating cycle in the reference system.

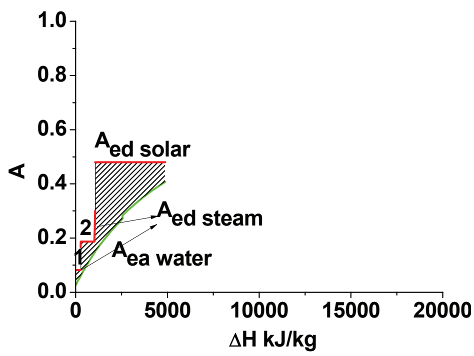

Figure 4 (b). Feed-water heating cycle in the partially repowered system.

Figures 5 (a) and (b) illustrate power generation and the exergy destruction of the power subsystem in the reference system and the partially repowered system, respectively. In these figures, ΔH refers to the amount of power generation. The steam turbine ($A_{ed\ turbine}$) acts as the energy donor, and the energy acceptor is represented by the horizontal line whose energy level is equal to 1 (environment). The exergy destruction is identified by the difference between the $A_{ed\ turbine}$ and 1. The steam expanded from 132 (535 ºC) to 25 bars (309 ºC) in the high-pressure turbine, from 22 (535 ºC) to 2 bars (242 ºC) in the mid-pressure turbine, and to 0.049 bars (33 ºC) in the low-pressure turbine, producing the power output of 7,653 and 8,609 kJ/kg-fuel for the reference system and the partially repowered system, respectively. On the basis of the input exergy of the system, these correspond to an exergy efficiency of 37.25% and 38.53% for the reference system and the partially repowered system, respectively.

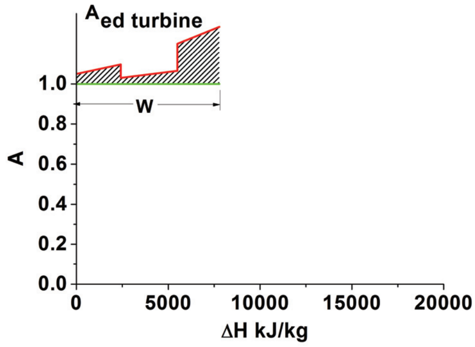

Figure 5 (a). Power subsystem for the reference system.

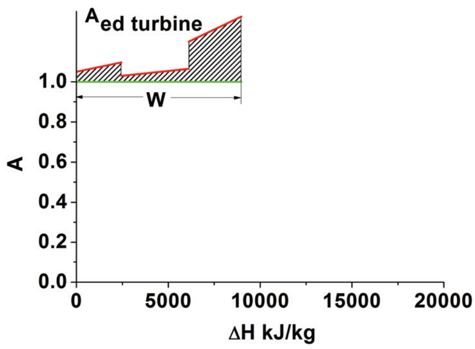

Figure 5 (b). Power subsystem for the partially repowered system.

4. Results and Discussion

The detailed exergy analysis of the proposed system has been graphically presented using the EUD methodology. To clarify the improvement and potential of the new system, additional features were compared and analyzed.

4.1. Potential of improvement in the performance

4.1.1. Increase in the work output of the steam turbine. In the partially repowered plant, solar thermal energy of around 300° C was utilized to heat the feed water, instead of the extracted steam that performs the work of expansion in the turbine. In this way, more work is generated from the steam turbine compared with the traditional coal-fired power plant under the condition of the same inputs of coal. This indicates that the steam turbine may be boosted and the thermal efficiency improved. For example, in the Xinjiang region in China, where there is an annual average solar sunshine of 3,037 hours, when a coal-fired power plant (135MWe) is partially repowered, it may yield a net increase in electricity of 51.9 million kWh in one year compared to the plant before it has been partially repowered.

It is worth emphasizing that unlike the other solar hybrid power plants with power boosters, this additional electricity does not need oversizing of the steam turbine in the proposed plant. This indicates that the previous steam turbine station may be reserved without being updated, thereby reducing the investment per kilowatt of the partially repowered plant.

4.1.2. Improve the net solar-to-electric efficiency. Solar-only thermal power plant continues to face problems until now. First, there is severe mismatch of the working fluid parameters among the absorber, the energy storage, and thermal cycle. This means that during the overall process of the conversion of solar optical energy into electricity, greater exergy destruction is achieved, thus the low net solar-to-electric efficiency. In addition, the upper process temperature in the power block is currently limited to 400 ºC by the heat transfer thermal oil, leading to low Carnot cycle efficiency, thereby lowering the total efficiency of the whole system. Furthermore, the main steam with low parameters in solar-only plants cannot match the large-capacity and high-parameter turbine with advanced and mature technologies. Taking the cumulative 354-MWe capacity of SEGS plants in the Kramer Junction as an example, California, even with the sunlight concentrated by about 70–100 times, the operating temperatures achieved ranged from 307–391° C (SEGS I–XI), and the annual solar-to-electric efficiency of the plants ranged from 9.3 to 13.6% (SEGS I–XI) (Enermodal Engineering Limited, 1999).

On the contrary, in this kind of solar-hybrid power plant, the solar thermal energy utilized at around 300 ºC is collected by the concentrator with a low concentration ratio of 30 to 70. Thus, a good match between the solar optical energy and the thermal energy absorbed by the evacuator absorber can be obtained, reducing the irreversibility of the process. Another aspect, during the process of solar thermal energy driving the feed-water heater, the energy level of solar thermal energy at around 300 ºC can be matched with that of the feed water at around 230 ºC. Irreversibility in this heat transfer process may be relatively less compared with that of the solar-only power plant where the energy level of the solar thermal energy at around 550 ºC, which has been absorbed by the absorber, is seriously mismatched with that of the working steam at around 300 ºC. In addition, with the aid of the relatively larger-capacity units of the coal-fired plant with higher internal turbine efficiency and the main steam with relatively higher parameters compared with a solar thermal power plant of small units, the steam can be converted into work more effectively. Thus, solar energy can be more effectively used in the solar-hybrid power plant. The net solar-to-electric efficiency may reach 15.03%, about 1.4–5.7 percentage points higher than the state-of-the art technology.

4.1.3. Highly-efficient utilization of mid-temperature solar thermal energy. In the partially repowered system, more steam is saved to boost the work output. The result is quite different from the conventional solar energy transformation at comparable medium temperatures by means of heat transfer, where the quality of solar thermal energy is decreased and the energy level is degraded. Conversely, the mid-temperature solar-heating feed-water process is capable of increasing the output work and electricity with higher quality of the traditional power plant. Hence, the integration of solar energy and fossil fuels is expected to more rationally utilize mid-temperature solar energy relative to direct solar- processed heat.

4.2. Reduction of CO_2 emissions

The mitigation of the emission of the greenhouse gas, CO_2, is one of the challenges being faced by humankind in this century. In the proposed partially repowered coal-fired power plant, CO_2 emissions may be reduced with the utilization of solar thermal energy. In general, if a traditional power plant provides an electric output of 1 kWh, it will emit CO_2 of approximately 1 kg to the environment. Consuming the same quantity of coal, the partially repowered system will produce 52 million kWh more electricity per year. Therefore, the partially repowered system will reduce CO_2 emissions by as much as 52,000 tons per year, which is 6% lower than that emitted by the plant before the partial repowering. When considering the certified emission reductions (CER) price of $11/t of CO_2 in the cleaner development mechanism (CDM) projects of China, the benefits from generating reduced CO_2 emissions for the partially repowered power plant can be $572,000 per year.

As of 2007, the total installed capacity of traditional coal-fired plants in China is estimated to be 556 million kW. Small units (≤100MWe) were estimated to generate approximately 15% or 82.79 million kW of this capacity (www.chinapower.com.cn/newsarticle/1073/new1073049.asp). The proposed partially repowered system could save 35.5 g of fuel per kWh; thus, small units with the combined generated energy of 251.43 billion kWh per year (during the sunshine time) could save as much as 8.93 million tons per year of the TCE used in this research. It can also decrease CO_2 emissions by 16.37 million tons per year, which is equivalent to about $180.07 million. Therefore, the proposed system may produce great economic benefit and provide a new option for clean energy technology.

4.3. Preliminary economic evaluation

The annuity method was used to evaluate the investment cost. The baseline parameters were as follows: annual average solar radiation of 610 W/m^2 and 3,037 full-load hours of completely solar operation per year. The investment cost of the concentrator was set as 187$/m^2 according to the data predicted for 2007 by Sargent & Lundy LLC Consulting Group (2003). Operation and maintenance (O&M) costs were fixed at 2% of the total investment. The discount rate was assumed at 10%, and the lifespan was 20 years. The preliminary evaluation investment is listed in Table 4.

It can be clearly seen that a net profit of $3.7 million could be obtained per year based on the on-grid solar power price of $0.16/kWh in China. Solar generation costs can be reduced to $0.09/kWh. Furthermore, the unit capital cost is near the value recorded in 2007 in terms of US dollar per kilowatt of between $3,500 and $5,000 per installed kilowatt (planetark.org/enviro-news/item/51669), which is lower than that of most other solar technologies. The proposed partially repowered system is comparable to and competitive with existing parabolic trough solar plants; the investment cost for SEGS (I–XI) is $3,800–2,890/kW and the electricity cost is $0.11–0.27/kWh (Muller-Steinhagen & Trieb, 2004). When the total cost is divided by the net profit, the payback period of 9.39 years was obtained.

Table 4. Preliminary evaluation of investment.

Total investment cost	Million $	34.78
Operation and maintenance cost	Million $	0.70
Annual average coefficient of device investment (CRF)	$	0.12
Annual cost of device investment	Million $	4.09
Net increased generation power	MWe	17.08
Increased electricity	Million kWh/y	52
Net increased profit	Million $/y	3.70
Pay-back period	Y	9.39
Solar-generation cost	$/kWh	0.09
Specific investment cost	$/kW	2,007

High cost is usually the primary restriction limiting the future development of green energy technologies, especially for developing countries such as China. Clearly, the system proposed in this research provides a promising way to use solar energy effectively at low costs. As fossil fuel prices continue to increase worldwide, this new method of generating electricity will be competitive in the global marketplace. Furthermore, with the improvement of the solar field efficiency, the required solar collector area can be reduced, leading to the decrease in investment required for operating the partial repowering plant. For instance, if the solar field efficiency improves from 0.6 to 0.7, investment and electricity costs will decrease to $1,721/kW and $0.08/kWh, respectively.

4.4. Further challenge of the proposed plant

In the proposed solar thermal partial repowering plant, greater exergy destruction in the solar feed-water heater exists compared with that of the plant before the partially repowered system (Figure 4). This resulted from the larger energy-level differences between solar thermal energy and the feed water. To decrease the exergy destruction in the solar-driven feed-water heater, a parabolic trough concentrator with a lower concentration ratio in the low-temperature section could be used to maintain the minimum temperature difference in the heat exchange equipment. For example, for the feed water in the temperature range of 78–100 ºC before the deaerator, a collector could be adopted with concentration ratio equal to 20 in order to yield heat of approximately 130 ºC, and not constantly at 300 ºC. In this manner, the energy-level difference between the two curves can be decreased (Figure 6). This concept may be achieved by further technological developments.

In addition, the evacuate absorber is operated at higher pressure. However, this technology of the evacuated absorber with a higher pressure has not yet been demonstrated. Consequently, this point will bring about risks on the operation of the proposed partially repowered plant. Although the mature technology of the heat-transfer thermal oil, as a medium, may be an option for saving and for continuous operation, the heat-transfer thermal oil adds extra costs to investment and O&M. Thus, it is a challenge to develop and originally manufacture an absorber with high pressure for the wide application of this kind of solar thermal partial repowering coal-fired power plant.

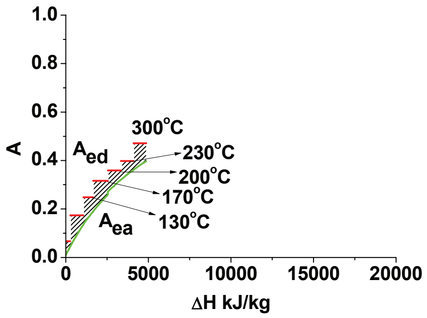

Figure 6. Solar feed-water heating system.

5. Conclusions

A novel feed-water heating system using solar thermal energy at 300 ºC was proposed and evaluated by means of graphical exergy methodology. Instead of using steam extracted from a turbine, mid-temperature solar energy was utilized to heat the feed water, which resulted in the work output increasing from 136.7MWe to 153.8MWe; meanwhile, the coal consumption of the system before and after partial repowering remained the same. Simultaneously, the net solar-to-electric efficiency of the partially repowered system was found to be 1.4–5.7% greater than that of the traditional parabolic trough solar plant (SEGS I–XI). Furthermore, the partial repowering technology produced considerable economic benefits, with lower investment cost of $2,007/kW and electricity cost of $0.09/kWh, and improved environmental benefits of a 6% CO_2 emission reduction compared with the previous system. The new system offers a promising approach for the utilization of mid-temperature solar thermal energy in partial repowering the traditional coal-fired power plant. The proposed system is expected to have a bright future in the electricity-generation market.

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Nomenclature

$\Delta\eta_{net}$ = Net solar-to-electricity efficiency
$W_{sol,cc}$ = Output work of the solar- hybrid power plant
W_{ref} = Output work of the reference system
I = Annual average direct incident radiation
S = Total area of the parabolic trough collector
LHV = lower heating value
EUD = Energy-utilization diagram
ΔH = Enthalpy change
$\Delta\varepsilon$ = Exergy change
$\Delta\varepsilon_{coal}$ = Exergy of coal
A = Energy level
TCE= Tonne of coal equivalent
T_o = Ambient temperature

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