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# Performance and emission reduction potential of renewable energy aided coal-fired power generation systems

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ABSTRACT

A renewable energy aided coal-fired power generation system (REACPGS) is proposed to provide a meaningful and promising way for energy conservation and emission reduction. General matrix models of the heat balance and exergy losses of REACPGS are established, and the thermo-economic performance, energy conservation and emission reduction potentials are investigated. The effects of system capacity, shunt coefficient and the acting position of auxiliary steam-generating system (ASS) on the overall performance are examined. Results show that the increments of thermal performance indicators in a 300 MW system are higher than those in a 600 MW system; it is a preferred choice to upgrade a 300 MW system integrated with ASS. The exergy loss coefficient of No.5 heater is the largest in all heaters, followed by that of No.2 heater; both No.5 and No.2 heaters dominate the critical energy conservation potential. Because the quality of bled steam for No.5 heater is inferior to that for No.2 heater, the benefits as ASS acting on No.2 heater are over than those on No.5 heater. Thermo-economic performance indicators are distinctly improved with increasing shunt coefficient, and reach the maximal values under the case of bled steam totally supplanted by ASS.



## 1. Introduction

Rapid economic development has pushed continuing growth of energy demands and led to severe pollutants emissions in the world. Unlike many industrialized countries, the primary energy is still dominated by coal in China [1]. The total installed capacity of coal-fired power systems is over 860 GW at the end of 2013, which providing nearly 70% of the gross electricity in China [2], and these coal-fired power systems constitute almost half of the total $CO_2$ emission and other pollutants emissions inclusive of $SO_2$, NOx and dust. According to China Statistical Yearbook–2013 [3], the total energy consumption of standard coal amounted up to 3.76 billion tons in 2012, and $CO_2$ emissions ranked the second in the world and will keep a rapid growth in the future. In the 2009 United Nations Climate Change Conference, Chinese government committed to achieve a $CO_2$ reduction of 40%–45% per capita GDP until 2025 on the base of the 2005 levels [4]. Therefore, the pollutants reductions in pulverized coal-fired power systems, including $CO_2$, $SO_2$, $NO_x$, dust etc., will contribute significantly to worldwide effort in reducing pollutants emissions [5].

Energy conservation measures for coal-fired power systems may be divided into two categories: structural aspect and technological aspect. In structural aspect, the newly installed units are almost adopted with higher steam parameters, applying clean coal technologies to diminish pollutants emissions. Additionally, many advanced technologies are widely applied to retrofit current units. For the limitations of materials and techniques employed, the potential from structural energy-saving is still constrained so far. Consequently, more attentions are concentrated on a new technological mode, which is seeking external energy to reform or integrate with traditional coal-fired power systems. Presently, the improvement of energy efficiency can be regarded as one of the most prevailing measures for reducing pollutants emissions and dependence on fossil fuels. A renewable energy aided coal-fired power generation system (REACPGS) is a creative mode based on the reasonable integration of renewable energy and conventional coal-fired power generation. REACPGS provides an effective way to reduce the cost of renewable energy power generation and to improve the utilization ratio of renewable energy [6-11].

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**Nomenclature**

| | |
|---|---|
| $A$ | the coefficient matrix in Eq. (3) |
| $b$ | the specific coal consumption, g/kWh |
| $C$ | the electricity generation cost, ¥/kWh; the coefficient matrix in Eq. (11) |
| $C_1$ | the reduction of electricity cost benefited from coal-saving and $CO_2$ reduction, ¥/kWh |
| $C_2$ | the government subsidy of utilization of renewable energy, ¥/kWh |
| $D$ | the flowrate of feedwater or steam, t/h; the coefficient matrix in Eq. (11) |
| $e$ | the specific exergy, kJ/kg |
| $E$ | the coefficient matrix in Eq. (3) |
| $f$ | the coefficient matrix in Eq. (11) |
| $h$ | the specific enthalpy, kJ/kg |
| $H$ | the annual operating hours, h |
| $H_T$ | the power output in turbine side, kJ/kg |
| $I$ | exergy loss, kJ/kg |
| $J$ | the coefficient matrix in Eq. (5) |
| $P_e$ | the unit power, kW |
| $q$ | the heat discharged, kJ/kg |
| $Q$ | the pure heat gained in a control unit, kJ/kg |
| $Q_T$ | the heat absorption capacity in turbine side, kJ/kg |
| $s_{AS}$ | the ratio of power output attributed to ASS |
| $S$ | shunt coefficient |
| $\alpha$ | the ratio of working medium flowrate to the total flowrate |
| $\beta$ | the specific exergy drop of bled steam, kJ/kg |
| $\chi$ | the coefficient matrix in Eq. (11) |
| $\varepsilon$ | coefficient, $\varepsilon_i = 1 - S_i$ |
| $\gamma$ | the heat discharge of drains, kJ/kg |
| $\eta_T$ | the absolute internal efficiency of a turbine, % |
| $\eta_{S,ex}$ | the exergy efficiency of REACPGS, % |
| $\varphi$ | the specific exergy drop of drains, kJ/kg |
| $\lambda$ | exergy loss coefficient |
| $\mu$ | the specific exergy rise of feedwater, kJ/kg |
| $\sigma$ | the heat absorbed in reheater, kJ/kg |
| $\tau$ | the specific enthalpy rise of feedwater, kJ/kg |
| $\omega$ | the specific turbine output, kJ/kg |
| $\xi$ | the coefficient matrix in Eq. (5) |

*Subscripts*

| | |
|---|---|
| a | auxiliary steam; |
| as | steam generated from ASS |
| AS | ASS |
| aw | feedwater passing through ASS |
| c | condenser |
| d | drains |
| fw | feedwater |
| i | the *i*th heater |
| n | condensate |
| o | coal-fired power generation system without ASS |
| p | pump |
| rh | reheat |
| S | REACPGS |
| w | water |
| 0 | main steam |

The investigation of REACPGS has attracted many researches so far. Eck and Zarza [12], Eck and Steinmann [13] established a hybrid power generation system model, including parabolic trough solar collectors and traditional steam power house, and the structure of hybrid power generation system was optimized. Dersch et al. [14] proposed an integrated solar combined cycle system (ISCCS), and examined the issues including when the ISCCS configuration was preferred over the solar electric generating systems (SEGS) power cycle configuration, and how the ISCCS plant design to optimise the integration of the solar field and power cycle; their study showed that when the ISCCS plants is properly designed and operated in the design manner, the ISCCS plants discharge lower specific $CO_2$ emissions than combined cycle plants under same operating conditions. Odeh's team [15-21] investigated three integrated scenarios of a direct steam generation (DSG) combined with a conventional power plant including boiling process, preheating process and preheating-boiling process, and the performance of different collector fields and power plant arrangements in Australia was examined; their results found that among three field-power house configurations, the specific energy consumption of boiling process is the lowest. Zhao and Yang [22] proposed two scenarios of a solar collector field located before and after an economizer in a coal-fired power generation system; a theoretical model of integrated arrangement was formulated and the thermal performance was compared. Cui et al. [23-24], based on the signal flow diagram theory and the principle of quality matching and cascade utilization, explored the coupled mechanism of solar energy aided coal-fired power generation system. Wu et al. [25] proposed three integrated modes of solar-coal hybrid power generation system, and the performance of the system was examined using the heat balance method. Li and Yang [26] proposed a two-stage integrated solar combined cycle with direct steam generation technology (two-stage ISCC-DSG); the DSG parabolic trough solar collectors were coupled to the bottoming steam cycle of a conventional power generation system, and optimum conditions for reheating and low-pressure steam in steam turbine cycle were suggested; their results showed that the two-stage ISCC system with solar heat integration to provide latent heat for vaporization exhibits better performance comparing with one-stage ISCC plant.

Mechthild et al. [27] applied Levelized Electricity Costs (LEC) to analyse the economic feasibility of an ISCCS power plant in Egypt, the impacts of variations in discount rate, solar investment, grant disbursement and fuel price on the LEC were evaluated; their results indicated that the LEC for the solar portion of the ISCCS (in the range of 10 US¢/kWh) is well below the actual typical solar LEC of 15 US¢/kWh, and a grant of 50 million US$ will reduce the cost of the ISCCS down to the level of a conventional CC. Hosseini et al. [28] analysed the technical and economic assessment of the first integrated solar combined cycle system with 67 MW solar field (ISCCS-67) in Iran; their study showed that 59 million US$ in fuel consumption and 2.4 million tons in $CO_2$ emission could be reduced during 30 years operating period in ISCCS-67; and the LEC of ISCCS-67 is 10% and 30% lower than the combined cycle and gas turbine, at the same capacity factor with consideration of environment costs. Zhu et al. [29] applied five evaluation methods to assess the solar contribution in solar aided coal-fired power plant systems (SACPGS); their results showed that the thermo-economic method based on the second law of thermodynamics is more suitable to the actual SACPGS than other methods and is appropriate for the evaluation in all operating conditions of SACPGS. Zhai et al. [30], based on the thermodynamic and thermo-economic theories, established a solar-aided coal-fired power generation system