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Technical and economic analysis of integrating low-medium temperature solar energy into power plant

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ABSTRACT

In order to mitigate CO_2 emission and improve the efficiency of the utilization of solar thermal energy (STE), solar thermal energy is proposed to be integrated into a power plant. In this paper, seven configurations were studied regarding the integration of STE. A 300 MWe subcritical coal-fired plant was selected as the reference, chemical absorption using monoethanolamine solvent was employed for CO_2 capture, and parabolic trough collectors and evacuated tube collectors were used for STE collection. Both technical analysis and economic evaluation were conducted. Results show that integrating solar energy with post-combustion CO_2 capture can effectively increase power generation and reduce the electrical efficiency penalty caused by CO_2 capture. Among the different configurations, Config-2 and Config-6, which use medium temperature STE to replace high pressure feedwater without and with CO_2 capture, show the highest net incremental solar efficiency. When building new plants, integrating solar energy can effectively reduce the levelized cost of electricity (LCOE). The lowest LCOE, 99.28 USD/MWh, results from Config-6, with a parabolic trough collector price of 185 USD/m^2. When retrofitting existing power plants, Config-6 also shows the highest net present value (NPV), while Config-2 has the shortest payback time at a carbon tax of 50 USD/ton CO_2. In addition, both LCOE and NPV/payback time are clearly affected by the relative solar load fraction, the price of solar thermal collectors and the carbon tax. Comparatively, the carbon tax can affect the configurations with CO_2 capture more clearly than those without CO_2 capture.

1. Introduction

In order to mitigate CO_2 emission, solar energy, as renewable energy, has attracted much attention for decades. Solar thermal power plants have been developed in different scales, from pilot plants to commercial applications. Concentrated Solar Power (CSP) is one of the most common technologies in the solar thermal power generation [1]. However, the CSP plant is hard to compete with fossil fuel fired power plants, due to the higher cost per kW and lower overall efficiency [2–5]. Meanwhile, to tackle the fluctuation of solar energy the standalone CSP is usually integrated with a thermal energy storage system, which further increases the investment cost. To overcome the disadvantages of solar energy and improve the power efficiency, it is normally proposed to integrate the solar thermal energy in conventional power plants. Zoschak and Wu [6] studied the direct integration of solar thermal energy (STE) with the fossil-fuel steam power plant. Seven methods using STE were studied and combining evaporation water and superheating steam was proved to be the preferred method. Ying and Hu [7] proposed a new concept of solar aided power generation (SAPG), in which STE is used to partly replace the bled-off steam in regenerative Rankine cycle. Zhu et al. [8] evaluated solar contribution of the SAPG system based on five methods. Apart from using concentrating solar collectors, low temperature solar collectors, such as vacuum tubes and flat-plate collectors can also be used in the SAPG, which can reduce the cost of collectors. However, due to the low temperature, it cannot increase the efficiency largely. STE can also be integrated into the combined cycle [9–12]. Even though there is a potential to increase the efficiency, the contribution of STE to the plant's overall electricity production is limited.

Although renewable energy, such as solar energy, is being developed and deployed, it alone is not enough to achieve the goal limiting average global temperature increase to 2 °C by 2050,

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according to the roadmap made by IEA; and CO_2 capture has been considered to play an important role. Currently, the post-combustion CO_2 capture technology based on chemical absorption processes (PCC) has been commercially available [13]. However, the main obstacle to the application of PCC is the high energy penalty and additional costs. The steam extraction for solvent regeneration results in an efficiency reduction about 9–12% of fuel lower heating value (LHV) [13,14]. Due to the low efficiency and high cost of producing electricity from STE directly, it has been proposed to use STE to assist CO_2 capture that can also contribute to the mitigation of CO_2. Comparing the operating conditions of the stripper reboiler and the indicative temperature of STE collected by solar thermal collectors (STC), it can be concluded that STE has the capability to provide the required thermal demand of chemical absorption in the post-combustion CO_2 capture. When STE is used to replace steam extraction, it can reduce the energy penalty caused by CO_2 capture and increase the overall efficiency of the power plant.

There have been some studies that investigate the techno-economic feasibility of solar-assisted post-combustion capture under different climatic conditions [14–23]. According to Matuszewski and Stevens [24], the integration of solar energy into the MEA based chemical absorption can increases the plant efficiency by 6%. The integration of STE with PCC can be done in different ways. STE can be used in the reboiler and provide the heat demand of the solvent regeneration directly [14,15,18]. It can also be used for high-pressure feedwater heating while the low pressure steam extracted from low-pressure turbine, instead, is used for post-combustion CO_2 capture [20,25]. Cohen et al. [21] presented another concept using high temperature solar collectors, in which the superheated steam above 900 kPa/350 °C is used in auxiliary turbine-generator or the compressor-driven let-down turbine, while the low temperature steam (120–150 °C) from turbines is used for solvent regeneration. Cau et al. [22] also evaluated the potential benefits arising from the integration of Ultra Super Critical (USC) steam power plants with CCS and concentrating solar systems. Even though the solvent regeneration in the stripper happens at low temperatures, the concentrated solar collectors, which have the ability to harvest STE at high temperatures, were adopted in most of the studies to provide the required heat demand for solvent regeneration. The mismatch between the collector ability and the temperature requirement can lead to non-optimal designs and operations.

According to the literature review, the technologies about both the utilization of solar thermal energy and CO_2 capture are facing a common challenge of high cost, which hinders the deployment in large scales. In order to promote the development of renewable energy and CO_2 capture technologies, carbon taxes, which are considered as a cost-effective means of reducing CO_2 emissions, have been adopted by more and more countries and regions. Currently, fifteen countries are implementing or have passed legislation for a direct carbon tax [26]. For example, British Columbia inaugurated its carbon tax on July 1, 2008 at a rate of $10 (Canadian) per metric ton of CO_2. The tax incremented by $5/tonne annually, reaching its current level of $30 per tonne of CO_2 in July 2012. Ireland enacted a carbon tax to cover nearly all of the fossil fuels used by homes, offices, vehicles and farms, based on each fuel's CO_2 emissions. It began in 2010 at €15/ton and rose to €20/ton in 2012, where it remains today [27]. The introduction of carbon taxes can have a clear and positive influence on the application of STE and post combustion CO_2 capture technologies. Even though many studies have been conducted focusing on the economic feasibility of solar thermal power and solar thermal assisted PCC [14,19,28], it still remains unclear which the most efficient and economical way to use STE is. This paper compared different ways using STE from both technical and economical perspectives. By taking account of carbon tax, the economy of the studied ways was calculated for two scenarios, including building a new power plant and retrofitting an existing plant. Corresponding to the different requirements about temperatures, both concentrating solar collectors and non-concentrating solar collectors, which have quite different prices, were involved. The objective is to provide some suggestions to the decision maker about using STE and CO_2 capture and guidelines regarding the system optimization.

2. System description

2.1. Reference system

A 300-MWe conventional coal-fired subcritical power plant (PC) without CO_2 capture is chosen as the reference plant. The system scheme is shown in Fig. 1. The plant consists of three high-pressure (HP) feed water heaters (FWHs), one deaerator, and four low pressure (LP) FWHs.

2.2. Integration of solar energy

Seven configurations to integrate solar thermal energy were studied in this paper.

- Config-1: the low temperature STE is used in LP feedwater preheaters, as shown in Fig. 2(a). Due to the low temperature, both low and medium/high temperature STC can be used. Therefore, Config-1 is further divided into Config-1a and Config-1b, corresponding to the applications of parabolic trough collector (PTC) and evacuated tube collector (ETC), respectively.
- Config-2: the medium temperature STE collected by PTC is used in HP feedwater preheaters as shown in Fig. 2(b).

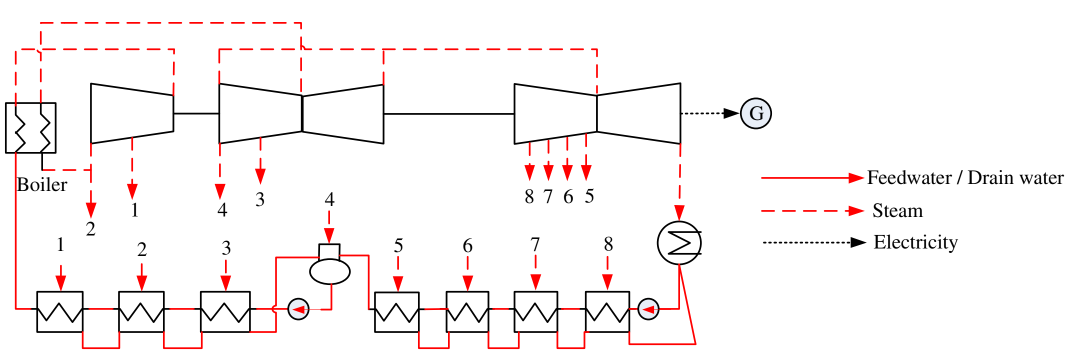

Fig. 1. System sketch of the reference PC system.