Available online at www.sciencedirect.com

SciVerse ScienceDirect

Solar Energy 86 (2012) 2975–2985

SOLAR ENERGY

www.elsevier.com/locate/solener

Performance and cost assessment of Integrated Solar Combined Cycle Systems (ISCCSs) using CO_2 as heat transfer fluid

Giorgio Cau, Daniele Cocco, Vittorio Tola *

University of Cagliari, Department of Mechanical, Chemical and Materials Engineering, Via Marengo 2, 09123 Cagliari, Italy

Received 22 December 2011; received in revised form 5 July 2012; accepted 5 July 2012
Available online 4 August 2012

Communicated by: Associate Editor Jayant K. Nayak

Abstract

In this paper, a performance and cost assessment of Integrated Solar Combined Cycle Systems (ISCCSs) based on parabolic troughs using CO_2 as heat transfer fluid is reported on. The use of CO_2 instead of the more conventional thermal oil as heat transfer fluid allows an increase in the temperature of the heat transfer fluid and thus in solar energy conversion efficiency. In particular, the ISCCS plant considered here was developed on the basis of a triple-pressure, reheated combined cycle power plant rated about 250 MW. Two different solutions for the solar steam generator are considered and compared.

The results of the performance assessment show that the solar energy conversion efficiency ranges from 23% to 25% for a CO_2 maximum temperature of 550 °C. For a CO_2 temperature of 450 °C, solar efficiency decreases by about 1.5–2.0% points. The use of a solar steam generator including only the evaporation section instead of the preheating, evaporation and superheating sections allows the achievement of slightly better conversion efficiencies. However, the adoption of this solution leads to a maximum value of the solar share of around 10% on the ISCCS power output. The solar conversion efficiencies of the ISCCS systems considered here are slightly greater than those of the more conventional Concentrating Solar Power (CSP) systems based on steam cycles (20–23%) and are very similar to the predicted conversion efficiencies of the more advanced direct steam generation solar plants (22–27%).

The results of a preliminary cost analysis show that due to the installation of the solar field, the electrical energy production cost for ISCCS power plants increases in comparison to the natural gas combined cycle (NGCC). In particular, the specific cost of electrical energy produced from solar energy is much greater (about two-fold) than that of electrical energy produced from natural gas.

Keywords: CSP systems; Parabolic trough collectors; ISCCS; CO_2

1. Introduction

Nowadays, a large number of R&D activities are carried out in the field of solar technologies for electricity generation based on both photovoltaic and Concentrating Solar Power (CSP) systems. In particular, in the field of CSP systems, parabolic trough collectors integrated with steam Rankine cycles are today the most commercially proven technology (Fernandez-Garcia et al., 2010). In CSP plants, solar energy produces a high temperature heat transfer fluid used for feeding a Heat Recovery Steam Generator. To increase plant availability, an energy storage system is usually installed. In the last few years, in addition to steam power plants, several alternative options have been proposed, mainly based on gas turbines and combined cycle power plants. In fact, solar energy can be used to heat the compressed air in simple cycle gas turbines (Buck et al., 2002; Fisher et al., 2004; Garcia et al., 2008; Sinasi et al., 2005) or in externally fired humidified air turbine systems (Zhao et al., 2003). Nevertheless, solar energy can also be used in more complex systems, such as steam reforming processes integrated with fuel cells or gas turbines (Tamme et al., 2001; Jin et al., 2003) or combined cycle power

* Corresponding author. Tel.: +39 070 6755709.
E-mail address: tola@dimeca.unica.it (V. Tola).

0038-092X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.solener.2012.07.004

plants, to produce additional steam for the bottoming Rankine cycle (Behar et al., 2011; Dersch et al., 2002, 2004; Donatini et al., 2007; Horn et al., 2004; Hosseini et al., 2005; Kane et al., 2000; Montes et al., 2011; Nezammahalleh et al., 2010). In particular, in the field of large CSP plants, Integrated Solar Combined Cycle Systems (ISCCSs) are one of the most interesting options as they allow the achievement of a significant improvement in the conversion efficiency of solar energy and reduce the importance of energy storage systems. Moreover, ISCCS plants reduce solar energy production costs since the additional cost of the combined cycle steam section is lower than the overall cost of a dedicated steam power plant (Horn et al., 2004; Dersch et al., 2004; Hosseini et al., 2005).

Worldwide, current CSP generating capacity is around 1300 MW, mainly located in the United States of America and Spain; also considering CSP systems under construction or under development, overall generating capacity is more than several GW. In the US, nine Solar Electric Generating Stations (SEGSs) have been in operation since the 1980s and 1990s, in California's Mojave Desert, with an overall generating capacity of more than 350 MW, and another plant is the Nevada Solar One with a net power output of 64 MW. Spain is the world's country with the higher CSP installed capacity, thanks to fourteen 50 MW plants in operation and nine plants under construction (SolarPACES, 2012).

Regarding ISCCS, nowadays several plants are operating in Italy, Iran and North African Countries. In Italy the Archimede Project was inaugurated in July 2010 in Priolo Gargallo (Sicily), leading to a 5 MW CSP plant integrated in a combined cycle of about 750 MW. Other ISCCS power plants with a larger solar section are currently operating in Iran (467 MW, with 17 MW from solar energy), in Morocco (470 MW, with 20 MW from solar energy), in Egypt (140 MW, with 20 MW from solar energy) and in Algeria (150 MW, with 20 MW from solar energy) (SolarPACES, 2012).

As is known, for all CSP solutions solar energy conversion efficiency increases with the maximum temperature of the heat transfer fluid (HTF). Almost all parabolic trough systems in operation or under construction use thermal oil as the HTF, which presents the important drawback of a low maximum operating temperature (about 400 °C). In this framework, the Italian Archimede project has proposed the use of molten salts (60% $NaNO_3$ and 40% KNO_3) as the HTF, making it possible to reach a maximum operating temperature of about 550 °C (Giostri et al., 2012). However, the main drawback of molten salts is their high solidification temperature (about 290 °C). To replace thermal oil and maintain high HTF temperatures, one possible choice is the direct production of steam in the solar collector, as in the most recent direct steam generation (DSG) solar plants (Birnbaum et al., 2011; Montes et al., 2009, 2011; Nezammahalleh et al., 2010; Zarza et al., 2006). Another possible option is the use of gaseous fluids as the HTF. In particular, the Italian ESTATE research Project, promoted by CRS4, Sardegna Ricerche, RTM SpA, Sapio Srl and the University of Cagliari, aimed at demonstrating the use of carbon dioxide at 550 °C in parabolic trough collectors. The overall cost of the research project is estimated at 11.4 million euros, and it has been co-funded by the Italian Ministry for Universities and Scientific Research (Baistrocchi et al., 2010; Cascetta et al., 2009; Cau et al., 2010).

This paper aims to evaluate the capabilities of integrated solar combined cycle power plants to efficiently convert the high temperature thermal energy produced by parabolic solar troughs using CO_2 as the heat transfer fluid. In particular, the study proposes to evaluate the expected performance of ISCCS power plants in function of solar radiation and for different operating conditions. Moreover, a preliminary assessment of the energy production cost has also been carried out.

2. ISCCS configuration

Fig. 1 shows a simplified scheme of the Integrated Solar Combined Cycle Systems analyzed in this paper. The ISCCS includes three main sections: the solar field (SF), the solar steam generator (SSG) and the combined cycle (CC) power plant.

The solar field is based on parabolic trough collectors connected in series to achieve the required CO_2 exit temperature and in parallel to achieve the required CO_2 mass flow. Also installed in the solar field is a CO_2 compressor for circulating the heat transfer fluid from the SF to the SSG.

In the solar steam generator the CO_2 is used to produce the steam for the combined cycle power plant. In this study, two different SSG configurations are considered and compared. In the first configuration (SSG-1), the solar steam generator includes the high-pressure preheating, vaporizing and superheating sections, whereas in the second configuration (SSG-2), it includes only the high and intermediate pressure vaporizing sections. In the latter case, water preheating and steam superheating are obviously carried out in the conventional Heat Recovery Steam Generator (HRSG). Moreover, the maximum steam mass flow produced by the SSG-2 section is closely related to the maximum thermal power available in the HRSG for water pre-heating and steam superheating. On the contrary, the influence of the HRSG thermal load on steam mass flow produced by the SSG-1 section is of minor importance, as it is simply related to the increase of the mass flow inside the HRSG steam reheating section.

The combined cycle power plant includes the gas turbine, the HRSG and the steam power plant. The gas turbine and the post-combustor of the HRSG (the latter can be used to increase the combined cycle power output during nights and other periods of low solar radiation) are fueled by natural gas. The steam cycle power section is based on a triple pressure level HRSG with steam reheating. The bottom part of Fig. 1 shows the integration between the SSG section and the HRSG for the two