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Performance assessment of USC power plants integrated with CCS and concentrating solar collectors

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ABSTRACT

This paper focuses on the evaluation of the potential benefits arising from the integration of Ultra Super Critical (USC) steam power plants with Carbon Capture and Storage (CCS) and concentrating solar systems. In particular, it reports on a comparative performance analysis of different integrating approaches, based on the design of the solar field to produce low-pressure saturated steam for the CCS solvent regeneration process and intermediate-pressure saturated and superheated steam for the introduction in the steam cycle. For the two different technical solutions, the comparative study calculates the increase in the annual energy production and net efficiency due to the solar energy contribution as a function of solar field size and for two different CO_2 removal efficiencies.

The study demonstrates that the integration of concentrating solar collectors can partially offset the efficiency penalties due to CO_2 removal in USC power plants and that the most efficient approach is based on the production of superheated steam while lesser benefits can be achieved by producing low-pressure saturated steam for the solvent regeneration process. It also demonstrates that the introduction of the steam produced by the solar field greatly affects the performance of the power plant that operates in an "off design" mode. For this reason, to avoid an excessive increase in the turbine steam mass flow, the solar energy contribution to the annual electricity production cannot exceed 2–3%. Overall, integration with the solar section can improve the efficiency of the USC-CCS power plant by about 1 percentage point.

Finally, the results of a preliminary economic analysis show that the solar assisted USC-CCS configuration may be able to operate with competitive solar energy production costs, especially with reduced solar field costs. In particular, the marginal levelized energy production cost of the most efficient solar assisted USC-CCS configuration is lower than that of the reference USC-CCS power plant for solar field costs lower than 110–115 €/m^2.

1. Introduction

To reduce CO_2 emissions produced by fossil fuels, different Carbon Capture and Storage (CCS) approaches are nowadays proposed. The most widely studied CCS approaches in the field of power generation plants are based on pre-combustion, oxyfuel combustion and post-combustion CO_2 removal processes [1–4]. In particular, Post-Combustion Carbon Capture (PCC) processes, especially chemical absorption with amine-based solvents, appear today the most suitable option for new and existing coal-based power plants [5].

Even for the most advanced CCS options, CO_2 capture, transport and storage introduces large energy penalties in power generation plants. In particular, to remove 90% of the CO_2 produced, the target of most CCS projects, a penalization of 9–12 percentage points on net efficiency is expected [6,7]. For CO_2 chemical absorption processes the largest energy consumption lies in the solvent regeneration phase, which is usually carried out by supplying low pressure steam (at about 130–140 °C). Since low and medium temperature thermal energy can easily be produced by solar radiation, in recent years several interesting options for integrating solar energy and CCS technologies have been studied [8]. Among the different options, integration between steam power plants with CCS and Concentrating Solar Collectors (CSC) is one of the most promising solutions [9].

Concentrating solar collectors are used to increase the temperature of a Heat Transfer Fluid (HTF) and therefore to produce high temperature thermal energy. The latter is usually converted into electrical energy by the power generation section of a Concentrating Solar Power (CSP) plant. CSP plants are often coupled with a

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Nomenclature

A_C	collector area
C_F	fuel costs
$C_{O\&M}$	operating and maintenance costs
C_T	total costs
F	focal length
h	specific enthalpy
L	collector length
m	mass
Q	thermal power
T	temperature
α	elevation angle
θ	incidence angle
γ	azimuth angle
η	efficiency

Acronyms

CCS	carbon capture systems
CSC	Concentrating Solar Collectors
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiation
DSG	Direct Steam Generation
ESP	ElectroStatic Precipitator
EVA	evaporating
FGD	Flue Gas Desulphurization
FWH	feed water heater
HP	high pressure
HPT	high pressure turbine
HTF	Heat Transfer Fluid
HTX	rich/lean amine heat exchanger
IAM	incidence angle modifier
IEA	International Energy Agency
IPT	intermediate pressure turbine
LCOE	Levelized Cost Of Energy
$LCOE_{s,m}$	marginal levelized cost of solar energy
LFC	linear Fresnel collectors
LP	low pressure
LPT	low pressure turbine
MEA	mono ethanol ammine
PCC	Post-Combustion Carbon Capture
PTC	parabolic trough collector
SAT	saturated
SCR	Selective Catalytic Reduction
SH	superheated
SPCC	Solar assisted Post-combustion Carbon Capture
TCI	Total Capital Investment
TES	thermal energy storage
USC	Ultra Super Critical

thermal energy storage (TES) system to offset the intermittence of solar energy and increase power plant dispatchability. Today, the current CSP world generating capacity is around 3000 MW and is rapidly increasing. More than 1300 MW of additional capacity is currently under construction and an installed CSP capacity of about 10 GW is expected before 2015. Spain is the country with the highest CSP production, thanks to the operation of more than 50 power plants with an installed capacity of about 2.3 GW [10,11].

With reference to CSP plants, different options are available for solar field (parabolic trough, linear Fresnel, solar tower and solar dish systems), power block (steam Rankine and organic Rankine cycles, Stirling engines, combined cycles, etc.), heat transfer fluid (thermal oil, molten salts, steam, etc.) and thermal energy storage section (active, passive, two-tank, thermocline, etc.) [12–15]. Today, parabolic trough collectors (PTC) are the preferred choice for commercial CSP plants, although linear Fresnel collectors (LFC) may be a viable alternative. In fact, in comparison to PTCs, LFCs have a simpler design, use less expensive mirrors and tracking systems, show lower land requirements and lower capital costs. However, the optical efficiency of LFCs is lower than that of PTCs [16–19]. Most commercial CSP plants use thermal oil as the HTF, whose maximum bulk temperature is 390–400 °C. One of the main R&D activities in the field of concentrating solar systems aims to raise the HTF temperature by replacing thermal oil with molten salts or with the direct production of steam in the solar field through the so-called Direct Steam Generation (DSG) solar plants [19–24].

The analysis of technical literature shows that the integration of concentrating solar collectors in steam power plants with CCS can be carried out by means of two main approaches [25–31]:

- production of low pressure steam for the regeneration process of the solvent used in post-combustion CO_2 capture systems, as well as for other low-temperature thermal energy requirements of the power plant. In this case, for a given fossil fuel input, steam production from solar energy reduces steam extraction from the low-pressure (LP) turbine and therefore increases its power output;
- production of high or intermediate pressure steam for the high-pressure (HP) and intermediate-pressure (IP) turbines. In this case, for a given fossil fuel input, steam production from solar energy raises the mass flow of the steam turbines and therefore increases the overall power output.

The use of solar energy in post-combustion CO_2 removal processes (often termed Solar-assisted Post-Combustion Carbon Capture, SPCC) has been studied in several papers [25–29]. In particular, Mokhtar et al. [25] proposed the integration of solar field based on linear Fresnel collectors to produce a part of the heat required by the solvent regeneration process of a 300 MWe coal-fired power plant with CCS. Zhao et al. [26] and Peng et al. [27] studied the integration of a solar field based on parabolic trough collectors to replace the steam extractions required to heat the feed water of a coal-fired power plant with CCS. Similarly, Li et al. [28] evaluated the technical and economic feasibility of a SPCC power plant where the thermal demand of the stripper reboiler was supported by the thermal energy produced by using two different solar collectors (vacuum tube and parabolic trough collectors). More recently, Qadir et al. [29] performed a techno-economic analysis for a coal-fired power plant retrofitted with a post-combustion CO_2 removal process where the thermal energy required by the solvent regeneration process was supplied by a solar field based on different solar collectors (flat plate, compound parabolic, linear Fresnel, evacuated tube and parabolic trough collectors). All studies demonstrated that solar integration is able to provide significant benefits to energy performance of power generation plants with CO_2 removal. The best option strongly depends on climatic conditions, process integration level and solar collector technology, but in general SPCC can improve the economic feasibility of CCS, especially for decreasing collector costs and increasing carbon dioxide emission prices.

All previous papers on SPCC systems focus on solar fields with low- and medium-temperature heat production. However, solar energy conversion efficiency increases with the maximum temperature of the HTF and therefore from a thermodynamic point of view the best integration approach would be based on hybrid DSG solar