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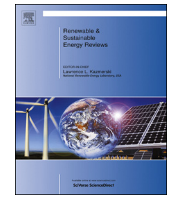

Potential solar thermal integration in Spanish combined cycle gas turbines

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ABSTRACT

Combined cycle gas turbines (CCGTs) are volumetric machines, which means that their net power output decreases at air temperatures above the design point. Such temperatures generally occur during periods of high solar irradiation. Many countries where these conditions occur, including Spain, have installed a significant number of CCGTs in recent years, with the subsequent yield losses in the summer. This implies enormous potential for solar hybridization, increasing production in peak hours and overall efficiency and reducing CO_2 emissions.

This paper analyzes the overall potential for solar thermal integration in 51 CCGTS (25,340 MW) in mainland Spain under different operating scenarios based on increasing yield, solar fraction and the hourly operational range adapted to the Spanish electricity market, considering actual meteorological conditions.

A production model for integrating solar energy into combined cycles is proposed and described and the code in R is freely released so that the assessment can be replicated.

Contents

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1. Introduction

Solar thermal energy has become a very attractive source of energy as a result of the rise in fossil fuel prices, external energy dependency on politically unstable countries and increased environmental awareness in some societies. Various concentrated solar thermal power technologies (CSP) have arisen such as tower plants, Fresnel and parabolic troughs with different heat transfer fluids (thermal oils, water, air, molten salts, etc.) [1,2]. However, the greatest growth has been in CSP technology based on parabolic troughs with thermal oil as the heat transfer fluid (PT-HTF) [3]. This technology has been operational since the 1980s, linked to the nine Solar Energy Generating Systems (SEGS) developed by Luz Solar International in the USA from 1982 to 1991. After a 15-year gap in which no CSP was developed, PT-HTF has spread since 2008, and its global installed capacity at the end of 2012 stood at 2.55 GW [4]. As a result of the learning curve of PT-HTF, mainly due to the cost reduction in solar field components, capital costs have decreased remarkably [4,5].

Nowadays, there is an increasing interest in improving efficiency in electricity production in combined cycle gas turbines (CCGTs). As a result of the volumetric machine behavior of gas turbines, a significant yield loss occurs at high air temperatures (first-order factor) and under conditions of low relative humidity and low pressure (second-order factors), with the consequent financial losses. The concept of integrating solar thermal energy in CCGT (ISCC) involves a relatively new technology, with a global solar installed capacity of about 200 MW [6], which has been operational since 2010, as shown in Table 1. In addition, two other ISCCs are under construction, the Agua Prieta II ISCC (Mexico, 464 MW CCGT, 14 MW solar) and the Ningxia ISCC (China, 92 MW). ISCCs take advantage of the fact that higher air temperatures are also associated with periods of higher direct normal solar irradiation. ISCCs have other technical advantages, such as a greater thermo-dynamical efficiency (fossil fuel consumed versus electricity generated) than CCGTs [7], the limitation in thermal inefficiency associated with daily start-ups and shutdowns of the steam turbine in a CSP plant [8], the lower cost of implementing a solar field in a existing CCGT than building an entire CSP plant [8], and the fact that operation and maintenance can be performed by the CCGT staff.

Different approaches and technologies are suitable for an ISCC power plant. However, the whole global installed ISCC capacity and most of the studies [8–10] are based on the PT-HTF technology. This is explained by its lower financial risk and the knowledge acquired in CSP plants with PT-HTF since the 1980s. Nevertheless, other possibilities arise depending on the working fluid, solar concentrating technology or the goal of integration. Regarding the working fluid, the direct steam generation technology applied to ISCCs is very promising [11–14] since it reduces the cost associated with the HTF and its intrinsic limitations in working fluid temperatures. Other working fluids such as the CO_2 have also been analyzed with parabolic troughs [15]. Regarding the method used to capture solar radiation, the solar tower technology has been analyzed with volumetric receivers using air as working fluid and transferring the heat into the Brayton cycle of the gas turbine [16–18]. The solar tower technology has also been studied in an ISCC power plant with HTF [19]. Linear Fresnel reflecting solar collectors have been considered in the potential hybridization with a CCGT [20]. Fresnel reflectors have also been analyzed with the aim to solve the air flow reduction problem caused by high inlet air temperatures, using the term *solar assisted combined cycle plant* [21]. These reflectors activate an absorption chiller that cools the inlet air. Another way to use the solar power consists of generating a syngas fuel from a chemical reaction using solar concentrated energy and mixing it with the original fuel in the combustor [22]. Solar steam can also be used for CO_2 capture in fossil fuel powered plants [22]. For a deep review on the status of the solar thermal and ISCC technologies the authors refer to Jamel et al. [23].

Fig. 1 represents a typical ISCC with PT-HTF. The solar field comprises different loops of parabolic trough solar collector assemblies (SCA) arranged in parallel, oriented on a North–South axis and therefore tracking the Sun from east to west. The heat transfer fluid temperature is regulated (to keep it constant and avoid fluid degradation) by controlling the speed of the main heat transfer fluid pump at the exit from the solar field. This heat is exchanged to generate steam in the solar steam generator and then injected into the medium pressure stage of the heat recovery steam generator (HRSG). ISCCs usually use solar thermal energy to displace latent heat in the HRSG, as a result of the similarities in the range of operating temperatures of the solar field (about 390 °C) and the medium-pressure stage of the steam turbine.

Many countries in the Middle East, the Mediterranean basin, and the southern region of the USA and elsewhere have installed a significant number of CCGTs in recent years, even though these areas experience high air temperatures over long periods, with the consequent negative impact on their electricity generation. For example, the installed CCGT capacity in mainland Spain is more than 25 GW, and most Spanish CCGTs experience direct normal irradiation in excess of 1700 kW h/m^2 year. This is enough irradiation to achieve a moderate levelized cost of electricity with PT-HTF, as is proved by Spain's total installed CSP capacity of 1950 MW at the end of 2012 [4], including some units with a similar range of irradiation. This means that there is enormous potential for improving CCGT efficiency and yield by means of hybridization with solar thermal energy [3,24].

Different assessments of the potential of ISCC have been proposed for individual CCGTs, such as the Yazd CCGT power plant [9,10,25] and the Hassi R'mel plant [26,27]. Some of these

Table 1
Global ISCC projects and their status.

Project	Country	Total capacity (MWe)	Solar capacity (MWe)	Status
MNGSEC	USA	1125	75	Operative since 2010
Archimede	Italy	750	5	Operative since 2010
Hassi R'mel	Algeria	150	25	Operative since 2011
Ain Beni Mathar	Morocco	470	20	Operative since 2011
Kuraymat	Egypt	140	20	In construction
Yazd	Iran	474	11	In construction
Victorville 2	USA	570	50	Under development
Palmdale (PHPP)	USA	573	50	Under development