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Modeling and analysis of process configurations for hybrid concentrated solar power and conventional steam power plants

Suvi Suojanen [a,*], Elina Hakkarainen [b], Matti Tähtinen [a], Teemu Sihvonen [a]

[a] VTT Technical Research Centre of Finland Ltd., Koivurannantie 1, 40101 Jyväskylä, Finland
[b] VTT Technical Research Centre of Finland Ltd., Vuorimiehentie 3, 02150 Espoo, Finland

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ABSTRACT

Availability and flexibility of variable renewable energy production can be increased without thermal energy storages by integrating intermittent energy production with load following energy production. This paper focuses on modeling, analysis and comparison of three hybrid configurations for concentrated solar power and conventional steam power plants. The configurations include feedwater preheating, cold reheat line and high pressure turbine concepts, in which linear Fresnel collector solar field with direct steam generation is applied to generate steam parallel with the steam boiler. The modeling is conducted using dynamic simulation software Apros®, which enables investigation of the system operation under varying process conditions. In particular, the focus is on the comparison of thermal load balance and interdependencies of the subsystems. In addition, the focus is on increasing the solar contribution, as the solar share is low in current commercial concepts. As a main conclusion, the more solar steam is fed to the system, the more different turbine sections and heat surfaces of the steam boiler are imbalanced, which leads to challenging system design. In addition, the maximum fuel and emission savings are not only determined by the achievable solar share, but also by the hybrid process design. The design of the hybrid system has to be optimized and modified according to the configuration in order to achieve higher peak solar share and fuel and emission savings than 20% achieved in this study.

1. Introduction

Renewable energy (RE) production, especially solar and wind power, has increased fast due to improved cost-competiveness of the RE technologies, concerns related to environment, energy security and energy availability, committed policy support and appropriate market design. In 2015, the global RE electricity production capacity was increased approximately by 147 GW, which was the largest annual increase ever [1]. The increasing share of variable solar and wind power sets challenges to the stability of the power grid due to rapid load changes. The load changes can be stabilized in a hybrid energy system, in which all the available solar and wind power is utilized and the rest of the electricity demand is covered by dispatchable energy sources [2].

In a hybrid concentrated solar power (CSP) and conventional power plant, the solar field is connected indirectly or directly to the conventional power plant to produce more electricity with less fuel and carbon dioxide (CO_2) emissions. Currently, the most successful hybrid solution is the integration of CSP solar field and combined cycle power plant, which has operational flexibility and uses natural gas as an energy source [3]. The indicative CO_2 emissions from natural gas combustion are 400 gCO_2/kWh, whereas the CO_2 emissions are 675 gCO_2/kWh from oil combustion, 825–1035 gCO_2/kWh from coal combustion and 1220 gCO_2/kWh from non-renewable municipal waste combustion [4]. In 2014, 45.9% of the world CO_2 emissions were emitted from coal combustion, 33.9% from oil combustion, 19.7% from natural gas combustion and 0.5% from industrial waste and non-renewable municipal waste combustion [5]. Thus, the CO_2 emission reduction requirements are larger for solid fuel-fired power plants than for combined-cycle power plants and oil burners.

1.1. Background of hybrid CSP and solid fuel-fired power plants

There are a few commercial hybrid concepts for CSP and solid fuel-fired power plants: Liddell Power Station in Australia, Kogan Creek Power Station in Australia, Sundt Solar Boost project in USA and Termosolar Borges in Spain [6]. In Liddell, a 9.3 MW_{th} linear Fresnel collector (LFC) solar field with direct steam generation

* Corresponding author.
E-mail addresses: Suvi.Suojanen@vtt.fi (S. Suojanen), Elina.Hakkarainen@vtt.fi (E. Hakkarainen), Matti.Tahtinen@vtt.fi (M. Tähtinen), Teemu.Sihvonen@vtt.fi (T. Sihvonen).

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Nomenclature

Abbreviations

η	efficiency [%]
CCS	carbon capture storage
CFB	circulating fluidized bed
CSP	concentrated solar power
DNI	direct normal irradiation [W/m^2]
DSG	direct steam generation
EIC	electric indication and control
ET	electric transmitter
FC	flow control
FIC	flow indication and control
FT	flow transmitter
FWH	feedwater preheater
LCOE	levelized cost of electricity
LFC	linear Fresnel collector
LIC	level indication and control
LT	level transmitter
HP	high pressure
IP	intermediate pressure
LP	low pressure
P	electrical power output [MW_e]
PIC	pressure indication and control
PT	pressure transmitter
PTC	parabolic trough collector
Q	thermal power [MW_{th}]
SAPG	solar aided power generation
SH	superheater
RE	renewable energy
RH	reheater
x	solar share [%]

Subscripts

boiler	CFB steam boiler
I	first law
e	electrical
solar	LFC solar field
th	thermal

(DSG) is retrofitted to an existing 2000 MW_e coal-fired unit to produce steam at 270 °C and 55 bar [7] for feedwater preheating and to replace part of coal consumption [8]. In Kogan Creek, a 44 MW_e LFC solar field with DSG was planned to be retrofitted to an existing 750 MW_e coal-fired unit to produce superheated steam at 370 °C and 60 bar into the cold reheat line [9]. The purpose was to increase the power output and fuel efficiency of the existing unit, but the project was delayed due to technical and financial issues [10] and was finally cancelled on March 2016 [11]. In Sundt, a 5 MW_e LFC solar field with DSG is integrated into an existing 156 MW_e coal and natural gas fired unit [12]. The power output of Sundt Unit 4 is increased due to solar integration, while the same amount of fuel is combusted. In Termosolar Borges, two 22 MW_{th} biomass and gas-fired boilers are applied to increase the availability and flexibility of a parabolic trough collector (PTC) solar field, which heat transfer fluid is thermal oil. The total power output of the hybrid system is 22.5 MW_e [13]. Thus, the LFC with DSG is the most applied and preferred CSP technology for hybridization with solid fuel-fired power plants due to its cost reduction potential, low cleaning water and land use requirements and direct connectability of the two steam cycles [6].

Based on the literature review, feedwater preheating, called as solar aided power generation (SAPG), is the most developed hybrid concept including a CSP field with DSG and a solid fuel-fired power plant. Yan et al. [14] and Suresh et al. [15] concluded that the most efficient SAPG configuration is the one, in which bled off steam to the feedwater preheater (FWH) with the highest pressure is replaced by solar steam. The maximum fuel saving is close to 5% if only one bled off steam is fully replaced whereas the maximum is close to 20%, if all the bled off steams are replaced [15]. Feng et al. [16] developed a thermo-economic evaluation method for the SAPG concept and conducted an evaluation for a case, in which different integration options of SAPG system are compared. Based on the evaluation, thermal efficiency of the SAPG system is lower than the stand-alone steam power plant. In addition, solar-to-electricity efficiency is the highest, as the bled off steam to the FWH with the highest pressure is replaced by the solar steam. Peng et al. [17] studied the thermodynamic performance of the SAPG system and concluded that exergy destruction is lower in the SAPG system than in stand-alone solutions.

Compared to the SAPG system, more benefits can be achieved in higher temperature solutions. Popov [18] analyzed a hybrid concept including high pressure (HP) FWH and economizer. This combination appeared to be more attractive option for future hybrid concepts than only replacing the bled off steam to the HP FWH. In addition, it was estimated that with such configuration the solar share could reach up to 25% of the overall power plant capacity. Cau et al. [19] concluded that the injection of superheated solar steam to the outlet of HP turbine is more efficient than producing saturated solar steam for the intermediate pressure (IP) turbine and for the solvent regeneration of a carbon capture and storage (CCS) process. According to Peterseim et al. [20], the solar field should generate steam parallel to a joint turbine rather than to the feedwater preheating or to the cold reheat line. As a consequence, the steam parameters of the LFC solar field should match with the live steam parameters of the steam boiler, which are around 540 °C and 160 bar for subcritical coal-fired units [6] and around 525 °C and 120 bar for biomass-fired units [20]. The LFC with DSG is capable of producing steam up to 520 °C [21] and 106 bar [22]. Thus, the solar field is suitable for parallel steam generation with biomass-fired units, which have lower live steam parameters than coal-fired units. One of the state-of-the-art biomass-fired boiler technologies is circulating fluidized bed (CFB) boilers, which are applied to units up to 800 MW_e [23]. The established benefits of CFB are high combustion efficiency and availability, broad fuel flexibility, low emission levels and low installation costs [24].

1.2. Purpose of the study

The previous studies on hybrid CSP power plants have mainly focused on the operational performance of the SAPG system, as the hybrid CSP systems have multiple advantages in respect to stand-alone solutions:

1. Higher energy and exergy efficiencies than stand-alone CSP [25] and steam power plants [26];
2. Higher solar-to-electricity efficiency than stand-alone CSP plant [14], which results in lower land use requirement [27];
3. Higher annual electricity generation than stand-alone CSP plant [28];
4. Lower levelized cost of electricity (LCOE) of CSP due to shared components and infrastructure and lack of thermal storage [28];