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Advances in the integration of solar thermal energy with conventional and non-conventional power plants

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ABSTRACT

Pollution and increasing fuel prices are the main focus for governments today. The main cause of pollution is existing electricity power plants that use huge quantities of fossil fuel. A new strategy should be applied in the coming decades based on the integration of existing power plants with renewable energy sources, such as solar and wind energy. Hybridization of existing power plants with solar energy is one proven option to overcome the problems of pollution and increasing fuel prices. In this paper, a review of the previous studies and papers for integrating solar thermal energy with conventional and non-conventional power plants was carried out. The focus on hybrid solar conventional power plants includes: the review of studies of hybrid solar–steam cycle power plants, integrated solar combined-cycle systems (ISCCS) and hybrid solar–gas turbine power plants, while for hybrid solar non-conventional power plants the focus of study is hybrid solar–geothermal power plants. The most successful option is ISCCS due to their advantages and the plans for implementation at various power plants in the world like in Tunisia, Egypt, Spain, and Iran.

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1. Introduction

With rapid depletion of fossil fuel reserves and their marked effects on the environment, the use of renewable energy sources needs to be accelerated. Therefore it is necessary to find adequate substitutes and plan a transition to other energy sources that provide minimum environmental impact and are available in sufficient quantities in order to satisfy demand and ensure the security of energy supplies. Solar energy is gaining more and more attention as a clean, free, and non-depleting source. However, the application of solar energy for power generation purposes is costly compared to conventional electricity generation systems, thus a new approach is needed to overcome this challenge.

Abbreviations: PTC, Parabolic trough collector; SH, Superheater; CLFR, Compact linear fresnel reflector; EC, Economizer; FPC, Flat Plate Collector; RH, Reheater; SCR, Solar central receiver; AH, Air Heater; ETC, Evacuated tubular collector; TSS, Thermal storage system; DSG, Direct steam generation; RC, Rankine cycle; HTF, Heat transfer fluid; CC, Combined cycle; FWH, Feed-water heater; GT, Gas turbine; EV, Evaporator; HP, High pressure; ISCCS, Integrated solar combined cycle system; IP, Intermediate pressure; SEGS, Solar electric generating system; LP, Low pressure; SD, Solar dishes; SAPG, Solar aided power generation; STS, Solar thermal system; ST, Steam turbine; STGHS, Solar thermal geothermal hybrid system; HRSG, Heat recovery steam generator

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Approximately 66% of world electricity production comes from fossil fuel power plants, such as steam-cycle power plants, combined-cycle (CC) power plants, and gas-turbine (GT) power plants that are also main sources of pollution [1]. Hybridization is an attractive option, using both solar energy and fossil fuels concurrently. In this paper, a review of studies and papers carried out since the 1970s until recently, on the integration of solar thermal energy with conventional and non-conventional power plants, is presented. Issues and advantages of the hybridization of solar thermal power in electricity generation was reviewed, described, and analysed by Williams et al. [2]. Four options for hybridization were compared, namely, redundant system hybridization, parallel fossil heater hybridization, solar augmented hybridization, and solar preheat hybridization. It was reported that well-designed hybrid plants can have significant advantages over solar only plants, particularly for near term markets. These advantages include the opportunity for higher energy conversion efficiency, lower capital investment in new technology, higher valued energy due to dispatchability, and lower energy costs.

2. Integration of solar thermal with conventional power plants

A methodology for structuring solar thermal power plants into sub-systems towards a standardized modelling approach was presented by Hirsch et al. [3]. The purpose of this study was to define guidelines for modelling, simulation and assessment of such systems focused on the following types: solar central receiver (SCR), parabolic trough collector (PTC), compact linear Fresnel collectors (CLFC) and solar dishes (SD). These terms are used here to make comparisons between the different types of hybrid systems. Three types of conventional power plants were selected as power blocks for integration with different types of solar thermal systems as described in the following sections.

2.1. Hybrid solar–steam power plants

In this section, a review of previous studies on the hybridization of Rankine cycle (RC) with solar thermal energy is presented. In general, the early work started in 1975 with Zoschak and Wu [4] studying seven methods of absorbing solar energy as the direct thermal input to an 800 MW fossil-fuelled central station steam power plant. SCR was chosen by the authors as the solar collecting field. The heat absorbing methods studied were feed-water heating, evaporation of water, superheating of steam, combined evaporation and superheating, reheating of steam, air preheating, and combined air preheating and feed-water heating. The heat balance for new hybrid cycles was carried out by General Electric Company. Their results showed the combined evaporation and superheating to be the preferred method for hybridization. Griffith and Brandt [5] developed a computer model to account for the energy flows and economics within a solar–fossil fuel hybrid power plant using a thermal storage system (TSS). The model calculated the power from an SCR on an hourly or quarter-hourly basis and determined the quantity of solar power directed to the TSS, the quantity of solar power directed to a specified load, the amount of power retrieved from the TSS, and the mass of fuel used by the fossil portion of the hybrid power plant. They showed the capital investment for a solar–fossil fuel hybrid system should not exceed 2.5 times the present value of the capital investment for a comparable fossil fuel power system if the hybridization is to be economically competitive.

Pai [6] proposed integration of a solar concentrator field to a 210 MWe coal-fired power plant by adding heat exchangers before each feed-water heater, as shown in Fig. 1. His results showed a 24.5% saving in fuel during the period of insolation through the heating of the feed water heater (FWH) by solar energy. Odeh et al. [7] modelled an alternative arrangement of the solar collector field and the power house back-up boiler. The model was linked with the direct steam generation (DSG) trough collector model to evaluate the best collector-back-up boiler arrangement. Their analysis showed that the solar energy contribution will be at the maximum if the collector is operated as a boiler.

Ying and Hu [8] modified a regenerative-reheat Rankine power cycle to use low temperature solar energy and other low temperature heat sources as the main heat source. Morrison et al. [9] studied the integration of CLFR into a Stanwell coal-fired power plant in Australia, they observed that the new CLFR has the potential to deliver the lowest cost solar thermal electric power compared to all solar thermal power systems. Ying and Hu [10] reported the thermodynamic advantages of using solar energy as an auxiliary heat source in a regenerative RC power plant. It was proved that the exergy merit index of the energy hit extremely high values that are far superior to the corresponding exergy efficiencies in other power systems with the same waste heat as the heat source alone. Hence, the solar aided system can run more efficiently than a conventional regenerative RC plant. It was also shown that making heat carriers in different temperatures with different types of collectors is relatively easy. In another paper, Ying and Hu [11] analysed the reheat–regenerative RC, investigating the optimal thermal and exergetic efficiencies for the combined system of the power cycle and collector, the optimum saturation temperature in the boiler and the optimum temperature of the fluid entering the solar field. It was found that a reheat–

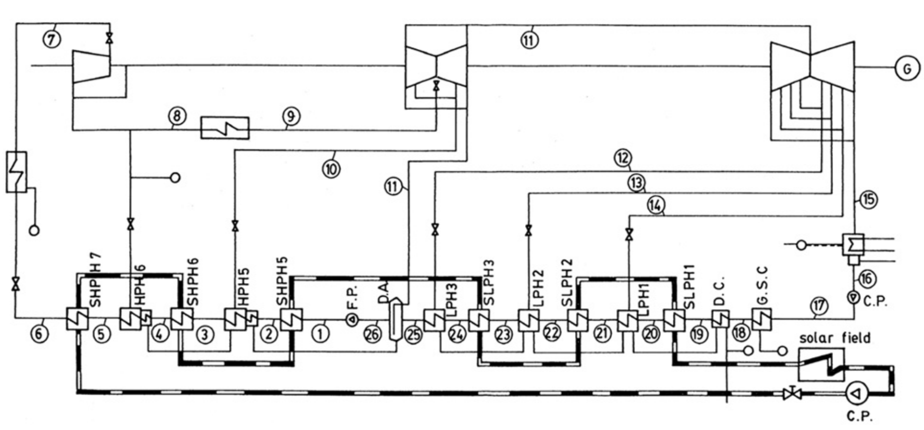

Fig. 1. Integration of solar concentrator field to conventional steam power plant by adding shell and tube heat exchangers before feed-water heaters [6].