Solar/biomass hybrid cycles with thermal storage and bottoming ORC: System integration and economic analysis

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Abstract

This paper focuses on the thermodynamic modelling and thermo-economic assessment of a novel arrangement of a combined cycle composed of an externally fired gas turbine (EFGT) and a bottoming organic Rankine cycle (ORC). The main novelty is that the heat of the exhaust gas exiting from the gas turbine is recovered in a thermal energy storage from which heat is extracted to feed a bottoming ORC. The thermal storage can receive heat also from parabolic-trough concentrators (PTCs) with molten salts as heat-transfer fluid (HTF). The presence of the thermal storage between topping and bottoming cycle facilitates a flexible operation of the system, and in particular allows to compensate solar energy input fluctuations, increase capacity factor, increase the dispatchability of the renewable energy generated and potentially operate in load following mode. A thermal energy storage (TES) with two molten salt tanks (one cold and one hot) is chosen since it is able to operate in the temperature range useful to recover heat from the exhaust gas of the EFGT and supply heat to the ORC. The heat of the gas turbine exhaust gas that cannot be recovered in the TES can be delivered to thermal users for cogeneration. The selected bottoming ORC is a superheated recuperative cycle suitable to recover heat in the temperature range of the TES with good cycle efficiency. On the basis of the results of the thermodynamic simulations, upfront and operational costs assessments and subsidized energy framework (feed-in tariffs for renewable electricity), the global energy conversion efficiency and investment profitability are estimated.

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1. Introduction

The European Commission is introducing new and ambitious targets for the penetration of renewable energy (27% of internal energy consumption), energy efficiency (reduction of 25% of energy consumption) and the reduction of greenhouse gas emissions (40% relative to 2005 levels) by 2030. These targets can be pursued by distributed heat and power generation, where renewable energy sources integrated with suitable energy storage systems can provide efficiently heat and electric power close to the end users. Concentrating solar power (CSP) and biomass-fired combined heat and power (CHP) plants can contribute towards all of these goals. CSP technologies generate electricity by concentrating the incident solar radiation onto a small area, where a heat transfer fluid (HTF) is heated. This thermal energy is then transferred by the HTF to a power generating system to drive a thermodynamic energy-conversion cycle. The integration of thermal energy storage (TES) can make CSP dispatchable and facilitate the overall energy conversion process. Nevertheless, solar energy is inherently intermittent such that even with TES the capacity factor of solar power plants is limited and often needs to be integrated by fossil boilers. Biomass can be an interesting alternative to fossil fuels to compensate the lack of solar energy: however, the thermal inertia of the furnace makes this technology well suited for base load operation but not for fluctuating operation to meet variable requests of heat and electricity from end users. TES can compensate the input and output energy fluctuations and overcome the individual drawbacks of solar and biomass as primary energy resources and allows such plants to achieve either base load or flexible operation [1][2].

The performance of a variety of system configurations of such hybrid plants under a variable solar input has been investigated in literature [3][4]. Some solar-biomass hybrid configurations are based on parabolic-trough collectors (PTCs), backup boilers and Rankine cycles [5][6], on the substitution of steam bleed regeneration with water preheating by solar energy [7] or on Fresnel collectors [8] to achieve higher temperatures. Some applications consider the use of solar towers or solar dishes and compressed air as HTF [9]. None of the previous research has addressed the integration of parabolic-trough CSP and molten salt TES with biomass combustion in externally fired gas turbines (EFGT). The use of biomass has been widely investigated in the literature as it provides added socio-economic and environmental benefits [10]; in small-to-medium scale CHP plants this includes dual-fuelling of biomass and natural gas in externally/internally fired gas turbines [11][12][13]. The influence of part load efficiencies on optimal EFGT operation was investigated in [14], while the improved energy performance and profitability of employing a bottoming ORC has been investigated in different energy-demand segments [15][16]. The literature on ORC systems and working fluid selection is also extensive[17][18][19]. In particular, a combined cycle with a 1.3 MW biomass EFGT topping cycle and 0.7 MW bottoming ORC plant was proposed in [20].

In the present paper, which goes beyond the work proposed in Ref.[20][21], the heat and power generation system is composed by independent “power blocks”, which are the generation sections (gas turbine and ORC), the thermal energy sources (biomass furnace and CSP plant), the TES and the thermal end users. The TES can compensate the solar input fluctuations and needs to be optimized to minimize exergy losses when heat is recovered from the topping cycle and from CSP to be transferred to the bottoming ORC. The technologies adopted for the TES and the ORC to meet these goals are described in the next paragraph.

2. Technology description and thermodynamic analysis

The main power blocks that compose the power plant are depicted in Fig 1. A detailed thermodynamic analysis of the EFGT is described in Ref. [20], while a similar EFGT-ORC combined cycle coupled to a CSP section is proposed in [21]. However, in the last configuration, the solar input is used to feed the topping gas turbine in combination to biomass fuel. The overall cycle pressure ratio of the EFGT is 12 and the TIT is 800 °C, which allows a low cost for the heat exchanger material (steel). Combustion air in the biomass furnace is taken from the ambient for a more flexible regulation, since the circuit of the working air flowing into the turbine and the circuit of the combustion air flowing into the furnace are decoupled. The rated LHV input produced by the biomass combustion is 9050 kW, the net electric power output is 1388 kW while the available heat flow at the turbine exit is equal to 4093 kWt at 390°C. Therefore, the temperature of the Hot Tank of the TES has been accommodated to 370°C. The available heat of the air exiting the turbine is firstly recovered in the heat exchanger HRMSH (Heat Recovery
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