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Cycle configuration analysis and techno-economic sensitivity of biomass externally fired gas turbine with bottoming ORC

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ABSTRACT

This paper focuses on the energy analysis of a combined cycle composed by a topping 1.3 MW Externally Fired Gas Turbine (EFGT) with direct combustion of biomass and a bottoming Organic Rankine Cycle (ORC). A non recuperative scheme is assumed for the EFGT in order to avoid the costs of the recuperator. This scheme presents lower conversion efficiency in comparison to a recuperative one, however the heat available for the bottoming cycle is at a higher temperature (about 400 °C). In the present work, evaporation pressure and superheating temperature of ORC cycle are ranged in order to examine different bottoming cycles, including supercritical ones. Different organic fluids are investigated, such as siloxanes and toluene, aiming to analyze how the fluid choice influences both the plant performance and important features for the ORC turbine design. On the basis of the results of the thermodynamic simulation, a thermo-economic assessment is proposed, to investigate the profitability of the bottoming ORC in comparison to only topping EFGT, and the most influencing techno-economic factors that influence the selection of the optimal cycle. In order to propose real case studies, the Italian bioenergy subsidy framework is assumed, and the sensitivity assessment includes the options of only electricity and CHP, at different biomass cost, thermal energy demand and heat selling price values.

1. Introduction

In the European Union, the European Commission (EC) Decision [1] has defined the GHG emission limits by 2020 compared to 2005 levels for each Member State (MS), in order to reduce GHGs of 20% on respect to 1990 levels. Heat and power generation from Renewable Energy Sources (RES) is recognized as a particularly important means of reducing GHG emissions [2].

In particular, small scale and on site CHP plants operated within ESCO (Energy Service Company) schemes can be promising for the residential and tertiary sector, which are commonly affected by high energy demand intensity and costs, and for the industrial sector, in particular in case of energy-intensive processes, concurrent heat and power demand, and high tariffs of electricity and heating [3]. The use of biomass in small scale CHP plants has been widely investigated in literature, including, among the others, topics such as biomass upgrading and processing technologies, logistics of supply, optimization of CHP plants sizing, location and operation. In the field of energy conversion of lignocellulosic biomass, the available technologies for small scale CHP (100 kWe to 1 MWe size) include two main options: (i) biomass pre-processing through gasification and (ii) direct combustion in grate or fluidized bed boilers. In this second option, externally fired MGT [4,5], Stirling engines [6,7] and Organic Rankine Cycles (ORC) [8,9] are largely investigated as technically viable alternatives to steam plants in order to efficiently convert the heat produced by the biomass combustion. An assessment of small scale biomass CHP plants including steam vs. ORC plants in different energy demand segments is given in [10]. The application of dual fuel schemes (direct biomass combustion and natural gas) in order to improve the efficiency of MGT has been examined in [11,12], while in [13] the technical and economical aspects related to the part load performance are examined.

Research on EFGT systems has considerably increased during last years, especially in configuration fired by biomass. In [14], a Aspen Plus and Matlab based simulation of EFGT coupled to syngas from biomass gasification is proposed, in order to explore the influence of fuel quality, dual fuel operation (natural gas mix) and other thermodynamic parameters on cycle performance. Other studies

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Nomenclature

A	surface area (m^2)
c_p	specific heat at constant pressure
h	enthalpy (kJ/kg)
H_T	equivalent heat demand (h/yr)
$\dot{m}$	mass flow (kg/s)
MW	molecular weight (kg/kmol)
p	pressure (bar)
P	power (kW)
P_T	thermal energy selling price (Eur/MW h)
$\dot{Q}$	heat power (kW)
S_p	size parameter (m)
T	temperature (°C)
$\dot{V}$	volume flow (m^3/s)
V_r	volumetric ratio

Greek

η	efficiency
χ	heat recovery ratio

Subscripts

a	air
amb	ambient
av	available
cr	critical
e	electric
eV	evaporation
g	gas
HR	heat rejected
in	inlet
is	isentropic
L	low (bottoming cycle)
out	outlet
rec	recuperator
v	vapor

Acronyms

EFGT	External Fired Gas Turbine
HRB	Heat Recovery Boiler
IC	intercooler
IRR	Internal Rate of Return
MDM	octamethyltrisiloxane
MD2M	decamethyl-tetrasiloxane
MM	hexamethyldisiloxane
NPV	net present value
ORC	Organic Rankine Cycle
RHE	Recuperative Heat Exchanger
TIT	turbine inlet temperature

[15–17] focus on methods to increase the efficiency both in simple cycle and in combined cycle configurations, investigating the use of metallic as well as ceramic materials for high temperature heat exchangers. Another configuration capable of enhancing the power output and efficiency of the EFGT, by increasing the mass flow through the turbine, the so called externally fired humid air turbine (EFHAT), is proposed in [18,19].

In [20], a small scale double shaft intercooled EFGT cycle is investigated, assuming a 50 kW biomass system with a grate combustor boiler and turbine inlet temperature of 750 °C. A preliminary sizing of the high temperature heat exchanger is performed, while the potential advantages of this externally fired configuration with respect to the existing technologies are discussed on the basis of numerical simulations in other works [21,22].

On the other side, a number of researches aimed to quantify the benefits of ORC bottoming cycles coupled to MGT [23–26]. In particular, in [23,26], a modified recuperative micro gas turbine is proposed in order to perform an externally fired scheme with direct combustion of biomass. This scheme, assuming a turbine inlet temperature of 900 °C, coupled to an optimized bottoming ORC cycle is expected to reach an electric efficiency of 23.5% with respect to 19.2% of the EFGT alone.

In [27] an interesting scheme for a small size gas turbine (1.3 MW of electric power) is proposed. An intercooled non recuperative cycle is considered with direct biomass combustion. Although this cycle has a relatively poor efficiency, the costs of investment per kW are lower on respect to a recuperative cycle because of the absence of the recuperator. Other interesting features are: higher specific work that determinates lower investment cost per kW, higher pressure ratio that allows for easier and more economic design of the heat exchangers of the air circuit. Due to the higher pressure ratio, the sensitivity of the cycle efficiency to pressure losses in the heat exchangers is much lower than in a recuperative cycle.

In the domain of thermo-economic assessment of energy conversion systems, several methodologies have been proposed in literature, as reviewed in [11], focusing on a number of renewable sources [28,29], a wide range of end user typologies [30,31], including residential, tertiary and industrial sectors, and a broad range of energy management strategies for the optimal system operation [32–34].

In the proposed research, a thermodynamic analysis of the bottoming ORC cycle is carried out in order to evaluate how the lower efficiency of the topping cycle can be compensated by an efficient bottoming cycle. The thermodynamic analysis is focused on the selection of the optimal design point for a given ORC fluid and on a comparison among different fluids. The ORC is much more suited than conventional steam turbines for small and micro CHP plants from a few dozen to some hundreds kWe. In facts, instead of water, ORC uses organic chemicals with favorable thermodynamic properties as working fluids so that the enthalpy drop is much lower and the flow can be expanded in a turbine by means of few stages.

The selection of the working fluid is a relevant issue in the ORC design. This selection is based on the temperature of heat sources and on environmental and safety regulations. In particular, refrigerant can be used for low temperatures (100–180 °C), hydrocarbons for middle temperatures (200–180 °C), while siloxanes and toluene are suitable for higher temperature (250–350 °C) [35].

The fluids can be classified as wet, dry and isentropic ones on the basis of the slope of the saturated vapor curve (dS/dT). Isentropic and dry fluids are preferred for ORC applications since they ensure a dry expansion avoiding droplet formation that can damage turbine blades, and allowing for saturated, subcritical or supercritical cycles. A review of ORC fluid selection has been proposed in a number of researches [36,37], nevertheless the selection of the best working fluid for a new application is still a difficult task.

The working fluid also influences the turbine design parameters (speed of revolution, number of stages, dimensions) and, in turn, its performance. The size parameter S_p and the volume expansion ratio V_r are often used for the turbine design. Macchi [38] suggests the use of efficiency prediction maps based on both V_r and S_P, both for single stage and double stage axial turbines. Moreover, different layout schemes could be adopted [39].

In the last section, following the methodology described in [11], a thermo-economic assessment is proposed, comparing the