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Thermo-economic assessment of externally fired micro-gas turbine fired by natural gas and biomass: Applications in Italy

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ABSTRACT

This paper proposes a thermo-economic assessment of small scale (100 kWe) combined heat and power (CHP) plants fired by natural gas and solid biomass. The focus is on dual fuel gas turbine cycle, where compressed air is heated in a high temperature heat exchanger (HTHE) using the hot gases produced in a biomass furnace, before entering the gas combustion chamber. The hot air expands in the turbine and then feeds the internal pre-heater recuperator, Various biomass/natural gas energy input ratios are modeled, ranging from 100% natural gas to 100% biomass. The research assesses the trade-offs between: (i) lower energy conversion efficiency and higher investment cost of high biomass input rate and (ii) higher primary energy savings and revenues from bio-electricity feed-in tariff in case of high biomass input rate. The influence of fuel mix and biomass furnace temperature on energy conversion efficiencies, primary energy savings and profitability of investments is assessed. The scenarios of industrial vs. tertiary heat demand and baseload vs. heat driven plant operation are also compared. On the basis of the incentives available in Italy for biomass electricity and for high efficiency cogeneration (HEC), the maximum investment profitability is achieved for 70% input biomass percentage. The main barriers of these embedded cogeneration systems in Italy are also discussed.

1. Introduction

The global focus on routes towards low carbon economies is increasing the attention on small scale (50 kWe to 1 MWe) distributed CHP generation. In particular, small scale CHP plants operated through ESCO (Energy Service Company) approaches are very promising in urban areas. In this case, community housing, leisure centers, hospitals, supermarkets and typical tertiary sector end-users present suitable energy demand intensity and high energy costs. Moreover, among all the renewable energy options, biomass is the only one that can offer the potentials for non-intermittent and predictable combined generation of heat and power. Despite of this, the use of biomass in dedicated small scale CHP plants presents a number of drawbacks, such as: (i) low conversion efficiencies in comparison to fossil fuels, (ii) complex logistics of biomass supply, transport and storage, (iii) relatively high investment and operational costs for both biomass plants and processing/transport facilities, and (iv) amenity issues such as particulate air emission levels (that, on the basis of biofuel type and conversion process, can be a major showstopper for urban areas) [1]. In order to overcome these barriers, while preserving the security and sustainability of energy supply, an optimal integration of bioenergy routes into existing energy systems and infrastructures should be pursued. In this context, dual fueling of biomass and fossil fuels into high efficiency CHP plants can play a relevant role.

The use of thermal energy from biomass as integrative source in natural gas fired plants has been widely addressed in the literature, considering various methods for biomass upgrading. In [2], a review of technologies for large scale biomass fired combined cycle plants is provided. Moreover, the use of biomass for atmospheric postcombustion of the exhaust gas at the outlet of the gas turbine is proposed, in order to reduce the natural gas consumption and increase the combined plant efficiency by the optimization of the heat recovery steam generator (HRSG) and of the bottoming cycle. The technological feasibility and the thermodynamic performances are examined with reference to repowering of existing GT plants and to greenfield plant configurations. In [3], the utilization of natural gas and biomass fuels in a combined cycle is assessed on the basis of the availability of oxygen and considering thermal operating conditions, heat loss condition and feedstock typologies, in order to achieve improved energy performances. In [4], computational simulations, techno-economic feasibility assessments and costs reduction perspectives of biomass/natural gas cofiring in a 145 MWe atmospheric gasification combined cycle is proposed.

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Nomenclature

F	primary input fuel (MW h/yr)
E	electricity (MW h/yr)
H	useful cogenerated heat (MW h/yr)
h	operating hours (h/yr)
η	efficiency (%)
P	thermal power input (kW)
p	% of input fuel (as LHV)
PE	electricity selling price (Eur/MW h)
PT	thermal energy selling price (Eur/MW h)
f_a	annuity factor $(yr)^{-1}$
R	revenues (kEur/yr)
C	costs (kEur/yr)
PES	primary energy saving (MW h/yr)
pes	primary energy saving index
$FPES$	fossil primary energy saving (MW h/yr)
$fpes$	fossil primary energy saving index
FFS	fossil fuel saving (MW h/yr)
S_{HEC}	further subsidy for HEC (kEur/MW h)
S	total subsidy cost (kEur/yr)
T	total
e	electric
t	thermal
g	gas
b	biomass
I	investment
f	fuel
O&M	operations and maintenance
HEC	high efficiency cogeneration
not-HEC	not high efficiency cogeneration

Superscript

r	reference (baseline)
r, g	baseline for gas
r, b	baseline for biomass

Acronyms

EFGT	externally fired gas turbine
IFGT	internally fired gas turbine
MT	gas microturbine
IPH	internal pre-heater
HTHE	high temperature heat exchanger
CHP	combined heat and power
NG	natural gas
HD	heat driven plant operation mode
B	biomass

The proposed strategy of gas turbine control is a mix of gas turbine derating and closing inlet guide vanes. An overview of technological options to increase the power to heat rate of CHP in size range of 1–20 MWe by means of biomass integration is proposed in [5], including economic feasibility and CO_2 emissions assessment.

1.1. Review of microturbine technologies

Distributed energy generation (DG, also called embedded, dispersed, decentralized or on-site generation) is not consistently defined in the literature, and some of the most relevant classification issues are addressed in [6]. The most widespread definitions of DG are based on the plant size, the location on respect to the electricity network, or the presence of on-site energy demand.

Among DG technologies, gas microturbines (MT) are expected to have steady growth in future energy service [7]. In many cases additional value can be gained if the thermal energy of exhaust gases can be recovered for local heat demand. MTs are typically single-shaft engines, where the turbomachinery and the electric generator have a common shaft rotating at high speed (up to 230,000 rpm). The high-frequency current from the generator is converted to grid frequency by an inverter, which enables variable-speed operation. The turbine inlet temperatures (TIT) in this case are typically in the range 800–1000 °C and the pressure ratio is low (3.5–5). Hence, the material costs can be kept at a reasonable level, using nickel/cadmium based superalloys for heat exchangers. The resulting power generation efficiency for a simple cycle is modest, but it can be improved by regenerative cycles, reaching electric efficiencies as high as 30% [8]. However, the use of recuperation increases the investment costs and needs to be justified economically. In CHP generation, the overall efficiencies of MTs are in the range 70–80%, and are influenced by the temperature of heat demand. The total investment costs for MT-based CHP are estimated to vary from 1000 to 1800 EUR/kWe, with cost increase up to 150% in case of externally fired gas turbines (EFGT) [9].

The use of biomass in MT is seen as very promising system for decentralised power generation and short bioenergy chains [10]. One of the most critical technical issues when using biofuels in gas turbines is represented by fuel quality. Experiences exist with biogas from anaerobic digestion, that is composed by 50–70% methane and is a tar-free gas, hence not too far from standard natural gas (NG) [11]. On the contrary, small scale thermo-chemical biomass conversion processes generate a low energy content and tar-rich gas, which must be upgraded by complex, expensive and energy-consuming processes, not easily applicable to small scale systems. In addition, these processes are very sensitive to physical and chemical characteristics of the biomass used. Several different approaches have been tested to use biomass fuels in MTs, as reviewed in [12]. Among the others, the following approaches have been proposed: (i) conversion of biomass into low-calorific gas through gasification, cleaning of the gas and direct combustion in modified MT combustion chambers [13–18], also in combination with solid oxide fuel cells [19]; (ii) conversion of biomass into pyrolysis bio-oil and direct combustion in modified MT combustion chambers [20,21]; (iii) combustion of liquid biofuels, such as bioethanol or fatty acid methyl-ester (FAME) oils, in standard or adapted MT combustors [22–24]; (iv) direct combustion of pulverized biomass in modified MT combustors [25]; and (v) external combustion of biomass (or syngas from gasification) in a furnace, and heating of the MT cycle working fluid (air) by means of a high temperature heat exchanger (HTHE). This last thermodynamic cycle is known as indirectly or externally fired gas turbine (EFGT).

1.2. Biomass fired EFGT

The EFGT cycle presents the advantages of gas turbines (low operational costs, high lifetime and reliability, relatively high energy efficiency even at small size) and the capability of using low quality biofuel [26–29]. Fig. 1 shows the conventional scheme of an EFGT, where biomass feeds an external furnace together with hot air from the turbine exhaust [30]. In this case, the turbine is fed by hot compressed air, heated in a HTHE to the required turbine inlet temperature (TIT) by the hot gas produced in the biomass furnace. A detailed evaluation of the EFGT thermodynamic cycle is proposed in [31], including an overview of the criteria adopted for design and selection of the HTHE materials, taking into account fouling and corrosion of metals exposed to biomass flue gases. In particular, high performance alloys are proposed in order