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Small scale biomass CHP: techno-economic performance of steam vs gas turbines with bottoming ORC

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Abstract

Small scale Combined Heat and Power (CHP) plants present lower electric efficiency in comparison to large scale ones, and this is particularly valid when biomass fuels are used. In most cases, the use of both heat and electricity to serve on site energy demand is a key to achieve acceptable global energy efficiency and investment profitability. However, the heat demand follows a typical daily and seasonal pattern and it is influenced by climatic conditions. During low heat demand periods, a lot of heat produced by the CHP plant is discharged. In order to increase the electric conversion efficiency of small scale biomass CHP plants, a bottoming ORC system can be coupled to the cycle, however this decreases the temperature and quantity of cogenerated heat available to the load. In this perspective, the paper proposes a thermo-economic analysis of small scale CHP plants based on steam turbine (ST) or externally fired micro gas turbine (EFGT) coupled to different typologies of bottoming Organic Rankine Cycles (ORC). The research assesses the influence of the thermal energy demand and CHP plant operational strategies on the global energy efficiency and profitability of the proposed cogeneration options, taking into account the part load efficiency and the heat to electricity ratio flexibility that could be achieved through a switch on-off of the bottoming ORC. The thermodynamic cycles and their part load efficiency are modeled by Gate-Cycle (Brayton cycles) and Cycle-Tempo (Rankine cycles). The research explores the profitability of bottoming ORC in view of the higher efficiency and electricity generation revenues but higher costs and reduced heat available for cogeneration in the case of bottoming ORC. The results indicate the optimal CHP technology and configuration for each energy demand segment and the relative key technical and economic factors in the Italian legislative framework.

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Keywords: CHP, biomass, Cycle Tempo, Steam Turbine, ORC

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Nomenclature

CHP	combined heat and power
ESCO	energy service company
ST	steam turbine
ORC	organic Rankine cycle
MGT	gas microturbine
EFMGT	externally fired micro gas turbine
ICE	internal combustion engine
DPBT	discount pay back time
IRR	internal rate of return
NPV	net present value

1. Introduction

Small scale CHP (Combined Heat and Power) generation can contribute to energy and social policy targets, such as competitiveness and sustainability of energy supply, decentralization and improved energy security, avoidance of distribution energy losses. CHP from Renewable Energy Sources (RES) is a promising option for reducing GHG emissions [1] and the use of biomass could also provide added socio-economic and environmental benefits, if organic by-products are recovered, and profits to the agricultural and forestry sectors, if domestic biomass supply chains are implemented [2]. Small scale and on site biomass CHP can be promising for the tertiary sector, which is commonly affected by high energy demand intensity and costs, and for the energy-intensive industrial sectors, in particular when heat and power demand occur at the same time and electricity and heating supplies present high cost [3].In the field of lignocellulosic biomass, the available technologies for small scale CHP (100 kWe to 1 MWe size) include the two main options of: (i) biomass pre-processing (through gasification or pyrolysis) coupled to both ICE [4,5] and MGT [6,7], and (ii) direct combustion in grate or fluidized bed boilers to fed externally fired MGT [8,9,10], Stirling engines [11,12], steam turbines [13] or ORC [14,15]. An overview of biomass combustion for small scale CHP is provided in [16], and in [17] a review of small scale biomass gasification coupled to different engines and turbines is proposed, while in [5] the techno-economic issues of decentralized CHP through biomass gasification coupled to engines and turbines are reviewed. Further comparisons between biomass gasification-ICE and combustion-ORC are proposed in [18], while [19] investigates the bottoming ORC coupled to a syngas-fed ORC. Other options of biomass and natural gas dual fuelling into small scale CHP by means of EFGT are explored in [20,21,22]. The influence of part load efficiencies on optimal operation of such biomass/natural gas fired MGT is investigated in [23].

The ORC is much more suited than conventional steam turbines for small and micro plants from a few dozen to some hundreds kWe. In facts, instead of water, ORC uses organic chemicals with favourable thermodynamic properties as working fluids so that the enthalpy drop is much lower and therefore the flow can be expanded in a turbine by means of few stages. There is a large literature on ORC cycles and in particular on the fluid selection for waste heat recovery applications [24,25]. A proposal of combined cycle with a topping 1.3 MW gas turbine fuelled by gasified biomass and a bottoming ORC plant can be found in [26]. Despite of the quite unconventional use of biomass boilers and ST for small scale CHP due to the aforementioned reasons, a relevant factor that could influence the selection of optimal technology is the temperature of heat demand for cogeneration. In fact, a major difference between ST and ORC is the temperature of heat available to match the load demand, which is significantly lower in the case of ORC. For this reason, in this paper, the trade-offs between higher electrical efficiency and higher investment costs of combined cycle in comparison to single (ORC, ST or MGT)cycles are addressed, taking into account the influence of the heat and power energy demand patterns. A further option of flexible ORC operation (switch on and off the bottoming ORC on the basis of the heat demand) is evaluated. The paper applies a standard thermo-economic methodology to different cycle configurations and energy demand segments, based on:(i) a simplified representation of energy demand patterns, (ii) a costs assessment and (i) discounted cash flow analysis. The methodology is applied to the cases of 100 kWe wood chips fired ST and MGT with or without bottoming ORC (of size respectively 125 and 20 kWe). The aim is to capture the influence of the energy demand segment on the CHP plant optimal configuration and evaluate if, and at what extent, an higher CHP investment cost of bottoming ORC is justified by an increased plant operational flexibility and conversion efficiency.

The economic profitability of the investments are appreciated on the basis of thermo-economic methodologies proposed in literature [27], and in light of the Italian policy measures available for renewable based cogeneration [28]. Three different energy demand patterns (industrial, tertiary and residential) are compared, and the results allow quantifying some of the key factors for the integration of bottoming ORC into ST and MGT for small scale CHP.

2. Technology description and thermodynamic modelling

The use of combined cycle schemes can increase the electric efficiency on respect to that one of the two separate plants, without the need of new technologies. In particular, in this work we consider two combined cycles: (i) a ST topping cycle and (ii) an EFGT topping cycle. An ORC is chosen for the bottoming cycle, in order to convert part of the heat rejected by the topping cycle in useful work. The combined cycles with topping ST and EFMGT (case A and E) are compared to the separate use of ST (case B), ORC (case C) and EFMGT (case D). In case of ST, the reduced volume of steam and the production of steam at pressure below 20 bar make the expander compact and the boiler quite simple and cheap. The typical boiler is, in this case, a fire-tube type. In case A, the steam exiting the ST (inlet-outlet temperature 220-150 °C and pressure drop 20-5 bar) is conveyed to the evaporator of the ORC plant. The organic fluid is then vaporized and brought to the thermodynamic condition requested for the admission in the turbine. The water exiting the evaporator still has a temperature suitable for low temperature heat demand (residential end users heat demand at 35°C). The bottoming cycle is an ORC in a recuperative configuration. We assumed a “dry fluid” with a dry expansion in the turbine, thus avoiding the droplet formation that may damage turbine blades. Recuperative heat exchangers are widely used in these cycles, in order to recover the heat of the organic fluid after the turbine expansion. In particular, the cycle contains a pump that supplies the fluid to the recuperator. The recuperator pre-heats the working fluid using the thermal energy from the turbine outlet. The evaporator produces the evaporation of the organic fluid up to the requested condition, by recovering the heat from the topping cycle. Thus, the vapour flows in the turbine, which is connected to a high-speed electric generator. At the exit of the turbine, the organic fluid goes to the hot side of the recuperator where it is cooled to a temperature a little higher than the condensation temperature. Finally, the condenser closes the ORC cycle. On the basis of the low steam temperature at the turbine outlet (150°C), refrigerants can be examined as suitable working fluids for the ORC cycle, and the Pentafluoropropane –R245fa- is here selected. Thermodynamic simulations have been carried out by means of Cycle-Tempo® for both the ST and ORC sections.

In the case of MGT, thermodynamic simulations have been carried out by means of Gate Cycle ® and based on commercially available Turbec EFMGT [29]. A recuperator is used to raise the net electric-efficiency from 10% of the simple cycle gas turbine to 23% of the recuperative Joule-Brayton cycle. The design hypotheses for these sections of the plant are the same adopted in previous works [10,21]. The biomass feeds the external furnace while combustion air is pre-heated in a dedicated heat exchanger, which recovers heat from exhaust combustion gas. The exhaust gas temperature at the gas turbine outlet (recuperator exit) is 270°C, hence siloxanes and toluene can be examined as suitable working fluids for the bottoming ORC cycle. The hexamethyldisiloxane –MM- is here selected, at a relatively low pressure of 8 bar.

In both topping cycle cases, the condensation temperature of the ORC section is assumed of 45°C in order to maximize the electric efficiency of the cycle. Consequently, the condensation heat can be used only for low temperature cogeneration. In case of high temperature heat demand, the bottoming ORC is not compatible with the CHP configuration and an evaporative cooling tower or an air condenser is needed in order to dispose of the waste heat. The main technical input parameters of the cycles are reported in Table 1, while further details and layout of the cycles are reported in [10,13].

A further scenario (case F) is considered, being the cycle configuration the same of case A, but assuming that the bottoming ORC is switched on/off in order to match the heat demand (in particular switched off during periods of high temperature heat demand of tertiary and industrial end-users, when the ORC operation is not compatible with the heat requirements of the load).Biomass boiler efficiency is assumed 88%.

All calculations are performed for ISO standard conditions (15°C, 1.013 bar and 60% relative humidity). Based on the cycle thermodynamic analysis, the net electric power output P_e, the total thermal energy input $E_{in,tot}$in the time horizon t, the electric efficiency η_e , thermal energy supplied to hot water for cogeneration Q_{HRB} , global thermal efficiency η_{th}, total (“*first law”*) efficiency for CHP generation η_{CHP} are calculated according to Eqns (1-6).The electric power output of the MGT or ST $P_{e,T}$ is evaluated from the turbine shaft power W_T through the electric generator conversion efficiency $\eta_{gen,T}$, which takes into account the losses of electric generator and inverter. In the same way, the electric power output of the ORC section is evaluated from the net mechanical power output W_{ORC} that is equal to the ORC turbine shaft power lessened by the power absorbed by the pump and the other organic losses. The total electric power of the combined cycle $P_{e,cc}$ is the sum of $P_{e,T}$ and $P_{e,ORC}$ and the total energy input $E_{in,tot}$ the time horizon t is due to the combustion of biomass flow rate $\dot{m}_b$, as from (3).

$$P_{e,T} = \eta_{gen,T} \times W_T \tag{1}$$

$$P_{e,ORC} = \eta_{gen,ORC} \times W_{ORC} \tag{2}$$

$$E_{in,tot} = \dot{m}_b \times LHV_b \times t \tag{3}$$

The overall electric efficiency of the combined cycle $\eta_{e,cc}$, the global thermal efficiency η_{th} and the first law efficiency η_{CHP} are respectively (being $E_{e,cc}$ and Q_{HRB} the useful electric energy and thermal energy in the time horizon t):

$$\eta_{e,cc} = \frac{E_{e,cc}}{E_{in,tot}} \tag{4}$$

$$\eta_{th} = \frac{Q_{HRB}}{E_{in,tot}} \tag{5}$$

$$\eta_{CHP} = \frac{E_{e,cc} + Q_{HRB}}{E_{in,tot}}. \quad (6)$$

Table 1. Technical parameters and resultsof the Cycle-Tempo and gate-Cycle modelling.

Case study	Unit	Case A ST+ORC	Case B ST	Case C ORC	Case D EFGT	Case E EFGT+ORC
Net electric power output (ISO)	kW	189	99	125	85	103
Total Thermal Power input	kW	1,136	966	1,114	366	366
Net Thermal Power output (for CHP)	kW	790	737	847	161	56
Shaft Power	kW	203	104	132	95	120
Net-electric efficiency (ISO)	%	16.6	10.3	10.5	23.2	28.0
Temperature at (topping) turbine exit	°C	143	111	67	270	270
Temperature at (bottoming) turbine exit	°C	77	-	-	-	70
mass flow rate (topping cycle)	kg/s	0.410	0.337	4.594	0.783	0.783
mass flow rate (bottoming cycle)	kg/s	3.78	-	-	-	0.605
Max Cycle Temperature	°C	220	220	130	900	900

3. Thermo-economic assessment

The assessment of global energy efficiency of each case study is carried out considering the three different end-user categories of industrial (i), tertiary (t) and residential (r) heat demand. The operating hours of the plants (base load operation mode) are assumed 7,500 (in agreement with data from manufacturers Progeco and Turbec [29,30]), while the useful cogeneration heat is calculated assuming heat demand of 4,000/1,800/1,200 hours/year at temperature of 110/90/35 °C, respectively for industrial (i), tertiary (t) and residential (r) consumers. The cost items and biomass consumption figures of Table 2 are assumed.

Table 2. Main capex and opex cost figures and biomass fuel consumption for the selected case studies

Description	Unit	Case A	Case B	Case C	Case D	Case E
Biomass consumption	t/year	2,036	1,731	1,995	657	657
Total upfront cost [3,4]	kEur	1,170	715	770	470	530
- Turbine cost	kEur	220	220	-	130	130
- HTHE cost (MGT)	kEur	-	-	-	217	217
- ORC generator cost	kEur	330	-	330	-	60
- Biomass Boiler cost	kEur	480	400	380	75	75
- Engin, develop, insur	kEur	60	60	60	48	48
Specific upfront cost	kEur/kWe	6.18	7.20	6.16	4.56	5.17
Operational cost (included fuel)	kEur/yr	191.26	153.34	178.36	65.21	67.91

The turn key investment and operational costs are personal estimates from manufacturers data and previous works [13,21].The O&M costs are 20 Eur/MWh for biomass based electricity. Biomass ash discharge costs are accounted for assuming unitary cost of 70 Eur/t of ash. The following input data are also assumed: LHV of biomass = 4.18 kWh/kg; cost of biomass = 80 Eur/t; electric autoconsumption of CHP plant = 5%; biomass electricity feed-in tariff = 287 Eur/MWh [28]; heat selling price =60/80/100 Eur/MWh respectively for industrial, tertiary and residential end users. The financial appraisal of the investment is carried out assuming the following hypotheses: (i) 20 years of operating life; no 're-powering' throughout the 20 years; zero decommissioning costs; (ii) maintenance costs, fuel supply costs, electricity and heat selling prices held constant (in real 2015 values); (iii) duration of feed-in tariff for biomass electricity of 20 years (iv) capital assets depreciated using a straight line depreciation over 20 years; (v) cost of capital (net of inflation) equal to 8%, corporation tax neglected, capital investments and income do not benefit from any support.

4. Results and discussion

In Fig. 1 the global conversion efficiency, η_{CHP} of the selected case studies in different end-user segments is reported (ratio useful heat + electricity generated vs input biomass energy).The industrial energy demand presents the highest global efficiency because of the high heat demand rate, and the case B, which maximizes the heat available to the load, appears the most suitable in this market segment, followed by case D (for the high temperature of heat available to match the industrial energy demand). In case F,the plant operational flexibility (switch on/off the ORC coupled to the ST on the basis of the heat demand) makes the difference in comparison to case A and C. In the tertiary end user segment, the global energy efficiency is lower in comparison to the industrial end user typology because of the reduced heat demand, and in this case the use of MGT (cases D and E, having the highest electric conversion efficiency) offers higher global energy performance. The market segment of residential customers is the only one where the low temperature heat discharged by the ORC cycle is compatible with the cogeneration (35°C of heat demand), hence the plant can maximize the electric efficiency also in in CHP configuration. This is the only market segment where the efficiency of case C is above 11%. Despite these conversion efficiencies appear quite low if compared to average values for large scale CHP (usually well above 75%), an accurate comparison should take into account the benefits of on site small scale generation on the broad energy system and use of renewable sources (biomass).

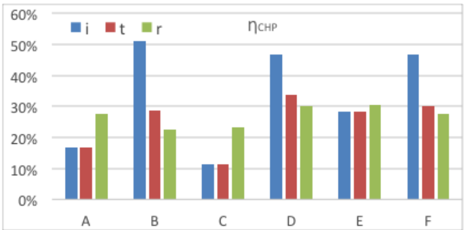

Fig. 1. Conversion efficiency (□ CHP) for CHP configurations A to F and industrial (i), tertiary (t) and residential (r) end-users

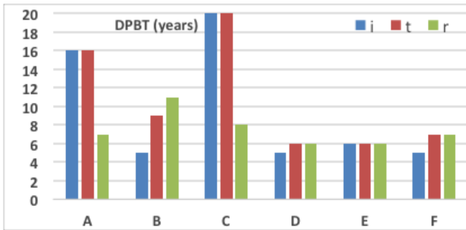

Fig. 2. Discounted pay back time (DPBT) of the investment for CHP configurations A to F and industrial (i), tertiary (t) and residential (r) end-users

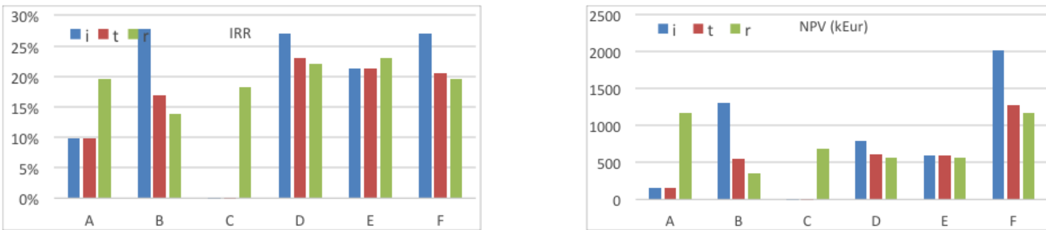

Fig. 3. IRR (left) and NPV (right) of the investment for the 6 case studies and 3 different energy demand segments.

The results of the financial appraisal are reported in Fig. 2 and 3.In the case of IRR, they appear similar to the global energy efficiency ones; as can be seen, for industrial end-users, the ST-CHP (case B), the MGT (case D) and the case F present the highest IRR, while case A and C are not profitable. However, in this case, the NPV is the highest for configuration F, and this is due to the higher investment cost and higher revenues in comparison to plant B. The flexible combined cycle (F) is the most profitable option also in the tertiary market segment, being in this case both the IRR and the NPV higher than in case B. Finally, the residential market segment is the only one where the ORC cycle in not-flexible operation mode is profitable.

5. Conclusions

In this paper, a thermo-economic comparison of the following biomass-CHP configurations is proposed: (A) ST + bottoming ORC, (B) ST, (C) ORC, (D) EFGT, (E) EFGT+bottoming ORC and (F) configuration (A) with option to switch on or off the bottoming ORC on the basis of the heat demand available. In the cases A-C and D, the focus is on a 1 MWt biomass boiler (while cases C and D have a 360 kWt biomass boiler), and the plants are operated to serve residential (r), tertiary (t) and industrial (i) heat demand. The thermodynamic cycles are modeled by Cycle-Tempo (steam turbines and ORC) and Gate-Cycle (gas turbine), while the energy demand is modelled by simplified indicators (temperature of heat demand, equivalent hours of heat demand per year). On the basis of the results of thermodynamic simulations, upfront and operational costs estimates, and Italian energy policy scenario (feed-in tariffs for biomass electricity), the maximum global energy efficiency and investment profitability is estimated, for each CHP configuration and energy demand segment. The highest conversion efficiency, obtained in case of industrial end users and case B (only steam turbine) results slightly above 50%, while the option of ORC switching (case F) increases the profitability in comparison to case A for industrial and residential market segments. The separate ORC cycle (case C) presents the lowest conversion efficiency, and itis higher than 11% only for residential market segment at low heat demand temperature, where the plant can operate in cogeneration configuration. The results show that the end user energy demand is a key factor to select the optimal CHP configuration. In particular, ORC cycles (both bottoming in a combined gas or steam turbine cycle and stand alone) appear to be profitable in case of low temperature heat demand, otherwise a flexible ORC is required to match the heat demand. For industrial users, a simpler configuration without ORC can be more competitive than a flexible ORC, on the basis of upfront costs, discount rate and feed-in tariffs. Further simulations to select the optimal ORC turbine output temperature should be carried out, in order to investigate the trade off between electric efficiency and temperature of heat demand.

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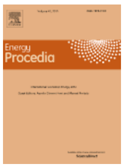

Biography

Antonio Pantaleo, electric engineer, hold his PhD at the Centre for Process Systems Engineering, Imperial College London, in bioenergy systems optimization and planning. He joined the DISAAT Department of University of Bari as assistant professor, and the Centre for Environmental Policy of ICL, as visiting research associate, in 2006. His research interests include spatially explicit modelling of bioenergy systems, CHP planning and optimization.