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Energy Procedia 00 (2015) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

The 7th International Conference on Applied Energy – ICAE2015

Thermo-economic assessment of small scale biomass CHP: steam turbines vs ORC in different energy demand segments

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Abstract

The energy performance and profitability of CHP plants, and the selection of the optimal conversion technology and size, are highly influenced by the typology of energy demand (load-duration curve, temperature of heat demand, heat and electricity load patterns). In the small scale range, where CHP can be particularly promising to match local heat and power demand, the technologies based on boilers coupled to steam turbines (ST) and bottoming Organic Rankine Cycle (ORC) can be operated in flexible mode to match the energy demand. This is particularly important when high temperature heat is required (i.e. industrial end users). In the case of solid biomass fired CHP, the boiler + ST/ORC option could be competitive with the alternatives of boiler + Stirling engine, externally fired GT or gasification + ICE. In this paper, a thermo-economic comparison of the following biomass-CHP configurations is proposed: (A) boiler + ST + bottoming ORC, (B) boiler + ST, (C) boiler + ORC and (D) configuration (A) with option to switch on or off the bottoming ORC on the basis of the heat demand available. The focus is on a 1 MWt biomass boiler, and the plants are operated to serve residential (r), tertiary (t) and industrial (i) heat and power demand. The thermodynamic cycles are modeled by Cycle-Tempo, while the energy demand is modeled through simplified indicators (temperature of heat demand, equivalent thermal demand hours). On the basis of the results of thermodynamic simulations, upfront and operational costs assessment, and Italian energy policy scenario (feed-in tariffs for biomass electricity), the global energy conversion efficiency and investment profitability is estimated, for each CHP configuration and energy demand segment. The results indicate the optimal CHP configuration for each end user and the key technical and economic factors in the Italian legislative framework.

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

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1. Introduction

A sustainable, secure and competitive energy supply represents the main pillar of EU energy policy. In addition to the 20-20-20 energy policy goals, the European Commission is now defining new and ambitious targets of renewable energy penetration (27% of internal energy consumption), greenhouse gas (reduction of GHG emissions of 40%) and energy efficiency (reduction of 25% of energy consumption) by 2030 [1]. In this context, small scale biomass fired CHP (Combined Heat and Power) can contribute to all these goals, including the development of decentralised energy generation, avoidance of electricity networks energy losses, increased energy security. Moreover, bioenergy could provide added socio-economic and environmental benefits when organic by-products are recovered and further income to the agricultural and forestry sectors is provided by means of domestic biomass supply chains [2]. In particular, small scale and on site CHP plants operated within ESCO (Energy Service Company) schemes can be promising for the tertiary sector, which is 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 specific field of lignocellulosic biomass energy conversion, 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 coupled to both internal combustion engines (ICE) [4,5] and gas microturbines (MGT) [6], included pyrolysis to fed similar gensets [7], and (ii) direct combustion in grate or fluidized bed boilers to fed externally fired MGT [8,9], Stirling engines [10,11] or Organic Rankine Cycles (ORC) [12,13]. An overview of biomass combustion for small scale CHP is provided in [14], and in [15] a review of small scale biomass gasification coupled to different engines and turbines is proposed, while in [5] the technical and economic issues of decentralized CHP through biomass gasification are reviewed, comparing engines and turbines options. Further comparisons between biomass gasification-ICE and combustion-ORC are proposed in [16], while [17] investigates the bottoming ORC coupled to a syngas-fed ORC. Other options of combined use of biomass and natural gas into small scale CHP by means of externally fired micro turbines are explored in [18, 19, 20]. The influence of part load efficiencies on optimal operation of such biomass/natural gas fired MGT has been investigated in [21]. A bottoming ORC could also be coupled to both MGT and ICE in order to increase the electric efficiency of the system but reducing the temperature of heat available for cogeneration. A number of researches aimed to quantify the benefits of this ORC bottoming cycle coupled to a MGT [22, 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 [24,25,26]. 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 [27]. In [28], a combined cycle composed by a 2 MW intercooled recuperated gas turbine fuelled by natural gas and a bottoming ORC plant is shown to be able to reach a net electric efficiency of over 43%. 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 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 (ST+ORC) in comparison to only ORC or only ST cycles are addressed, taking into account the influence of the heat and power energy demand patterns, assuming the further option of flexible ORC operation (switch on and off the ORC section on the basis of the heat demand) and considering the electricity and cogeneration subsidies available in the Italian policy framework. The main aim of the paper is thus to propose a standard thermo-economic methodology for financial appraisal of different thermodynamic cycle configurations in a number of energy demand segments, based on a combination of Cycle-Tempo thermodynamic modelling, a simplified representation of energy demand patterns, a costs assessment and discounted cash flow analysis. This methodology is then applied to the case of 1 MWt biomass boilers coupled to ST and/or ORC generation systems (corresponding electric output in the range 100-200 kWe) in order 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 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 [29], and in light of the Italian policy measures for renewable heat and electricity generation and high efficiency CHP [30]. 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 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 plants that compose the combined cycle, without the need of new technologies. In particular in this work, we consider a combined cycle composed by a ST as topping cycle and an ORC as bottoming cycle, that is able to convert part of the heat from the ST in useful work. This cycle (case A) is compared to the separate use of ST (case B) and ORC (case C). The reduced volume of steam and the production of steam at a pressure not higher than 20 bar make the expander compact and the boiler simple and low cost. The typical boiler is, in thus case, a fire-tube type. In case A, the steam exiting the ST at (220-150 °C, 20-5 bar) is conveyed to the evaporator of the ORC plant. Here the organic fluid is vaporized and brought to the thermodynamic condition requested for the admission in the turbine. The water exiting the evaporator has still 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 drop generation that can 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 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. The condensation temperature of the ORC section is assumed of about 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. 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. The layout of the combined cycle (case A) and of the separate steam turbine (case B) and ORC (case C) cycles are reported respectively in Fig.1 and 2, while further technical input parameters are reported in Table 1. The input data for case D are the same of case A when the plant operates in CHP configuration with low temperature heat demand or in only electricity mode (bottoming ORC switched on), and the same of case B when the plants operates in CHP configuration with high temperature heat demand (tertiary and industrial end users, bottoming ORC switched off). Further input parameters are as follows: biomass boiler efficiency = 88%; mechanical/isoentropic efficiency ST and ORC Turbine = 90/75%; electric genset efficiency =92%; ST and ORC Turbine nominal power (case A) = 70 and 120 kWe respectively).

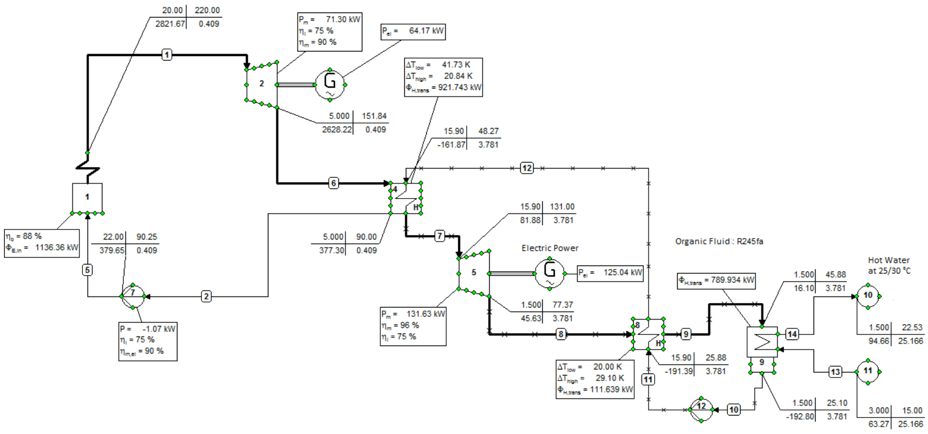

Fig. 1– Layout from Cycle Tempo for case A with the main thermodynamic parameters of the cycle (Legend in Fig. 2)

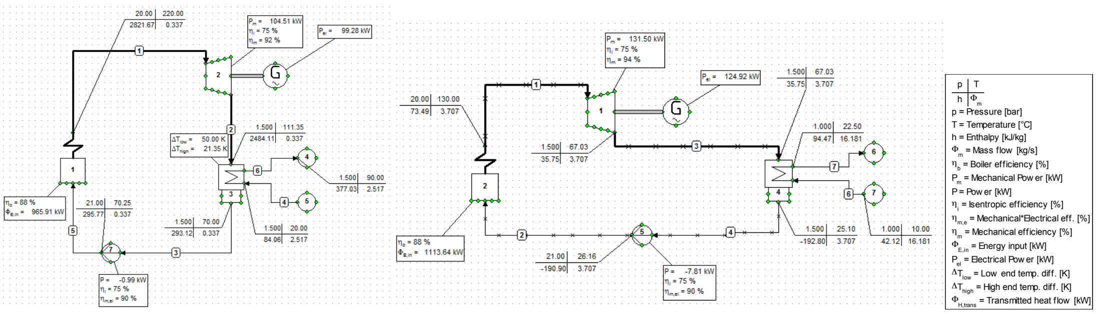

Fig. 2 – Layout from Cycle Tempo for case B (left) and C (right)

Tab. 1 – Technical parameters and results of the Cycle-Tempo modelling.

Case study	Unit	Case A	Case B	Case C
Net electric power output (ISO)	kW	189	99	125
Total Thermal Power input	kW	1,136	966	1,114
Net Thermal Power output (for CHP)	kW	790	737	847
Shaft Power	kW	203	104	132
Net-electric efficiency (ISO)	%	16.6	10.3	10.5
Gas temperature at (top) turbine exit	°C	143	111	67
Gas temperature at (bot) turbine exit	°C	77	-	-
mass flow rate (top)	kg/s	0.410	0.337	4.594
mass flow rate (bot)	kg/s	3.78	-	-
Max Cycle Temperature	°C	220	220	130

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 (baseload operation mode) are assumed 7,500 (in agreement with data from manufacturer [31]), 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/tertiary/residential consumers. In order to carry out the profitability assessment, the main cost items and biomass consumption figures of Table 2 are assumed. The turn key investment and operational costs are personal estimates from manufacturers data and data collected from case studies. 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 further input data are 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 [30]; 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 2014 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.

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

Description	Unit	Case A and D	Case B	Case C
Biomass consumption	t/year	2,036	1,731	1,995
Total upfront cost [3,4]	kEur	1,170	715	770
- Turbine cost	kEur	220	220	-
- ORC generator cost	kEur	330	-	330
- Biomass Boiler cost	kEur	480	400	380
- Engin, develop, insur	kEur	60	60	60
Specific upfront cost	kEur/kWe	6.18	7.20	6.16
Operational cost (included fuel)	kEur/yr	191.26	153.34	178.36

4. Results and discussion

In Fig. 3 the global conversion efficiency of the selected case studies in different end-users 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 study B, which maximizes the heat available to the load, appears the most suitable technology in this market segment, followed by case D where the plant operational flexibility (switch on/off the ORC on the basis of the heat demand) makes the difference in comparison to case A and C. The same conclusions can be drawn for the tertiary end user segment, being the global energy efficiency lower in comparison to the industrial segment because of the reduced heat demand. 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 and at the same time operate in CHP configuration. This is the only market segment where the efficiency of case C are 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 and use of renewable sources (biomass).

The results of the financial appraisal are reported in Fig. 5, and, in the case of IRR, they appear similar to the global energy efficiency ones; it results that, for industrial end-users, the steam turbine CHP (case B) and the combined cycle with the option to switch off the ORC to maximize the heat delivered to the load (case D) present the highest IRR, while case A and C are not profitable. However, in this case, the NPV is the highest for configuration D, and this is due to the higher investment cost and higher revenues in comparison to plant B. The flexible combined cycle (D) is the most profitable option also in the tertiary market segment, being now 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.

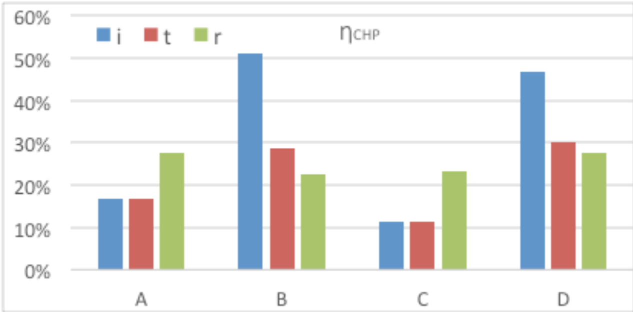

Fig. 4 –Conversion efficiency (η_{CHP}) for CHP configurations A to D and industrial (i), tertiary (t) and residential (r) end-users

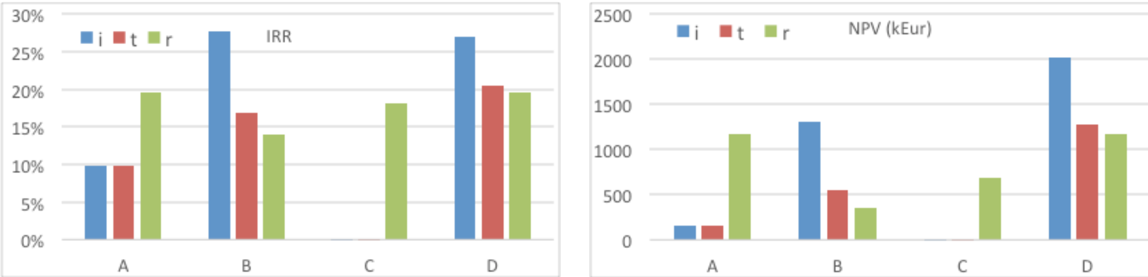

Fig. 5. IRR (left) and NPV (right) of the investment for the 4 case studies and 3 different energy demand segments.

5. Conclusions

In this paper, a thermo-economic comparison of the following biomass-CHP configurations is proposed: (A) boiler + ST + bottoming ORC, (B) boiler + ST, (C) boiler + ORC and (D) configuration (A) with option to switch on or off the bottoming ORC on the basis of the heat demand available. The focus is on a 1 MWt 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, 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 D) makes the difference in comparison to case A for industrial and residential market segments. The separate ORC cycle (case C) presents the lowest conversion efficiency, and it is 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 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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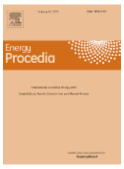
Acknowledgements

Thanks are given to Progeco Srl for the input data provided for thermo-economic modelling.



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, thermo-economic assessment of energy investments.

Appendix A. Schematic of CHP configurations under investigation

The schematics of the CHP configurations under investigation are reported in Figure A.1. Case study D assumes the same cycle configuration of case study A, but including a modulation of the bottoming ORC cycle on the basis of the heat demand (ORC switched on in absence of suitable thermal energy demand from the end-user).

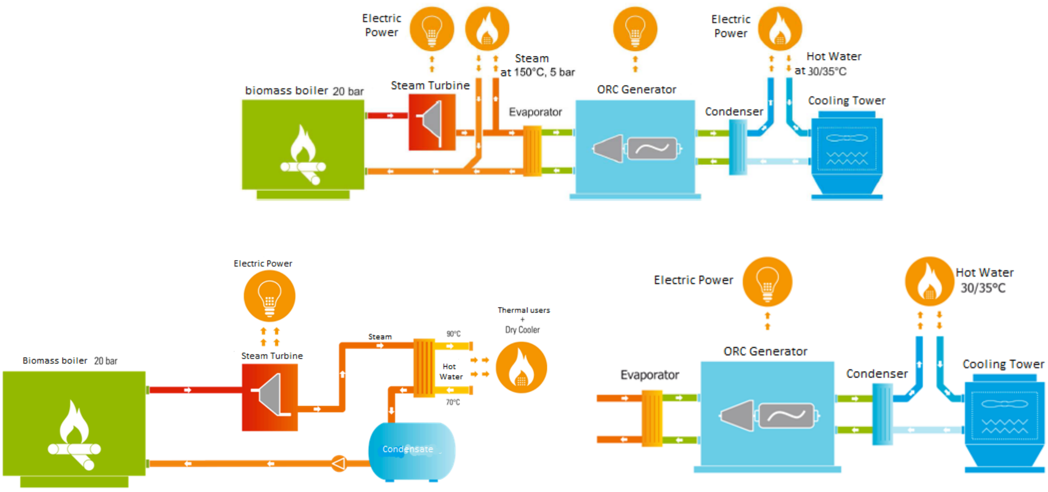


Fig. A.1 Schematic of the CHP cycles under investigation [32]. Top: case A: combi-cycle including 70 kWe topping steam turbine and 120 kWe bottoming ORC; Bottom left: case B: only steam turbine – 70 kWe; bottom-right: only ORC – 120 kWe

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