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Techno-economic analysis of biomass-fired ORC systems for single-family combined heat and power (CHP) applications

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Abstract

The aim of the paper is the investigation of the energetic performances and the economic feasibility of Organic Rankine Cycles (ORCs) for biomass single-family combined heat and power (CHP) generation. To this purpose, a parametric energy analysis has been performed to identify the proper system configurations. Subcritical and transcritical cycles, with saturated and superheated conditions at the turbine inlet, have been analysed and the impact of internal regeneration on system behaviour has been studied.
The work reveals the large influence of the maximum temperature and the noticeable effect of the internal regeneration on the ORC system performances and the relative energy saving capabilities.
An economic feasibility analysis has been performed for single-family users, taking into account the Italian scenario and the incentives for high efficiency cogeneration. The results in terms of return on investment and net positive value highlight that biomass-fired ORC system appears an attractive option for single-family CHP applications.

Organic Rankine Cycle; combined heat and power; biomass; micro-scale; energy demand; single-family application.

1. Introduction

The combined heat and power (CHP) production is considered today an effective alternative to conventional systems with separate electric and thermal generation due to the higher energy efficiency and saving capability [1-3]. In this framework, biomass-fired Organic Rankine Cycles (ORCs) represent an attractive solution for sustainable and

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Nomenclature

c	Cost
CHP	Combined Heat and Power
CS	Net Metering contribution
EEC	Energy Efficiency Certificates
E	Electric energy
EUF	Energy utilisation factor
i	Interest rate
N	Investment period
NPV	Net present value
ORC	Organic Rankine Cycle
η	Efficiency
P	Power output
PBP	Payback period
PES	Primary energy saving index

reliable energy supply in small and micro-scale CHP applications, where traditional plants are technologically and economically unfeasible [4-6].

In particular, ORC systems offer several advantages compared with conventional systems owing to the lower costs and maintenance requirements, better partial load performances, faster start-up and stop procedures and higher flexibility and safety [7-9]. To this purpose, the definition of the proper system configurations and operating conditions is crucial to optimise the efficiency of ORC systems [10-12]. Specifically, in biomass-fired ORC systems, a thermal oil circuit is required to avoid local overheating and to prevent organic fluids from becoming chemically unstable. In fact, during the combustion, the flame temperature is usually larger than 900°C and the maximum operating temperature can reach value up to 400°C [13]. Moreover, it is worthy to notice that for combined heat and power production the condensation temperature is relatively high (80-120°C) [7,14-15]. As a consequence, most organic fluids for low temperature applications cannot be used due to the high vapour pressure at these temperatures [7].

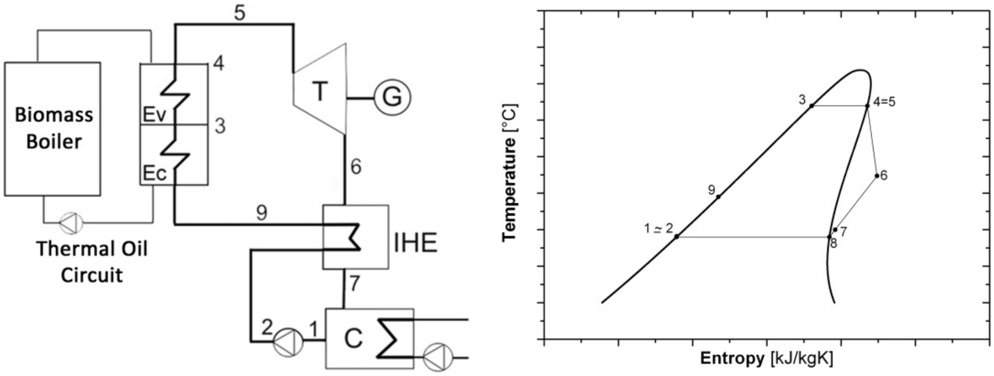
During the last decade, the attention of researchers community and manufacturers was mainly focused on saturated ORC cycles. On the other hand, the adoption of internal regeneration and transcritical conditions appears of great interest, because these configurations may lead to high efficiencies and competitive costs [16-17].

The scope of the paper is the techno-economic analysis of biomass Organic Rankine Cycles for single-family CHP applications. In fact, few investigations on micro-scale biomass ORCs are present in literature, despite the large potential of micro-CHP systems to overcome problems of energy affordability, supply security and environmental protection and to fulfil household energy demands [5-6].

To this purpose, the investigation has been focused on single-family applications and the influence of both the operating conditions and the internal regeneration on the ORC behaviour has been examined. Finally, the economic feasibility of biomass-fired ORC systems for CHP generation has been investigated considering the national legislation and incentive schemes.

2. Methodology

The Organic Rankine Cycle (ORC) consists primarily of a pump system, an evaporator, a turbine/expander, and a condenser (Figure 1a). The pump supplies the organic fluid to the evaporator (1-2 process), where the fluid is preheated (2-3) and vaporized (3-4). The vapour flows into the turbine where it is expanded to the condensing pressure (5-6) and, finally, it is condensed to saturated liquid (6-1). Sometimes, an internal heat exchanger (IHE) can be used to recover the thermal energy at the turbine outlet (6-7) and preheat the compressed liquid before the



a) b)

Fig. 1. Typical layout (a) and T-s diagram (b) for an Organic Rankine Cycle with internal heat exchange. Saturated cycle. C: Condenser, Ec: Economyser, Ev: Evaporator, T: Turbine, G: Electrical generator, IHE: Internal heat exchanger.

entrance in the evaporator (2-9) in order to improve the system efficiency. Figure 1b shows the corresponding cycle in the T-s diagram for a typical dry organic fluid with saturated conditions at the turbine inlet.

A thermodynamic model has been developed to characterise the performances of biomass Organic Rankine Cycles [18-19]. To this purpose, the REFPROP database [20] has been integrated with the energy model to define the thermodynamic properties of the organic fluid. For the analysis, a steady state condition has been assumed, while pressure drops and heat losses in the system components have been neglected. The ORC performances have been expressed in terms of electric and cogeneration efficiencies, energy utilisation factor, and primary energy saving index.

The electric efficiency is defined as

$$\eta_{el} = \frac{P_{el}}{\dot{Q}_{th}} \tag{1}$$

where P_{el} is the ORC electric power;
$\dot{Q}_{th}$ is the thermal input of the biomass boiler.

The ORC net electric power P_{el} is evaluated as follows:

$$P_{el} = \eta_{em} P_u \tag{2}$$

where P_u is the net power output;
η_{em} takes into account the mechanical and electrical losses.

As cogeneration merit parameter, the cogeneration efficiency η_{cog} and the energy utilisation factor *EUF* have been evaluated as follows [21-22]:

$$\eta_{cog} = \frac{P_{el}}{\dot{Q}_{th} - \dfrac{\dot{Q}_{cog}}{\eta_{th,ref}}} \tag{3}$$

$$EUF = \frac{P_{el} + \dot{Q}_{cog}}{\dot{Q}_{th}} \tag{4}$$

where $\dot{Q}_{cog}$ is the thermal power from the condensation process used for cogeneration;
$\eta_{th,ref}$ is the reference efficiency of a conventional boiler that should be used to produce $\dot{Q}_{cog}$ separately.

Furthermore, the primary energy saving index PES has been considered [23]:

$$PES = 1 - \frac{\dot{Q}_{th}}{\frac{P_{el}}{\eta_{el,ref}} + \frac{\dot{Q}_{cog}}{\eta_{th,ref}}} \tag{5}$$

where $\eta_{el,ref}$ is the reference efficiency for the separate electrical power production in a conventional energy system.

The PES index is also fundamental to evaluate if a CHP system can access to the Italian incentive system (the "Net Metering" and "Energy Efficiency Certificates" contribution [24]). Specifically, according to the National Authority of Energy and Gas [23], a cogeneration unit, with electrical power larger than 1 MW_{el}, should present a PES value larger than 10% in order to access to the "High-Efficiency CHP" contributions. For small and micro-scale applications ($P_{el} < 1MW_{el}$ and $P_{el} < 50\ kW_{el}$ respectively) the cogeneration incentives are obtained when the PES index is higher than zero.

For the Net Metering scheme a contribution is obtained, according to the following equation:

$$CS = \min(O_E; C_{EI}) + CU_{sf} \cdot E_s \tag{6}$$

where O_E is the cost of the electricity withdrawn from the grid;
C_{EI} is the value of the electricity injected into the grid;
CU_{sf} is the specific contribution related to injections and withdrawals of electricity;
E_s is the electric energy exchanged with the grid.

Moreover, the yearly primary-energy saving capability of the CHP unit, expressed in tonnes of oil equivalent (toe), defines the number of "Energy Efficiency Certificates" (EEC).

2.1. Operating conditions

Decane has been selected as working fluid for the energetic analysis due to its high operating temperatures, consistent with the requirements of biomass systems [25-26], and the low critical pressure (21.03 bar).

The investigations have been carried out considering both subcritical and transcritical cycles with saturated and superheated conditions at the expander inlet. Table 1 shows the critical temperature and pressure of the selected organic fluid, and the operative conditions assumed in the investigation. In particular, according to the literature, the condensation temperature has been set to 100°C for CHP applications, in order to satisfy the needs of heating networks or other low heat applications [7,27]. Minimum evaporation temperature has been set to 200°C while the maximum value has been chosen to avoid the presence of liquid during the expansion phase and it depends on the slope of the saturated vapour curve in the T-s diagram [25]. For transcritical cycles, the supercritical pressure has been set equal to 1.03 p_{crit}, as suggested in literature [28]).

Table 2 summarises the main assumptions used for the parametric energy analysis. Specifically, the expander and pump efficiencies have been imposed equal to 0.70 and 0.60 respectively, the internal heat exchanger efficiency has been set to 0.95 and the global efficiency of the heating process (from biomass to organic fluid through the thermal oil circuit) is 0.85, according to the literature [7,15]. Furthermore, the reference efficiency of the conventional boiler and the reference efficiency for the separate electrical power production have been set equal to 0.86 and 0.33, respectively, while the temperature at the exit of the internal heat exchanger (T_7) has been imposed 10°C higher than the condensation temperature [7,23].

Table 1. Operative conditions and ORC configurations.

Critical conditions		
Critical temperature	[°C]	344.55
Critical pressure	[bar]	21.03
Saturated cycle conditions		
Condensation temperature	[°C]	100
Condensation pressure	[bar]	0.10
Evaporation temperature	[°C]	200 ÷ 337
Evaporation pressure	[bar]	1.87 ÷ 18.96
Superheated cycle conditions		
Condensation temperature	[°C]	100
Condensation pressure	[bar]	0.10
Evaporation temperature	[°C]	250
Evaporation pressure	[bar]	5.04
Maximum temperature	[°C]	260 ÷ 400
Transcritical cycle conditions		
Condensation temperature	[°C]	100
Condensation pressure	[bar]	0.10
Maximum pressure[a]	[bar]	21.66
Maximum temperature	[°C]	350 ÷ 400

[a]Supercritical pressure.

Table 2. Main assumptions for the energetic analysis.

Expander isentropic efficiency, η_t	[%]	70
Pump isentropic efficiency, η_p	[%]	60
Internal heat exchanger efficiency, η_{IHE}	[%]	95
Internal heat exchange temperature difference, ΔT	[°C]	10
Boiler and thermal oil circuit efficiency, η_{bt}	[%]	85
Electro-mechanical efficiency, η_{em}	[%]	90
Thermal reference efficiency, $\eta_{th, ref}$	[%]	86
Electric reference efficiency, $\eta_{el, ref}$	[%]	33
Biomass lower heating value (dry basis), H_i	[MJ/kg]	18
Biomass humidity, φ	[%]	10

The economic viability of the system has been examined, considering the Italian legislation and incentives system. Table 3 shows the main assumptions used for the economic analysis. The investment period has been considered equal to 20 years and a 5% interest rate has been set.

The natural gas and electricity savings have been estimated considering the mean rates for the residential sector (89 €/m^3 for natural gas and 19 c€/kWh for electricity [23]), while the specific cost of the biomass has been imposed equal to 200 €/t. Furthermore, to evaluate the ORC economic benefit, it is worthy to notice that "High-Efficiency CHP" units (PES > 0 for mini or micro CHP) can access to the "Net Metering" incentive scheme and "Energy Efficiency Certificates" contribution. Specifically, the "Energy Efficiency Certificates" contribution is 86.98 €/toe, while the specific incentive for the exchanged energy CU_{sf} has been estimated equal to 6.8 c€/kWh, according to GSE [24].

In order to evaluate the influence of the possible decrease in the CHP cost, due to the expected progressive technical development and large-scale production, the cost of the biomass-fired ORC system has been varied from 5000 to 10000 €/kW$_{el}$, that represents the current capital cost for micro-scale CHP systems. Furthermore, the self-consumed electric energy has been calculated considering the daily thermal and electric load profiles of single-family users.

Table 3. Main assumptions for the economic analysis.

Investment period, N	[years]	20
Interest rate, i	[%]	5
Specific revenue for the saved natural gas, r_{ng}	[c€/m^3]	89
Specific revenue for the saved electricity, r_{el}	[c€/kWh]	19
Specific value of the electricity injected into the grid, $r_{el,inj}$	[c€/kWh]	10
Specific cost of the electricity withdrawn from the grid, $c_{el,wit}$	[c€/kWh]	8
Specific incentive for electricity exchanged with the grid, CU_{sf}	[c€/kWh]	6.8
"Energy Efficiency Certificates" contribution, EEC	[€/toe]	86.98
Specific cost of biomass, c_b	[€/t]	200
Specific cost of ORC system, c_{ORC}	[€/kW$_{el}$]	5000 ÷ 10000
Maintenance cost of ORC system, C_{main}	[€]	$100 + 0.01 \cdot E_{el}$

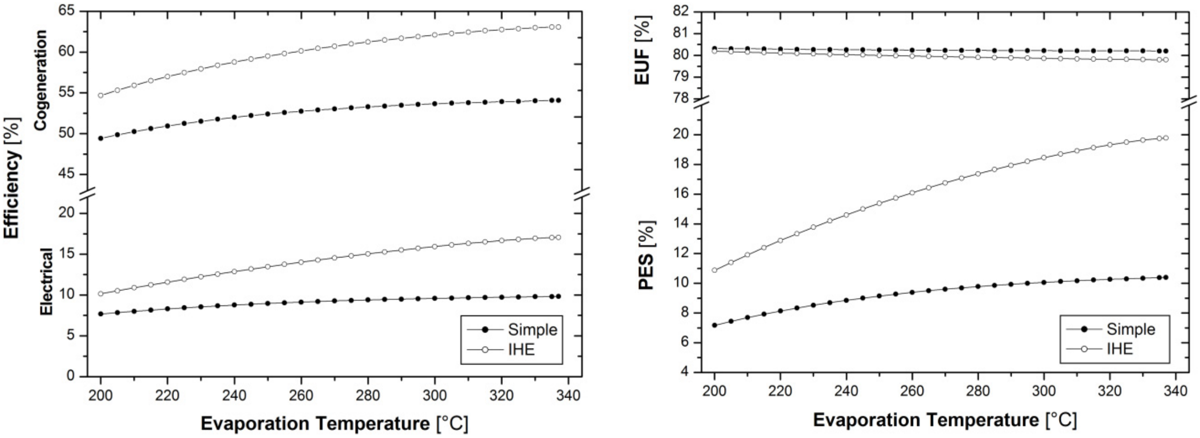
3. Results

The energetic performances of biomass ORC systems for single-family CHP applications have been analysed. Decane has been adopted as working fluid due to its low critical pressure (21.03 bar) and the high operating temperatures, consistent with the requirements of biomass systems [25-26].

Figure 2a illustrates the effect of the evaporation temperature on the electric and cogeneration efficiencies. Specifically, the figure refers to saturated ORC cycles with and without internal regeneration (IHE and simple cycle, respectively). The results show the progressive increase in electrical and thermal performances with the evaporation temperature, according to the literature [12, 29-30]. At 200°C the electric and cogeneration efficiencies are 7.7% and 49.4%, respectively while the corresponding values reach 9.8% and 54.1% at the maximum evaporation temperatures (357 °C). Furthermore, Figure 2 illustrates the noticeable influence of the internal heat exchange (IHE) on the system performances. Specifically, at 200°C, the two dimensionless parameters raise to η_{el} = 10.1% and η_{cog} = 54.7%, whereas the highest performances (η_{el} = 17.6% and η_{cog} = 63.1%) are found at 337 °C. The upsurge in ORC performances is due to the increase in cycle efficiency and to the higher organic mass flow rate when internal regeneration is adopted.

The energy utilisation factor *EUF* and the primary energy saving index *PES* have been considered as CHP merit parameters. Figure 2b highlights that the energy utilisation factor presents similar values for the different evaporation temperatures (79.8%÷80.3%). Specifically, the highest performances are found without internal regeneration due to the larger cogeneration contributes.

Conversely, PES index is more sensitive to the operating conditions. The behaviour of the dimensionless parameter with the evaporation temperature reflects the trend of the electrical production. The higher saving capability (PES = 19.8%) is found at the maximum temperature when the internal heat exchange is employed.



a) b)

Fig. 2. Influence of the evaporation temperature on ORC electrical and cogeneration efficiencies (a). Effect of the evaporation temperature on EUF and PES index (b). Saturated cycle.

It is noteworthy that the primary energy saving index is always higher than 7.1% and, as a consequence, all the investigated configurations can access to the "High-Efficiency CHP" incentives.

Furthermore, the influence of the superheating process on the energetic characteristics of micro-CHP systems has been analysed. A twofold behaviour in electrical and cogeneration efficiencies is found, depending on the presence of internal heat exchange (Figure 3a). An increase of about 2.7% in system performances is observed with internal regeneration, moving from saturated conditions (250°C) to 400°C, owing to the higher fluid energy at the expander exit. Conversely, a decrease in electrical (-1.6%) and cogeneration (-3.8%) efficiencies with the maximum temperature is observed without the internal regenerator.

Figure 3b compares the EUF and the PES parameters. Similar energy utilisation factor values are registered for the different superheated configurations (~80%). As already observed, the PES index is more sensitive to the system arrangement. The twofold behaviour of the dimensionless parameter with the maximum temperature reflects the trend of the electric performance. For the simple cycle, the better results are found at 260°C (PES = 8.9%), while the internal heat exchange guarantees the higher saving capability (PES = 19.1%) at 400 °C.

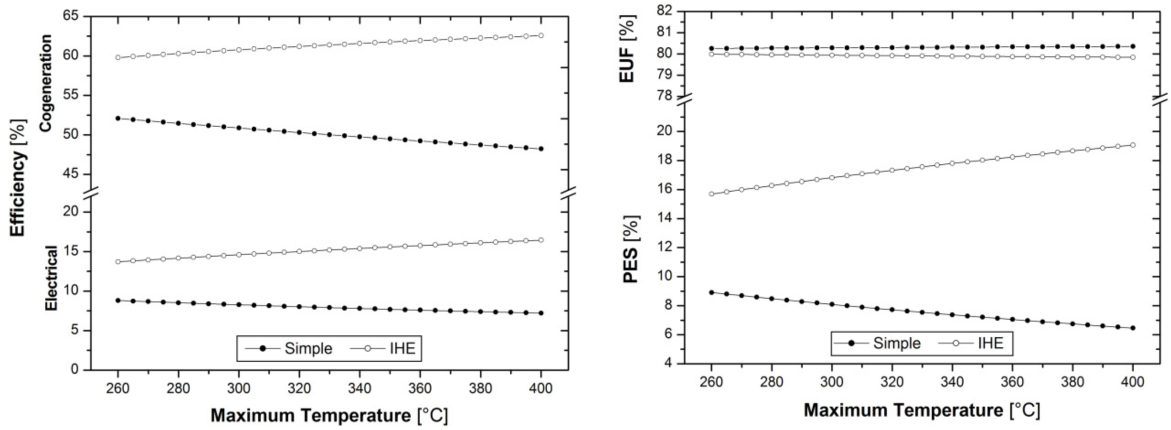


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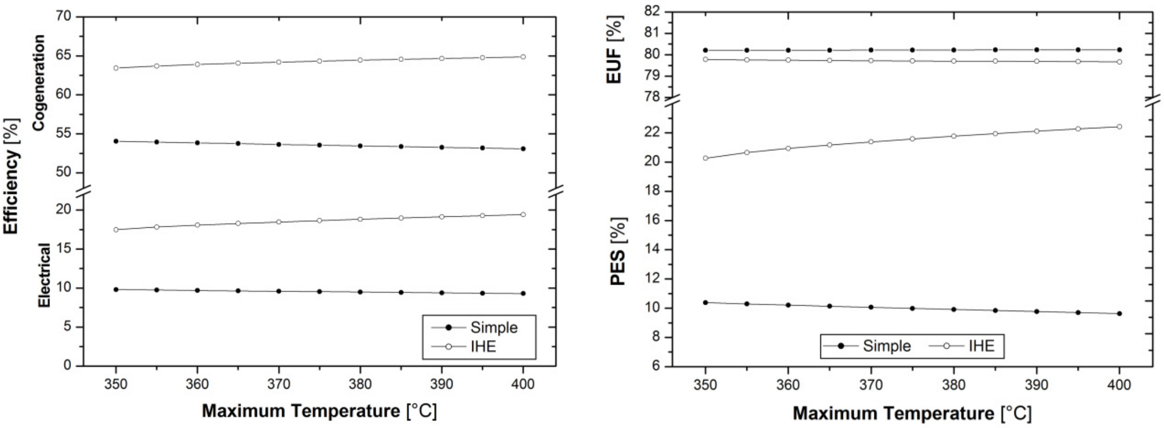
Fig. 3. Influence of the maximum temperature on ORC electrical and cogeneration efficiencies (a). Effect of the maximum temperature on EUF and PES index (b). Superheated cycle.



a) b)

Fig. 4. Influence of the maximum temperature on ORC electrical and cogeneration efficiencies (a). Effect of the maximum temperature on EUF and PES index (b). Transcritical cycle.

Moreover, the influence of the transcritical conditions on the energetic performances of the CHP system has been analysed. When the internal heat exchange is absent, a slight decrease in the electric and cogeneration effectiveness with the maximum temperature is registered (Figure 4a). Furthermore, the results depict that the internal regenerator produces the highest electric efficiency (19.4%). The primary energy saving index confirms the improvement in the system performances when the transcritical conditions and the internal heat exchange are adopted. In these conditions, PES values range from 20.3 to 22.4% (Figure 4b). The energy utilisation factor is always close to 80%.

Finally, the results of the previous energetic investigation have been used to analyse the economic feasibility of biomass ORC systems for a typical single-family in Southern Italy. The Italian tariff and incentives scenario have been considered. The single-family thermal load and the corresponding electric demand have been estimated considering the typical daily profiles in winter, summer and intermediate seasons [31]. The electric demand takes into account the consumption of domestic lighting systems and appliances, including air conditioners during the hot season, while the thermal load is based on the mean space heating and hot water demand. Specifically, the thermal and electric demands per year have been evaluated equal to 9029 kWh_{th} and 2616 kWh_{el}, respectively. More details are provided in literature [31-32]. The investigation has been done to satisfy the domestic thermal demand, according to the Italian legislation [33-34]. To this purpose, the proper thermal power of the CHP system has been evaluated adopting the maximum rectangle method [35] and a 2.35 kW_{th} has been found as the suggested value of the heating unit for a single apartment, with a 3842 operating hours per year.

The economic analysis has been performed considering the system configurations that guarantee the highest electric and thermal performances. In particular, results suggest adopting transcritical conditions with internal heat exchange and maximum temperature to maximise electric power. In this case, the electric power is P_{el} = 0.76 kW_{el} when the thermal size of the CHP system is fixed to 2.35 kW_{th}. On the other hand, the superheated arrangement without IHE should be adopted to assure the better thermal performances but the minimum electric power is obtained (P_{el} = 0.23 kW_{el} when $\dot{Q}_{cog}$ = 2.35 kW_{th}). A self-consumed electric energy close to 50% of the ORC produced electricity has been found, considering the daily thermal and electric load profiles of domestic users.

Figure 5 compares the net present values (NPVs) and the payback periods (PBPs) for the two CHP configurations. To this purpose, the specific cost of the biomass-fired ORC unit has been varied from 5000 to 10000 €/kW_{el}. The figure shows that the better economic results are found when the system with the highest thermal performances is used, due to the lower investment cost. Particularly, the payback period is always lower than 8 years and is lower than four years when the specific cost is reduced to 5000 €/kW_{el}. After 10 years, NPVs is about 1700 € and 500 € when the Organic Rankine Cycle costs are 5000 and 10000 €/kW_{el} respectively, while the corresponding net positive values are always higher than 2300 € after 20 years. It is noteworthy that the CHP unit with the highest electric power presents larger cash flows due to the higher electric production and incentive contribution, but the larger investment costs determine a payback period lower than 10 years only when the ORC specific cost reaches 5000 €/kW_{el}.

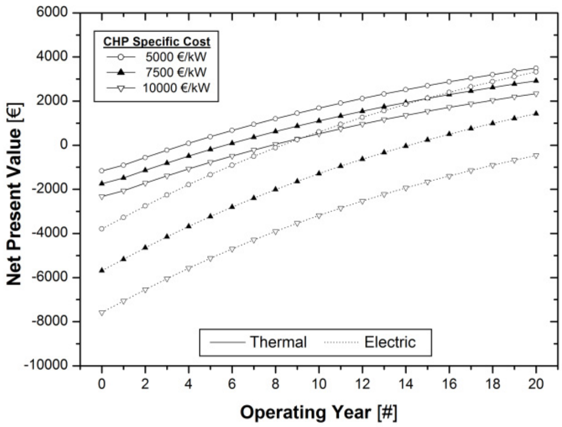


Fig. 5. Influence of the CHP specific cost and system arrangement on payback period and net present value.

4. Conclusions

The work has focused on the analysis of the energetic performances of biomass Organic Rankine Cycles for single-family combined heat and power generation. Specifically, subcritical and transcritical cycles have been investigated with saturated and superheated conditions at the expander inlet. Furthermore, the impact of the internal heat exchange has been evaluated.

The analysis demonstrates that the evaporation temperature significantly affects the ORC electric and cogeneration efficiencies: the higher the thermal level, the higher the system performances. This effect is amplified with the adoption of the internal regeneration.

For saturated conditions, in simple cycle configuration, the highest electrical efficiency is 9.8% while the corresponding value raises to 17.1% when the internal heat exchange is used.

When superheating technique is adopted the electric efficiency presents a different behaviour. A positive influence of the maximum temperature is registered with the IHE, whereas a decrease is noticed without internal heat exchanger. The analysis of the cogeneration efficiency reveals similar trends, with a slighter effect of the maximum temperature. It is interesting to notice that transcritical conditions guarantee the highest electric performances (η_{el} = 19.4%). In this case, a special attention should be focused on the higher operating pressure (p_e = 21.66 bar) with respect to the subcritical arrangements (p_e = 1.87 ÷ 18.96 bar).

The comparison between the different micro-ORC units put in evidence that EUF presents similar values (~80%) and all the analysed configurations have PES values larger than zero (6.5÷22.4%). Consequently, all the single-family biomass ORCs can access to the Italian “High-Efficiency Cogeneration” contributions.

The results of the previous energetic investigation have been used to analyse the economic feasibility of biomass ORC systems for a typical single-family in Southern Italy. The Italian tariff and incentives scenario have been considered. The CHP thermal power has been fixed to 2.35 kW_{th} to satisfy the household thermal demand and the units with the highest electric and thermal performances have been considered.

The analysis demonstrates that the biomass-fired ORC systems represent a very interesting solution for single-family applications if the arrangement with the highest thermal performances is adopted. Specifically, the payback period is about 8 years when the ORC specific cost is fixed to 10.000 €/kW_{el} and reduces to about four years if the specific cost is 5000 €/kW_{el}. Conversely, the ORC unit with the largest electric power presents a breakeven point lower than 10 years only when the ORC specific cost reaches 5000 €/kW_{el}.

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