

Efficiency enhancement in existing biomass organic Rankine cycle plants by means of thermoelectric systems integration

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Abstract

This work investigates, from a thermodynamic point of view, the possibility of integrating thermoelectric systems (TES) in existing solid biomass-fuelled ORC CHP plants in a cost-effective way. Thus, a simple plant layout was proposed. The benefits achieved in the overall plant performance, constrained by several technical parameters of the subsystems involved, are assessed in terms of the Second Law efficiency and other characteristic parameters such as the First Law efficiency and the Primary Energy Savings Ratio. The main conclusion obtained is anticipating the fact that exists a certain optimal TES driving temperature value leading to the maximisation of the plant's performance. According to the specific results extracted from the examples evaluated (TES integrated in Toluene and MDM ORC CHP plants), this temperature is about 245°C and 210°C, respectively, which leads to an increase in the overall Second Law efficiency of the plant up to 7-8%. Hence, it is clear that thermoelectric systems can contribute to the enhancement of the performance and to do so, there are guidelines to be considered prior to the detailed design of such systems to be integrated in existing ORC CHP plants.

Keywords: Organic Rankine cycle (ORC), thermoelectric generation, biomass, combined heat power (CHP)

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1. Introduction

The Strategic Research Priorities for Biomass Technology [1] identify the research and development activities needed to accomplish the 2020 objectives. One of the targets is to achieve a substantial increase in the electrical efficiency of combined heat and power (CHP) plants. A technology specific mix of decreasing costs (investment, maintenance), efficient cost effective storage systems and increasing their electric efficiency and their availability will reduce the electricity production costs of biomass based systems.

Considering CHP systems fuelled by solid biomass, organic Rankine cycle (ORC) is a widespread technology, mainly in the range of 1 – 2MW_e [2]. In 2016, the total installed capacity worldwide is nearly 300 MW_e [2], with an average electric efficiency range of 17-23% [3]. One of the recent research tendencies in ORCs is the development of new ORC concepts, for example the two-stage ORC with turbine bleeding [4]; but also the integration of ORCs with other technologies in order to increase their performance in comparison to conventional configurations and their stand-alone use, such as micro gas turbines [5] or solid oxide fuel cells [6].

Thermoelectric systems (TES) are based on thermoelectric materials, which are solid-state energy converters whose combination of thermal, electrical, and semiconducting properties allows them to be used to convert heat into electricity or electrical power directly into cooling and heating [7]. Their development and integration are being extensively studied in the scientific literature over the past two decades, with special focus on three main topics in the past years: development of new materials, modelling and performance analysis, and integration with renewable sources and technologies [8]. Recent developments in materials have been extensively addressed by LeBlanc et al., with focus on cost considerations from both points of view of the materials and the systems [9]. Considering modelling and performance of TES, from the theoretical and experimental points of view, many authors have contributed to the development of this technology using different approaches, for example, Höglblom et al. developed a novel framework for accurate characterisation and simulation of a thermoelectric system's performance [10]. Finally, novel uses of TES have been proposed for:

- The development of new applications, such as the optimized design of wearable devices proposed by Hyland et al. [11], the modelling of thermoelectric elements to recover waste heat from marine on-board

37 seagoing vessels addressed by Georgopoulou et al. [12], or the modelling
38 of flat-plate solar TES for space applications by Liu et al. [13].

- 39 • The integration with multiple energy sources. Liu et al. presented the
40 modelling, experimental validation and cost considerations studies on
41 TES for low-temperature geothermal resources [14]. A thermoelectric
42 system using a heat pipe evacuated tube collector with mini-compound
43 parabolic concentrator was studied in depth by Dai et al. for solar
44 applications [15]. Orr et al. performed an extensive review of waste
45 heat recovery systems in vehicles via the combination of TES and heat
46 pipes [16]. A pellet-fuelled thermoelectric cogeneration system was
47 conceptualised and modelled by Alanne et al. [17].
- 48 • The performance enhancement of multiple existing technologies. Wu
49 et al. obtained useful results for the design and optimization of a novel
50 combined molten carbonate fuel cell, TES and regenerator [18]. Ja-
51 worski et al. performed the experimental investigation of TES coupled
52 with phase change material modules [19]. A novel concept using TES
53 integrated into 1 kW Brayton cycle was investigated by Yazawa et al.
54 [20]. And finally, Aberuee et al. [21] studied the performance of a novel
55 integration consisting on solar TES and desalination.

56 Thus, following the research tendencies on thermoelectric systems and
57 ORCs, the present study intends to shed light upon the possibility of inte-
58 grating TES in existing ORC CHP plants as a mean for improving the plant
59 performance, contributing to provide response to unanswered questions such
60 as:

- 61 • How can the possible performance enhancement be quantified?
- 62 • Are there any optimal design guidelines to develop such integration?

63 The aim of this work is to analyse the performance of a novel bio-fuelled
64 ORC+TES CHP configuration, contributing to the recent findings of the sci-
65 entific literature. Through a thermodynamic analysis general design guide-
66 lines are provided for the proposed integration layout, which also takes into
67 consideration the main technical parameters of the subsystems involved.

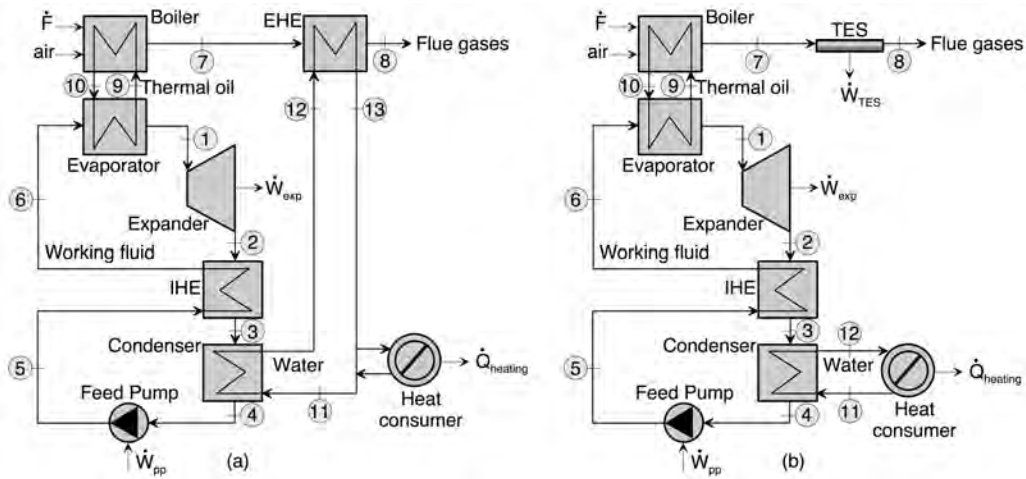


Figure 1: Biofuelled plant layout: (a) ORC CHP; (b) ORC+TES CHP

68 2. Methodology

69 A steady-state thermodynamic model, developed under the EES envi-
 70 ronment [22], was implemented to assess the possible integration of thermo-
 71 electric systems in existing ORC CHP plants driven by biomass combustion.
 72 The purpose of the model is to quantify the potential efficiency enhancement
 73 achieved with such integration, and to assess the influence of the main design
 74 parameters.

75 2.1. System description

76 Figure 1 depicts the layouts of a typical ORC CHP plant (a) and its
 77 potential combination with a TES (b). It represents a very simple integration
 78 proposal, with the main aim of seeking cost-effectiveness avoiding important
 79 modifications in existing ORC CHP plants, which will also entail higher
 80 technical risks.

81 The biomass is fed to the boiler where, through its combustion, an amount
 82 of useful heat rate is transferred to a thermal oil loop (process 9-10, Figure
 83 1). The oil loop acts as the heat source of the ORC, entering the evaporator
 84 to generate vapour (1), which expands in a turbine, thereby producing
 85 useful work. Then, the fluid exhausted from the expander (2) enters the low-
 86 pressure side of the internal heat exchanger (IHE) and the fluid exhausted
 87 from the pump (5) is conveyed to the inlet of high-pressure side of the IHE,
 88 thereby transferring heat from the low pressure (2-3) to high-pressure side

89 (5-6). The cycle rejects heat at a low pressure in the condenser (3-4), which
 90 is used to supply a certain heating demand (heat consumer). The biomass
 91 boiler pinch point forces the flue gases to have such a temperature (higher
 92 than the acid dew point limit [23]) that enables the possibility of extracting
 93 a small amount of extra heat rate in an external heat exchanger (EHE, pro-
 94 cesses 7-8 and 12-13, Figure 1a), which is used to raise the temperature of
 95 the ORC cooling fluid in the condenser prior to the heating supply to users
 96 at a fixed temperature (13-11, Figure 1a). A second possibility for using
 97 this amount of extra heat rate is to couple a thermoelectric system at the
 98 exhaust of the boiler (7-8, Figure 1b). Both alternatives can have positive
 99 effects on the efficiency of the plant. On the one hand, in the “conventional”
 100 alternative, the recovery of a part of the thermal energy in the flue gases in
 101 the EHE allows the average temperature of heat rejection to decrease, hence
 102 increasing the ORC efficiency [24]. On the other hand, the coupling of the
 103 TES increases the overall electricity production but also requires an increase
 104 of the temperature in the condenser due to the need for a fixed stable tem-
 105 perature supply to heat users, producing a decrease in the ORC efficiency.
 106 Hence, the different effects on the efficiency enhancement between both alter-
 107 natives should be assessed in depth by means of a thermodynamic model in
 108 order to fully understand the potential improvement of the TES integration.

109 2.2. Model description

110 As described in previous works [25, 26], the heat transfer rate in the
 111 heat exchangers of the cycle (evaporator, condenser and IHE) and the work
 112 (expander, pump) are expressed as a function of the mass flow rate (\dot{m}) and
 113 the enthalpy difference. Then, the energy balance in the plant is modelled
 114 as follows. The useful heat rate generated by means of the combustion of
 115 biomass to the thermal oil loop is absorbed by the working fluid in the
 116 different evaporation stages (Equation 1).

$$\dot{Q}_{ev} = \dot{m} \cdot (h_1 - h_6) \quad (1)$$

117 The work produced from the expansion of the vapour in the turbine is
 118 determined by Equation 2.

$$\dot{W}_{exp} = \dot{m} \cdot (h_1 - h_2) \quad (2)$$

119 The heat rate exchanged in the IHE between the high and low-pressure

120 sides of the ORC (Equation 3) can be calculated from both sides, and con-
 121 sidering a certain value of effectiveness (ε).

$$\dot{Q}_{IHE} = \varepsilon \cdot \dot{m} \cdot (h_2 - h_5) \quad (3)$$

122 The heat extraction from the power cycle occurs by means of the cooling
 123 fluid in the condenser (Equation 4).

$$\dot{Q}_{cd} = \dot{m} \cdot (h_3 - h_4) \quad (4)$$

124 The work required to raise the pressure level in the cycle with the feed
 125 pump is determined by Equation 5.

$$\dot{W}_{pp} = \dot{m} \cdot (h_5 - h_4) \quad (5)$$

126 The additional energy content in the exhaust gases is absorbed by the
 127 cold fluid in the EHE (\dot{Q}_{EHE}), in Figure 1a, or the TES (\dot{Q}_{TES}) in Figure
 128 1b.

$$\dot{Q}_{EHE} = \dot{Q}_{TES} = \dot{m}_{gas} \cdot (h_7 - h_8) \quad (6)$$

129 The heat supplied to the users is the sum of \dot{Q}_{cd} and \dot{Q}_{EHE} in the “con-
 130 ventional” alternative, while it is only \dot{Q}_{cd} in the proposed “thermoelectric”
 131 alternative.

132 Both the efficiencies of the ORC and the TES affect the power output of
 133 both subsystems according the Equations 7 and 8, where \dot{W}_{ORC} is the net
 134 power output of the ORC ($\dot{W}_{exp} - \dot{W}_{pp}$).

$$\dot{W}_{ORC} = \dot{m} \cdot (h_1 - h_2 - h_5 + h_4) \quad (7)$$

$$\dot{W}_{TES} = \eta_{TES} \cdot \dot{Q}_{TES} \quad (8)$$

135 The most characteristic parameter of the ORC is its energy efficiency
 136 (First Law), defined by Equation 9.

$$\eta_{ORC} = \frac{\dot{W}_{ORC}}{\dot{Q}_{ev}} \quad (9)$$

137 The thermoelectric module located at the exhaust of the biomass boiler
 138 absorbs heat (\dot{Q}_{TES}) at a high temperature (200 – 300°C) and rejects heat to
 139 the ambient while generating electricity by means of the thermoelectric effect.

140 This effect consists on producing voltage by a circuit made from two differ-
 141 ent conductors when one of the junctions is heated. When a temperature
 142 difference between two junctions is created, a voltage is produced between
 143 its open ends. Many thermoelectric couples can be connected in series elec-
 144 trically, and in parallel thermally, by sandwiching them between two plates
 145 to form a module (Figure 2).

146 The conversion efficiency of the TES depends on the performance of the
 147 thermoelectric material, indicated by the average figure of merit, \overline{ZT} , and
 148 the temperatures of the hot (T_H) and cold (T_C) sides, as shown in Equation
 149 10 [17].

$$\eta_{TES} = \frac{T_H - T_C}{T_H} \cdot \left[\frac{\sqrt{1 + \overline{ZT}} - 1}{\sqrt{1 + \overline{ZT}} + \frac{T_C}{T_H}} \right] \quad (10)$$

150 The hot side performance of the TES, as a heat exchanger, is determined
 151 by Equation 11, providing a “thermal indicator” as a first approach to the
 152 TES design.

$$UA_{TES} = \frac{\dot{Q}_{TES}}{\Delta T_{TES}} \quad (11)$$

153 2.3. Model inputs, hypothesis and design parameters

154 Some assumptions were made from the overall point of view: neglection
 155 of thermal losses in the system and consideration of 120 °C as the lower
 156 restriction for the system’s exhaust temperature. The latter is a constraint
 157 linked to the acid dew point of the flue gases [23].

158 From the ORC perspective, the selection of the working fluids, pressure
 159 levels and superheating degrees has a twofold justification. First, Toluene
 160 and MDM have been selected due to the fact that are the most used ones in
 161 existing plants [3]. Other novel fluids could be considered, such as R1234ze
 162 or R1234yf, however their wide commercial use is still far ahead and hence
 163 they are out of the scope of this study, which focuses on analysing the possi-
 164 ble efficiency enhancement in existing ORC CHP plants. Second, the opti-
 165 mal pressure levels (High, Low) and superheating degrees considered are the
 166 optimal ones in terms of Second Law efficiency performance, according to
 167 previous studies [25]. Other assumptions of the model are a minimum pinch

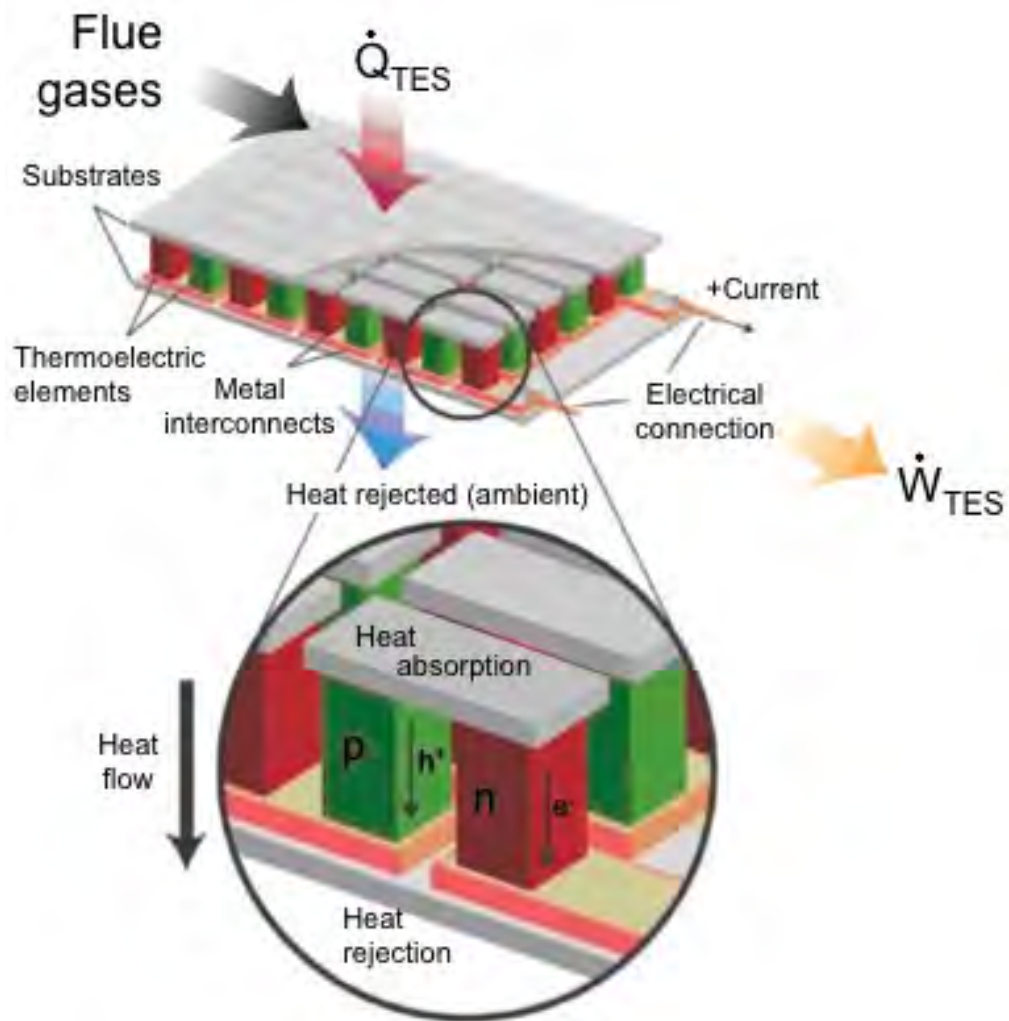


Figure 2: Schematic of the thermoelectric system (Adapted from [27])

168 point of 10 K at the evaporator, condenser and boiler; and a subcooling de-
 169 gree of 5 K [28]. The expander and pump isentropic efficiencies are set to
 170 75% (including mechanical losses), while the IHE effectiveness is set to 80%
 171 [29, 30]. Pressure losses in the ORC were considered as a 2% in the pipes
 172 and 10 kPa in the heat exchangers [26], while in the TES were neglected
 173 for the flue gases. The plant’s useful energy input is 85% of the primary
 174 energy from biomass. Finally, the main consideration for the TES is the
 175 selection of the thermoelectric material. The present work considers thermo-
 176 electric materials with different average figure of merit values and adequate
 177 performance in the temperature range studied [9], e.g.: nanobulk magnesium
 178 silicide ($\overline{ZT} = 0.67$), bulk bismuth-telluride alloy ($\overline{ZT} = 1.05$) and nanobulk
 179 bismuth-telluride alloy ($\overline{ZT} = 1.52$).

180 2.4. Model outputs

181 The main outputs of the thermodynamic model are the First and Second
 182 Law efficiencies of the overall plant, defined by Equations (12) and (13) [31]:

$$\eta_I = \frac{\dot{W}_{TOTAL} + \dot{Q}_{heating}}{\dot{F}} \quad (12)$$

$$\eta_{II} = \frac{\dot{W}_{TOTAL} + \dot{E}_{heating}}{\dot{E}_{biomass}} \quad (13)$$

183 where \dot{W}_{TOTAL} is the net power output of the overall plant ($\dot{W}_{ORC} +$
 184 \dot{W}_{TES}) and $\dot{Q}_{heating}$ the thermal energy supplied to the heat users. $\dot{E}_{biomass}$
 185 is the exergy flow rate of the biomass, which has been largely demonstrated
 186 to be satisfactorily approximated to their higher heating value [32]. $\dot{E}_{heating}$
 187 is the exergy flow rate of the heating production, which is calculated ac-
 188 cording to Equation 14 where, as an approximation, $T_{heating}$ is the average
 189 temperature of the heat supplied to users and T_0 is the reference temperature
 190 level².

$$\dot{E}_{heating} = \dot{Q}_{heating} \cdot \left(1 - \frac{T_0}{T_{heating}}\right) \quad (14)$$

191 The analysis of the Primary Energy Savings Ratio (*PESR*) complements
 192 the First and Second Law efficiency results of the plant. This parameter is

² $T_0 = 20^\circ\text{C}$

193 considered by several national policies to support efficient plants [33] and it
 194 shall be calculated according to Equation 15, where $\eta_{ref,e}$ and $\eta_{ref,th}$ are the
 195 characteristic efficiencies of the corresponding reference subsystems defined
 196 by Directive 2004/8/EC [34] for combined electricity and heat production³.

$$PESR = 1 - \frac{\dot{F}}{\frac{\dot{W}_{TOTAL}}{\eta_{ref,e}} + \frac{\dot{Q}_{heating}}{\eta_{ref,th}}} \quad (15)$$

197 3. Results and discussions

198 3.1. Optimization results

199 The performance of the ORC+TES CHP plant was optimized using the
 200 direct search algorithm [35], the Second Law efficiency as the objective func-
 201 tion and the temperature of the thermal oil loop exhausted from the boiler
 202 (T_9) as the continuous variable. The latter limits the heat source temper-
 203 ature of the thermoelectric system, due to its location at the outlet of the
 204 biomass boiler and its pinch point value. Figure 3 shows the variation of
 205 UA_{TES} and η_{TES} as a function of the TES driving temperature.

206 In Figure 4⁴, η_{ORC} , η_I , η_{II} and $PESR$ are depicted as a percentage vari-
 207 ation achieved by the TES integration alternative (Figure 1b) with respect
 208 to the “conventional” plant (Figure 1a) operating in optimal conditions [26].

209 The raise of T_9 has opposite effects on the efficiencies of the overall CHP
 210 system. On the one hand, the First law efficiency tends to decrease with
 211 the raise of T_9 while, on the other hand, the Second Law efficiency (and
 212 $PESR$) clearly increase. However, the performance of the system should be
 213 optimized in terms of Second Law efficiency maximization [26]. Hence, the
 214 optimal T_9 value is about 245 °C. It also shall be considered that for some
 215 very low values of T_9 the Second Law efficiency of the proposed alternative
 216 is lower than the “conventional” one.

217 The efficiencies of the subsystems (ORC and TES) and the heat transfer
 218 conductance of the hot side of the TES also increase with the increment of
 219 T_9 . This last issue is important, since an increase of UA_{TES} supposes a cost
 220 increase of the TES (a greater heat exchanger is required).

³ $\eta_{ref,e} = 0,25$; $\eta_{ref,th} = 0,86$

⁴An average value of $\overline{ZT} = 1.05$ (bulk bismuth-telluride alloy) was considered

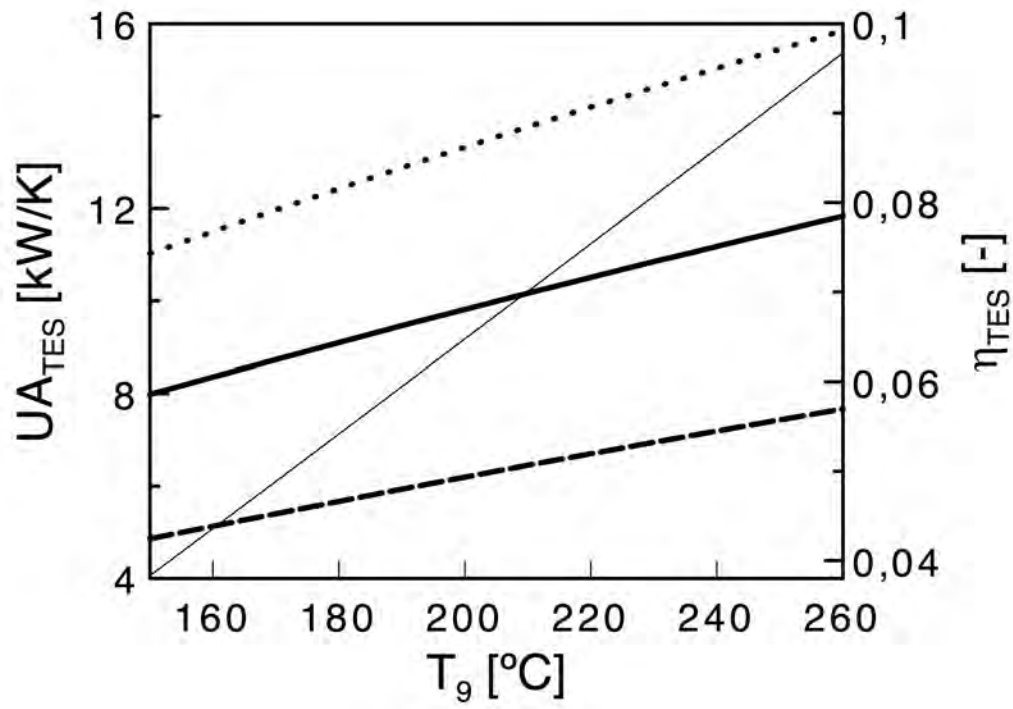


Figure 3: Variation of the TES heat transfer conductance and efficiency as a function of the TES driving temperature in a Toluene-ORC+TES CHP plant. UA_{TES} solid thin line; $\eta_{TES}(\overline{ZT} = 0.67)$ dash line; $\eta_{TES}(\overline{ZT} = 1.05)$ solid thick line, $\eta_{TES}(\overline{ZT} = 1.52)$; dot line

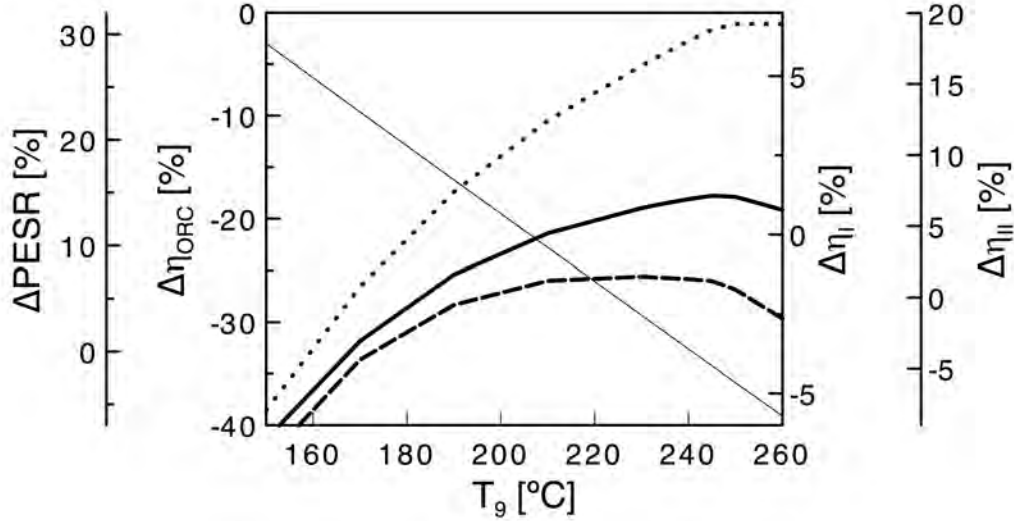


Figure 4: Variation of the First Law efficiency of the ORC subsystem, the First and Second Law efficiencies of the plant and its Primary Energy Savings Ratio as a function of the TES driving temperature. $\Delta\eta_{ORC}$ dot line, $\Delta\eta_I$ solid thin line, $\Delta\eta_{II}$ solid thick line and $\Delta PESR$ dash line

221 Similar, but less pronounced tendencies are observed in CHP ORC plants
 222 with MDM as working fluid. In view of the results shown in Figures 5 and
 223 6⁵, there is not a clear optimal point as in the case of Toluene, however, the
 224 values between 200 – 240°C can be considered adequate.

225 The rationale behind the peak reached by both η_{II} and $PESR$ is sum-
 226 marised hereafter. The increase of T_9 has a positive effect on the ORC’s
 227 average temperature of heat addition [24], hence increasing the ORC effi-
 228 ciency (Figures 4 and 6). Nevertheless, the constant pinch point (10 K)
 229 between states 7 and 9 is responsible for an unavoidable decrease in \dot{Q}_{ev}
 230 which causes a decrease in \dot{W}_{ORC} and \dot{Q}_{cd} . Moreover, when T_9 is higher a
 231 higher amount of energy is available in the combustion gases exhausted from
 232 the boiler and at a higher temperature (T_7). This results in a higher TES
 233 efficiency (see Equation 10 and Figures 3, 5) and a \dot{W}_{TES} increase. In other
 234 words, the increase of T_9 has a positive effect on both the ORC and the
 235 TES efficiencies, but the former progressively losses importance with respect

⁵An average value of $\overline{ZT} = 1.05$ (bulk bismuth-telluride alloy) was considered

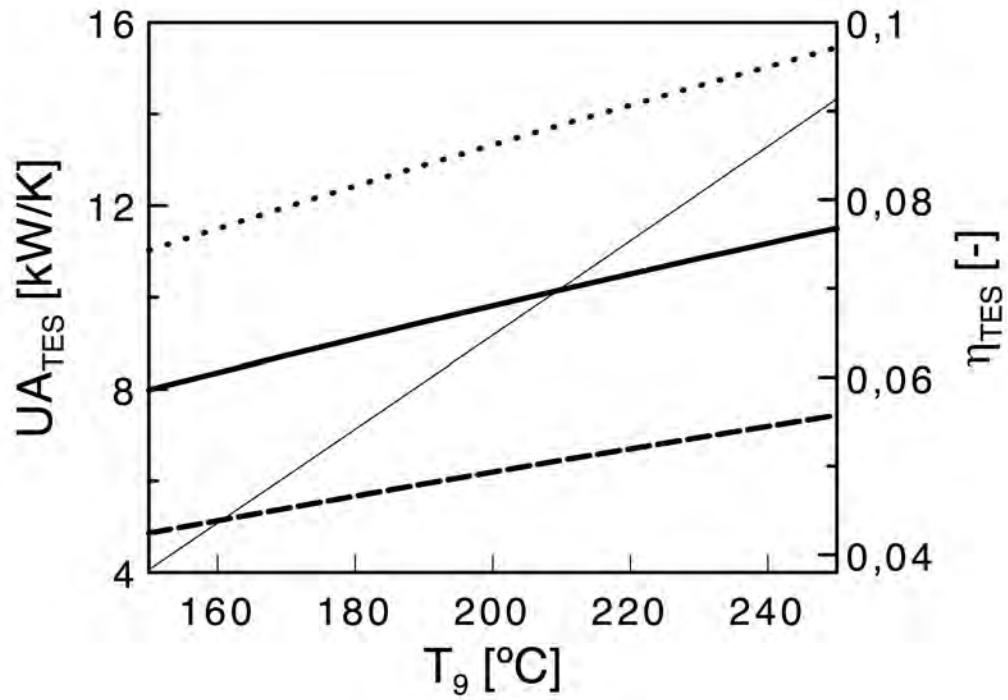


Figure 5: Variation of the TES heat transfer conductance and efficiency as a function of the TES driving temperature in a MDM-ORC+TES CHP plant. UA_{TES} solid thin line; $\eta_{TES}(\overline{ZT} = 0.67)$ dash line; $\eta_{TES}(\overline{ZT} = 1.05)$ solid thick line, $\eta_{TES}(\overline{ZT} = 1.52)$; dot line

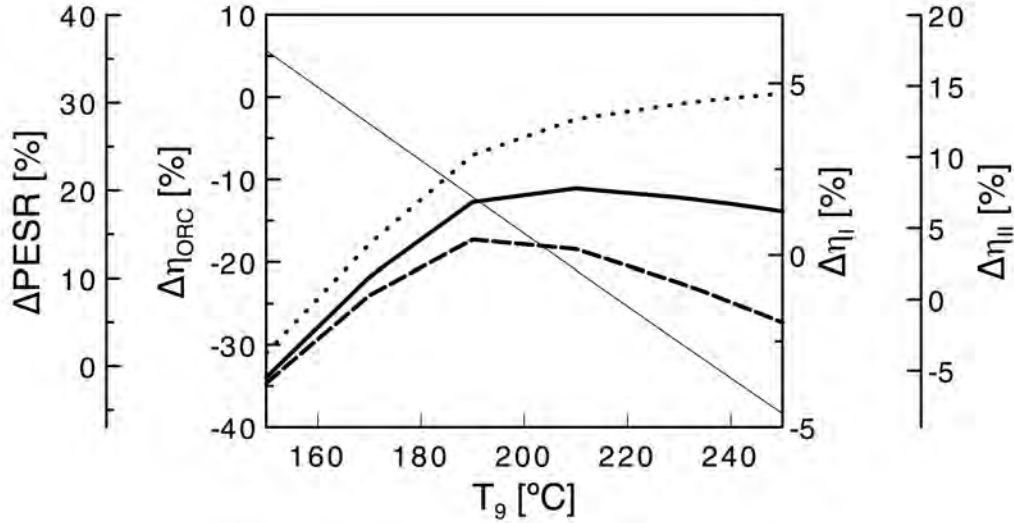


Figure 6: Variation of the First Law efficiency of the ORC subsystem, the First and Second Law efficiencies of the plant and its Primary Energy Savings Ratio as a function of the TES driving temperature. $\Delta\eta_{ORC}$ dot line, $\Delta\eta_I$ solid thin line, $\Delta\eta_{II}$ solid thick line and $\Delta PESR$ dash line

236 to the latter in terms of work produced. Due to the higher ORC efficiency
 237 in comparison to the TES, there is a T_9 value which maximises the overall
 238 Second Law efficiency and the PESR of the plant, as a consequence of an
 239 equilibrium between the increase of both efficiencies (ORC and TES) and the
 240 not excessive decrease of the ORC output power. In summary, it is important
 241 to consider as a general design guideline the optimal value of T_9 maximising
 242 the Second Law efficiency and PESR, which in this case according to the
 243 hypotheses considered is between 210 and 245°C, as seen in Figures 4 and 6.

244 While the performance enhancement is evident, the integration of a TES
 245 in the ORC CHP plant implies a very slight impact on the working conditions
 246 of the ORC (see Figure 7⁶), consequently only slight changes in its operation
 247 are expected.

248 However, the TES simple integration allows a maximum increase in the
 249 Second Law efficiency of the plant of 7% for Toluene and 8% for MDM. In
 250 addition it increases the overall plant performance in terms of the W/Q ratio,

⁶Thermodynamic states shown correspond to points in Figure 1

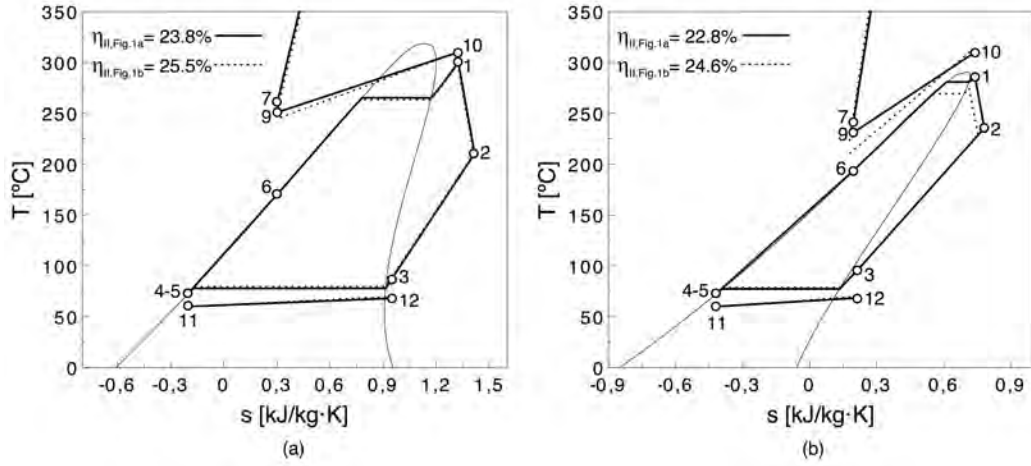


Figure 7: Temperature-entropy diagram of the plant (Solid line: ORC CHP plant; Dash line: ORC+TES CHP plant): (a) Toluene-ORC, (b) MDM-ORC

251 the annual power generation and the annual CO₂ savings. The CO₂ savings
 252 results shown in Table 1⁷ were estimated considering the operation of the
 253 plant, exclusively, and the corresponding emission factor of a biofuelled CHP
 254 plant⁸.

255 3.2. Effect of the thermoelectric material

256 As it could be expected, the material selection plays a crucial role in
 257 the final performance of the TES. In Figure 8 the influence over the perfor-
 258 mance of the TES, and the First and Second Law efficiencies of the plant of
 259 three thermoelectric materials (nanobulk magnesium silicide, bulk bismuth-
 260 telluride alloy and nanobulk bismuth-telluride alloy) with different figure of
 261 merit are shown.

262 The significant difference in \overline{ZT} between the nanobulk magnesium sili-
 263 cide ($\overline{ZT} = 0.67$) and the nanobulk bismuth-telluride alloy ($\overline{ZT} = 1.52$)
 264 (127% increment in \overline{ZT}) leads to minor impacts on the First and Second
 265 Law efficiencies of the plant (1% and 2%, respectively) for an optimal value
 266 of T_9 .

⁷An average value of $\overline{ZT} = 1.05$ (bulk bismuth-telluride alloy) and 6000 h/y of operation were considered

⁸340 kgCO₂/(MW h) [36]

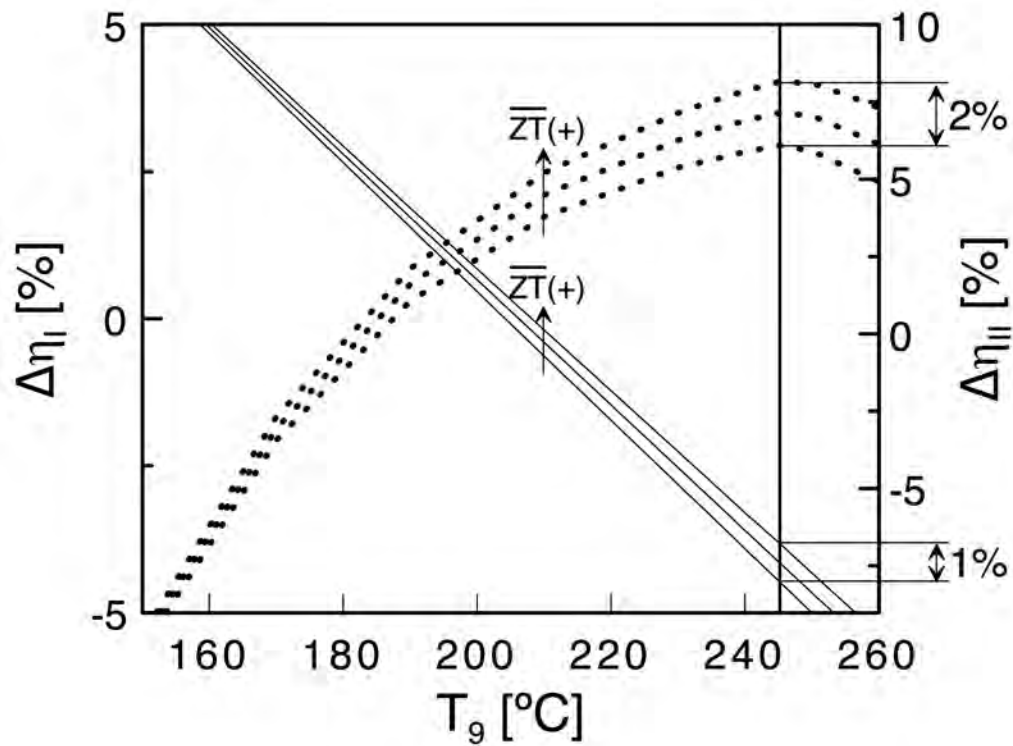


Figure 8: Variation of the First (solid line) and Second Law (dot line) efficiencies of the Toluene-ORC+TES CHP plant as a function of the TES driving temperature, depending on the thermoelectric material

Table 1: Ratio W/Q , annual power generation, annual CO₂ savings, Second Law efficiency (η_{II}), Primary Energy Savings Ratio ($PESR$), First Law efficiency (η_I), ORC efficiency (η_{ORC}), TES efficiency (η_{TES}) and heat transfer conductance of the TES (UA_{TES}) results per ORC working fluid

	Figure 1a		Figure 1b	
	Toluene	MDM	Toluene	MDM
Ratio W/Q (-)	0.26	0.23	0.32	0.28
Power generation (MWh/y)	1185	1094	1238	1135
CO ₂ savings (tCO ₂ /y)	-	-	87	73
η_{II} (%)	23.8	22.8	25.5	24.6
$PESR$ (%)	25.4	23.5	27.1	26.6
η_I (%)	77.0	77.1	73.8	76.7
η_{ORC} (%)	23.9	21.5	23.5	21.0
η_{TES} (%)	-	-	7.6	7.0
UA_{TES} (kW/K)	-	-	13.8	10.2

267 4. Conclusions

268 The main objective of this work was to propose a simple way of integrating
 269 thermoelectric systems into bio-fuelled ORC CHP plants with the aim of
 270 evaluating its performance and extract conclusions about its possible future
 271 application.

272 A thermodynamic model has been used to obtain general design guidelines
 273 for the proposed integration layout, which also take into consideration the
 274 main technical parameters of the subsystems involved.

275 According to the questions raised in the introduction, the main conclu-
 276 sions can be summarized as follows. For the proposed plant layout exists an
 277 optimum TES driving temperature that maximizes the Second Law efficiency
 278 of the overall plant, which shall be considered as a general design guideline
 279 for the proposed plant layout. In the examples evaluated in the present work,
 280 this temperature is about 245°C in the case of a Toluene-ORC CHP plant and
 281 about 210°C in the case of a MDM-ORC CHP plant (although values in the
 282 range of 200 – 240°C can be considered adequate), which leads to an increase
 283 in the overall Second Law efficiency of the plant up to 7-8% (for an average
 284 figure of merit of 1.05). The Primary Energy Savings Ratio of the plant
 285 showed similar tendencies, with maximum increases of 7% (Toluene-ORC)
 286 and 13% (MDM-ORC).

287 Further perspectives of this work are related to different possibilities than

288 the one proposed hereby for integrating thermoelectric systems in existing
 289 ORC CHP plants, for example to increase the efficiency of the biomass boiler
 290 by means of preheating the combustion air with the heat rejected in the cold
 291 side of the TES.

292 Nomenclature

\dot{E}	Exergy flow rate (kW)
\dot{F}	Biomass energy flow (kW)
h	Specific enthalpy (kJ/kg)
\dot{m}	Mass flow rate (kg/s)
$PESR$	Primary energy savings Ratio (%)
\dot{Q}	Heat rate (kW)
s	Specific entropy (kJ/(kg K))
T	Temperature (°C)
UA	Heat transfer conductance (kW/K)
\dot{W}	Mechanical or electrical power (kW)
\overline{ZT}	Average figure of merit (-)

Greek letters

Δ	Difference (-)
ε	Effectiveness (-)
η	Efficiency (%)

Subscripts and superscripts

0	Reference conditions
cd	Condenser
ev	Evaporator
exp	Expander
gas	Hot gases
I	First law
II	Second law
pp	Pump
ref, e	Reference electric
ref, th	Reference thermal

Abbreviations

CHP	Combined Heating and Power
EHE	External Heat Exchanger
IHE	Internal Heat Exchanger
MDM	Octamethyltrisiloxane
ORC	Organic Rankine Cycle
TES	Thermoelectric System

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