Exergoeconomic analysis and comparison between ORC and Kalina cycles to exploit low and medium-high temperature heat from two

Exergo economic analysis and comparison between ORC and Kalina cycles to exploit low and medium-high temperature heat from two different geothermal sites

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KEYWORDS

Geothermal energy, binary cycle, Kalina, ORC, Exergo Economic, Electricity production cost

Abstract (240 words)

The Organic Rankine (ORC) and Kalina (KC) Cycles represent two different technologies suitable to exploit low and medium temperature geothermal heat resources. In this work, the performances of KC, CO_2 and ORC cycles, the latter using different working fluids, for power generation from two geothermal fluid reservoirs are compared from an energy and exergo-economic perspective.

Two different case studies are discussed: the first one referred to a medium-temperature heat sourceof 212 °C (Mt. Amiata, Italy), the second one to a low-temperature heat sourceof 120 °C (Pomarance geothermal basin, Italy).

For each case study,cost rate balances and auxiliary equations for all components were evaluated, as well as the flow rate and unit exergy cost for each stream.

The results for the medium temperature case study showed that, among the considered cycles, an ORC with R1233zd(E)achieves the bestexergoeconomic performance. The cost of the produced electricity was found to be 8.85 c€/kWh, which is 3% lower than that of the KC. On the other hand, for the low temperature case study, the KC shows the best performance,being able to produce 22 – 42% more net power than the ORC; in this case, the cost of electricity produced by the KC was foundat 12.5 c€/kWh, which is 24-34% lower than the typical value for an ORC with different working fluids.

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29 **NOMENCLATURE**

Symbols

c_{j_k}, c_{i_k}	Flux costs, [€/kJ]
$cost_{fuel_{kJ}}$	Geothermal fluid specific exergy cost, [€/kJ]
$cost_{Wt_{kJ}}$	Turbine power specific cost, [€/kJ]
$cost_{kWh_{el}}$	Produced KWh cost, $\left[\frac{c€}{kWh}\right]$
$\dot{C}_P$	Output product cost, [€/s]
$\dot{C}_F$	Fuel cost, [€/s]
ex	Specific exergy, [kJ/kg]
f	Exergo-economic factor
h	Enthalpy, [kJ/kg]
i_{eff}	Effective interest rate
n	Power plant lifespan (yr)
P	Pressure, [Pa, bar]
Q	Thermal power, [kW]
R	Heat resistance, [K/W]
s	Entropy, [kJ/kg-K]
T	Temperature [K, °C]
$\dot{Z}$	Capital Investment
x	Ammonia mass fraction [−]
W	Power, [kW]
$\dot{m}$	Mass flow rate, [kg/s]

Greek symbols

η	First law efficiency, [-]
η_{II}	Second law efficiency, [-]
ρ	Density, [kg m^{-2}]

Subscripts

0	Reference state
1, 2, 3, …	Cycle reference points
base fluid	Ammonia water mixture before separator
Geo	Geothermal fluid
in/out	Inlet/Outlet

Acronyms

CEPCI – Chemical Engineering Plant Cost Index

EES – Engineering Equation Solver

KC – Kalina Cycle

PEC – Purchased equipment costs

TCI – Total Capital Investment

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1. Introduction

In recent years, an increasing interest towards the exploitation of low temperature heat to produce electricity, both from renewables and industrial wastes, is coming out. Among renewables, geothermal energy presents the highest availability, as it does not substantially depend on weather conditions. Nowadays, the technology for the electricity conversion of geothermal energy achieved a wide market application, with over 10,000 MWe installed. However, the exploitation of conventional resources (high- and mediumtemperature) almost reached its maximum potential, and the not yet utilized fields are often at low or moderate temperature. On the other hand, there is a growing interest towards the exploitation of low temperature geothermal resources to produce electricity. Anyhow, it is a challenging task due to thermodynamic, environmental and economic issues; conventional conversion methods, indeed, do not guarantee viable solutions.

The environmental sustainability of geothermal energy conversion systems was deeply addressed employing life cycle analysis as an evaluation tool (Bayer et. al, 2013, Bravi and Basosi, 2014, Frick et. al., 2013, Saner et. al., 2010). A relevant documented issue is the release of non-condensable gases to the environment, containing several kinds of contaminants. Only the use of binary cycles (like ORCs or Kalina) coupled to the complete reinjection of non – condensable gases could give a valuable answer to the improvement of sustainability of geothermal power plants, as demonstrated in (Bravi and Basosi, 2014, Frick, S., et. al., 2013, Saner et. al., 2010). These cycles, also working with novel and environmentally friendly fluids (low GWP) are a pivotal point for the exploitation of low temperature geothermal resources.

Recently, numerous studies on the assessment of ORC as geothermal energy conversion systems (Zeyghami, 2015; Walraven et al., 2015), including optimal working fluids selection (Liu e al., 2013) and zeotropic mixtures (Liu et al., 2014).were carried out.

A very efficient configuration of geothermal conversion system is the combined heat and power arrangements, which allows a decisive enhancement of net plant efficiency (Fiaschi et al., 2014). Another interesting way to enhance ORC geothermal plant efficiencies is to consider supercritical configuration power plants (Arslan and Yetik, 2011).

Another technology, which holds high efficiency for low temperature resources, is the Kalina cycle (KC), based on an ammonia-water mixture as working fluid in place of a pure substance. In the early eighties of the twentieth century, Alexander I. Kalina proposed this new thermodynamic cycle (Kalina, 1982). Among the advanced thermodynamic cycles, KC is the most significant improvement in energy systems design since the advent of the Rankine cycle in the mid of the 19th century, and is acknowledged to be an ambitious competitor of the ORC (Zhang, 2012). The main trait of non-azeotropic mixtures, such as the ammonia-water mixture, is the transition phase at variable temperature during

vaporization and condensation. This peculiarity allows a better coupling between the heat capacities of the fluids in both evaporator and condenser, thus reducing the irreversibilities due to the heat transfer and, therefore, enhancing the overall efficiency of the system (Valdimarsson, 2003).

Many parametric studies were carried out on the performance evaluation of KC with ammonia-water mixture for the exploitation of low temperature heat resources, also including exergy analysis (Ibrahim and Kovach, 1993, Nag and Gupta, 1997). It was found that the increase of the ammonia mass fraction would hold positive effects on the turbine losses, while increasing the evaporator losses. This trend is due to better matching of the thermal profiles between the heat source and the working fluid, allowing a reduction of irreversibility at the evaporator when the ammonia mass fraction is lower. Fiaschi et. al. (2015) investigated a new configuration of KC for low temperature geothermal resources including a chiller, thus making the power cycle a cold cogeneration and power unit by exploiting the properties of the ammonia-water mixture after the expansion in the turbine.

1.1. Comparison studies of KC and ORCs

In the research carried out by Valdimarsson (2003), it was shown that the capital costs of the KC for the exploitation of low temperature heat resources are comparable with those of ORC. Furthermore, it was also demonstrated that, for the same heat input, the power output of the KC resulted higher than that produced by the ORC. Both cycles were analysed with first and second law approach by Rodriguez et al., 2012. From the comparison of the results, it was shown that the KC is capable of producing about 18% more power output than the ORC at comparable costs per energy unit. The research performed by Victor et al. (2013) involved the optimization of ORCs and KC in the 100 – 250°C temperature range with the objective of maximizing the cycles efficiency. They assessed an optimized compositions of a new water – alcohol mixture as working fluid for the KC and demonstrated how this new mixture could increase the efficiency of the cycle, especially in the 220-250° C range. Fu et al. (2013) did a comparison between ORC and KCs in a novel application for the exploitation of geothermal energy waste heat recovery in oil fields. Li and Day (2014) evaluated and compared the performance of KC and trans-critical CO_2 cycles for the exploitation of low temperature enhanced geothermal systems by the means of thermo-economic analysis. The main results were that the KC could achieve a higher thermal efficiency and net power output, while exhibiting lower costs of kWh, mainly due to the lower impact of heat exchanger costs.

On the whole, the literature addresses KC as one of the best thermo-economic performing cycles for the exploitation of low temperature geothermal resources. Energy, exergy and exergo-economic analysis to compare dual pressure/dual fluid ORC_S and KC were carried out by Shokati et al. (2015). The turbine was identified as the critical component for both ORCs and KC, holding a high impact both on irreversibilities and investment costs. Among the investigated

cycles, the dual-pressure ORCs achieved the highest power output (15% more than the base ORC), whereas KC had the lowest specific energy costs, (66% less than the basic ORC). In his research, Arslan (2010), stated that KC is preferable to the ORCs when the temperature of the heat source is below 413 K.

A comparative analysis of KC and ORC thermodynamic performance was carried out by (Bombarda et al., 2009) on a case study involving the recovery of waste heat from two 900 kWe diesel engines. The obtained results demonstrated how the power output of the cycles for medium-high temperature heat sources would be comparable. However, the KC would require a maximum operating pressure considerably higher than the ORC, as well as an increase in power plant complexity. On the other hand, for low temperature heat resources, the KC appears to be competitive. A thermodynamic and thermo-economic comparison of ORCs, KC and TLC (Trilateral Rankine Cycle) for the exploitation of low temperature heat resources, was carried out by Yari et al. (2015). They concluded that the highest power output could be achieved from TLC, while the lowest energy costs from ORC with n-butane as working fluid.

At present, very few power plants adopting KC were installed; they confirmed good performance levels. Currently, in Europe there are three only: the geothermal power plant in Husavik, Iceland (Leibowitz and Micak, 1999); and two plants in Germany, built by Siemens between 2007 and 2009 (Knapek and Kittl 2007, Mergner et al., 2013).

Several interesting studies on the comparison between KC and ORCs are available, *but a thorough comprehensive investigation of the two options with different heat resources, based on the same exergo-economic model, appears to be still missing*. Indeed, as it can be noticed from the literature survey, the outcomes are sometimes widely discordant: on one side, there are optimization studies concluding that the best solution is the ORC (Bombarda et al., 2009; Yari et al., 2015). On the other hand, there are studies claiming KC as the best performing power plant over ORCs in the field of binary cycles (Valdimarsson, 2003; Rodriguez et al., 2012; Victor et al., 2013; Fu et al., 2013; Li and Day, 2014; Shokati et al., 2015; Arslan, 2010). The discrepancies found in literature may also depend on the specific characteristics of the resource and on the different applied calculation models for the analysis.

In the present study, a thermodynamic and exergo-economic analysis and comparison of the basic ORC, with different working fluids (including mixtures) and cycle conditions (including supercritical cycles), and KCs is presented for two different representative case studies of geothermal resources. Both thermodynamic cycles were designed and optimized from exergy and exergo-economic perspective, in order to achieve the highest possible performance for a fixed heat input.

The main goal of this study is, therefore, the investigation and comparison of optimized solutions adopting KC and several ORC cycles to the two selected case studies, largely different in size, in order to assess the *optimum suitable*

temperature of the resource and the boundaries of KC – ORC convenience, either from thermodynamic and exergo-economic points of view.

2. Methodology

2.1. Mt. Amiata Case Study

Two real case studies were modelled as the basis to assess the applicability of KC system. The first case study is that of the medium-high enthalpy geothermal field of Mt. Amiata, Italy. It is a water-dominant hydrothermal system localized at 3000-3500 m depth, where the geothermal fluid in the reservoir is at temperature and pressure of about 325° C and 250 bar respectively.Currently, this resource is exploited by the single-flash geothermal power plant technology. Indeed, the geothermal fluid, during its ascending path undergoes a flash process at about 600-800 m depth, due to the decrease of the hydrodynamic pressure gradient. The Amiata geothermal field was selected as a case study because of the difficulties encountered in using the local resource with flash power plant technology.The brine is particularly rich in antimony sulphide (Stibnite), which precipitates in the flash drain at temperature below 140°C and is responsible for the scaling of the ducts, causing drastic reductions of the passage sections. In order to prevent the scaling of Stibnite, the introduction of a borehole pump upstream the flash point was proposed, thereby maintaining the geothermal fluid under pressurized liquid conditions, from the extraction to the re-injection reservoir. The required pump head and power were calculated modelling the friction and heat losses in the geothermal fluid extraction duct. This site is also critical because of the pollutants (mainly CO_2, H_2S, Hg and NH_3) contained in the Non-Condensable Gases (NCG, about 7% in volume of the steam fraction).The current technological solution applied to flash power plants is the catalytic gas treatment (patented AMIS process, Baldacci et al., 2005), which guarantees extensive abatement but has relevant costs and affects the power plant availability; moreover, the CO_2 contained in the geothermal resource is released to the atmosphere (Fiaschi et al., 2014).

2.1.1. Borehole pump

One of the topicsof this research is closely related to the characteristics of the medium – hightemperature geothermal fluid of Mt. Amiata field.It was considered as a pressurized liquid,to be directly reinjected after the heat transfer to the power cycle, in order to reduce the environmental hazard related to the incondensable gas released to the atmosphere such as carbon dioxide, methane and hydrogen sulphide, while avoiding the scaling of silicate and calcium carbonate and inhibit the generation of Stibnite. Another method to avoid the scaling of Stibnite, could be increasing the PH of the fluid. Mechanical or Chemical removal are anyhow necessary when prevention is not suitable: nonetheless, both of

them require long periods of downtime (Brown, K., 2011), justifying therefore the investigation of further solutions. In order to fulfil the pressurized liquid condition, the utilization of a borehole pump located inside the well at 800 m depth from the ground level was assumed.

The pressurized fluid, after having delivered its sensible heat to the working fluid, is re-injected at a fixed 150°C temperature, in order to avoid any sedimentation of stibnite while ensuring, at the same time, a correct management of the geothermal field.

2.2. Pomarance Case Study

In order to verify that KC is preferable to the ORCs for low temperature heat source (Arslan, 2010), a low temperature geothermal resource was also investigated. Specifically, the Pomarance geothermal field was selected as the second case study. Currently, the Pomarance heat resource is exploited for providing heat, through a district-heating network, to the namesake town. The analysed cycles were coupled to the superheated water circuit, which provides heat at 120° C.

2.3. Cycles configurations

The main components of the KC are similar to those of an ORC power plant. The main difference is the presence of a separator, which is a specific feature of the KC. The flow splitting allows an improved internal recuperation of the cycle. The schematics of the analysed cycles, KC on the left and ORC on the right, are shown in figure 1.On the working fluid side, the NH_3-H_2O mixture enters the evaporator at point 3 and exits in under-saturated vapour conditions (point 4).The working fluid is not entirely vaporized and it is sent to a vertical separator, which splits the NH_3-H_2O mixture into an ammonia rich vapour (point 5) and an ammonia-lean water-rich saturated liquid (point 7). The ammonia-rich vapour exits from the top of the separator and gets into the turbine, where it expands down to the condenser pressure (point 6). After the expansion, the ammonia-rich vapour is mixed with the ammonia-lean liquid stream, thus producing again the original mixture composition(point 9). Upstream the condenser, two recuperative heat exchangers are included in the process. The Low-Temperature Recovery heat exchanger (RLT) pre-cools the condenser stream and represents the first pre-heating stage, which reduces the final evaporator heat duty. A second, High Temperature heat Recovery process (RHT) takes place between the preheated condenser stream and the ammonia-lean, water-rich mixture. The final result is the reduction of the external heat duties, both for the condenser (points 10-11), and evaporator (points 3-4). A throttle valve (points 7b-8) provides the necessary pressure adjustment before mixing. A pump (points 11- 1) provides the necessary pressure rise from the condenser to the evaporator pressure levels.

The analysed ORC basic configuration allows sub-critical, trans-critical and super-critical operations.

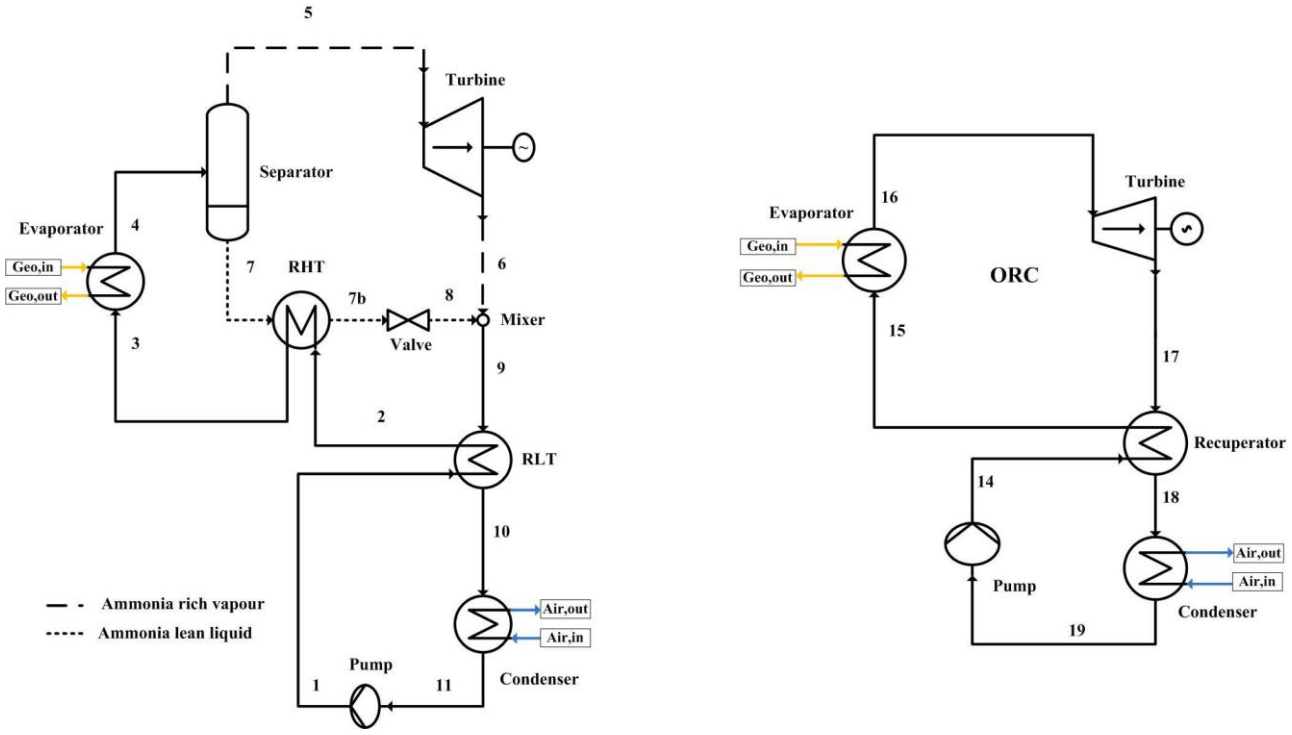


Figure 1 Schematic of KC (left side) and ORC cycle (right side)

Figure 2 shows the T-h diagram of the NH_3-H_2O mixture within KC. The continuous black line represents the basic mixture composition. The blue dotted line represents the ammonia – rich vapour expansion and mixing transformations. The yellow dotted line represents the ammonia – lean mixture heat transfer, throttle valve and mixing processes. As it is seen, the recuperated mixture at point 9 still has high temperature and enthalpy, which is favourable for internal heat recuperation.

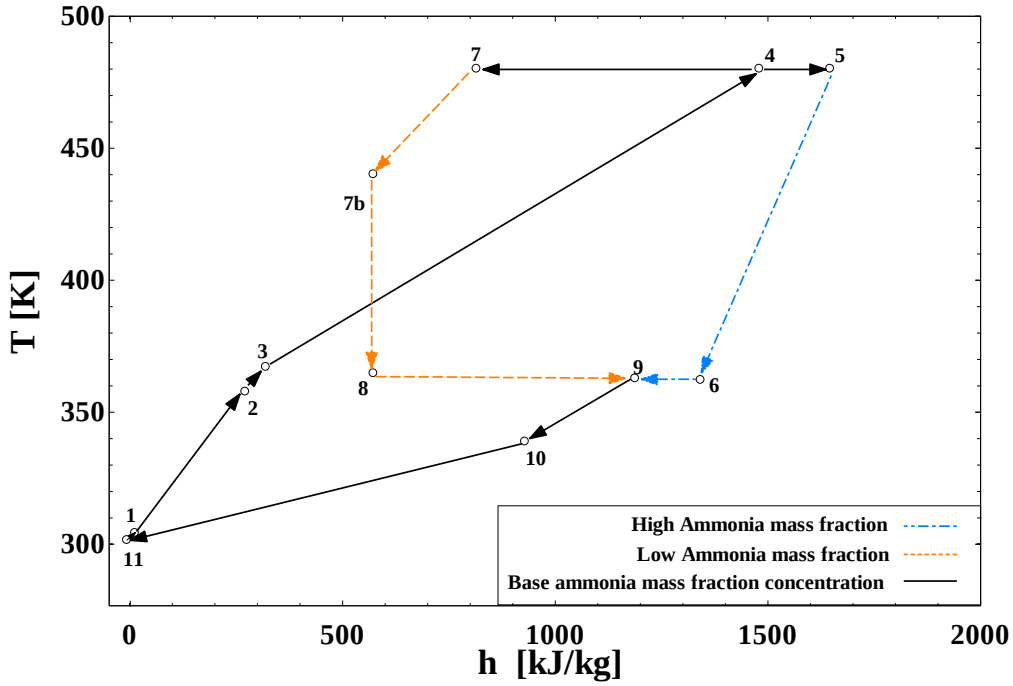


Figure 2T-hdiagram of KC

2.4. Thermodynamic analysis and model validation

The calculation models proposed in this work were developed by Engineering Equation Software (EES, Klein and Nellis, 2012). The main assumptions were the steady operation of power plants and the geothermal fluid modelled as pure water. The implemented equations were numerically solved, with locally–evaluated real fluid cycle properties. When mixtures where considered, the EES-Refprop interface allowed the evaluation of real fluid thermodynamic properties. The fundamental equations (mass and energy balances) were written for each component of the powerplants, following general rules (Klein and Nellis, 2011).The thermodynamic model was validated comparing the results obtained with published literature results(Shokati et al., 2015), as shown in Table 1.

Table 1KC operating conditions: (a) present work (b) ref.(Shokati et. al., 2015). Input parameters: Tgeo = 133,5 °C; Pgeo = 3 bar; x[4] = 0,8455; Peva = 40bar

Stream	Temperature (°C)		Ammonia mass fraction		Flow rate (kg/s)	
	a	b	a	b	a	b
1	16.88	15.89	0.8455	0.8455	2.56	2.56
2	31.78	31.3	0.8455	0.8455	2.56	2.56
3	56.85	57.53	0.8455	0.8455	2.56	2.56
4	118.45	118.5	0.8455	0.8455	2.56	2.56
5	118.45	118.5	0.9736	0.9776	1.77	1.75

6	30.37	28.29	0.9736	0.9776	1.77	1.75
7	118.45	118.5	0.5584	0.5679	0.79	0.81
7b	36.55	36.52	0.5584	0.5679	0.79	0.81
8	37.08	37.1	0.5584	0.5679	0.79	0.81
9	36.78	36.52	0.8455	0.8455	2.56	2.56
10	31.96	30.65	0.8455	0.8455	2.56	2.56
11	16.14	15	0.8455	0.8455	2.56	2.56

2.5 Exergy and Exergo – economic analysis

The exergy analysis combines the First and Second Laws of Thermodynamic, allowing the evaluation of the efficiency of the energy system and the irreversibilities (exergy destructions) of its components (Szargut, J. et al., 1988). The exergy analysis became one of the most powerful tools for the design and analysis of energy systems and power plants (Kotas,1985). Indeed, the concept of exergy is able to evaluate the actual thermodynamic values (and thus costs) of energy flows. Combining economic and thermodynamic analysis, the exergo-economic analysis employs the cost principles to exergy.

The exergo-economic equations of a system, working under steady conditions, are evaluated from the balance of the input and output costs:

$$\sum_{\text{output}} \dot{C}_{P,tot} = \sum_{\text{input}} \dot{C}_{F,tot} + \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM} \quad (1)$$

Where:

- $\dot{C}_{P,tot}$ is the output product cost [€/s]
- $\dot{C}_{F,tot}$ is the fuel cost (or any another required resource necessary to the operation of the component) [€/s]
- $\dot{Z}_{tot}^{CI}$ is the specific capital cost [€/s]
- $\dot{Z}_{tot}^{OM}$ is the specific operation and maintenance cost [€/s]

$\dot{Z}_{tot}^{CI}$ e $\dot{Z}_{tot}^{OM}$ arecalculated dividing the total annual investments, operation and maintenance costs (coming from the economic analysis), by the total yearly working time, expressed in suitable units. Their sum is the overall cost rate $\dot{Z}$:

$$\dot{Z} = \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM} \quad (2)$$

Table 2summarizesthe exergo-economic balances and the auxiliary equations (Bejan, A., et al., 1996), which are logic statements that allow defining the missing number of conditions to solve the cost equations applied to each component.

Table 2 –Exergo-economic balance equations of power plant components

	KC	ORC Cycle
Evaporator	$c_4 * \dot{E}x_4 = c_3 * \dot{E}x_3 + \dot{C}_{fuel} + \dot{Z}_4$ $\dot{C}_{fuel} = c_{fuel_{kJ}} * (\dot{E}x_{GEO_{in}} - \dot{E}x_{GEO_{out}})$	$c_{16} * \dot{E}x_{16} = c_{15} * \dot{E}x_{15} + \dot{C}_{fuel} + \dot{Z}_{14}$ $\dot{C}_{fuel} = c_{fuel_{kJ}} * (\dot{E}x_{GEO_{in}} - \dot{E}x_{GEO_{out}})$
Separator	$c_5 \cdot \dot{E}x_5 + c_7 \cdot \dot{E}x_7 = c_4 \cdot \dot{E}x_4 + \dot{Z}_5$ $\frac{c_5 \cdot \dot{E}x_5 - c_4 \cdot \dot{E}x_4}{\dot{E}x_5 - \dot{E}x_4} = \frac{c_7 \cdot \dot{E}x_7 - c_4 \cdot \dot{E}x_4}{\dot{E}x_7 - \dot{E}x_4}$	-
Turbine	$c_{Wt_{kJ}} \cdot \dot{W}_T + c_6 \cdot \dot{E}x_6 = c_5 \cdot \dot{E}x_5 + \dot{Z}_6$ $c_6 = c_5$	$c_{Wt_{kJ}} \cdot \dot{W}_T + c_{17} \cdot \dot{E}x_{17} = c_{16} \cdot \dot{E}x_{16} + \dot{Z}_{15}$ $c_{16} = c_{17}$
Mixer	$c_9 \cdot \dot{E}x_9 = c_6 \cdot \dot{E}x_6 + c_8 \cdot \dot{E}x_8 + \dot{Z}_7$	-
Throttle valve	$c_8 \cdot \dot{E}x_8 = c_{7b} \cdot \dot{E}x_{7b} + \dot{Z}_8$	-
High Temperature Recuperator	$c_{7b} \cdot \dot{E}x_{7b} + c_3 \cdot \dot{E}x_3 = c_7 \cdot \dot{E}x_7 + c_2 \cdot \dot{E}x_2 + \dot{Z}_3$ $c_7 = c_{7b}$	$c_{18} \cdot \dot{E}x_{18} + c_{15} \cdot \dot{E}x_{15} = c_{17} \cdot \dot{E}x_{17} + c_{14} \cdot \dot{E}x_{14} + \dot{Z}_{16}$ $c_{17} = c_{18}$
Low Temperature Recuperator	$c_{10} \cdot \dot{E}x_{10} + c_2 \cdot \dot{E}x_2 = c_9 \cdot \dot{E}x_9 + c_1 \cdot \dot{E}x_1 + \dot{Z}_2$ $c_9 = c_{10}$	-
Condenser	$c_{11} \cdot \dot{E}x_{11} = c_{10} \cdot \dot{E}x_{10} + \dot{Z}_1$	$c_{19} \cdot \dot{E}x_{19} = c_{18} \cdot \dot{E}x_{18} + \dot{Z}_{17}$
Pump	$c_1 \cdot \dot{E}x_1 = c_{11} \cdot \dot{E}x_{11} + c_{Wp_{kJ}} \cdot \dot{W}_{pump} + \dot{Z}_9$ $c_{Wp_{kJ}} = c_{Wt_{kJ}}$	$c_{14} \cdot \dot{E}x_{14} = c_{19} \cdot \dot{E}x_{19} + c_{Wp_{kJ}} \cdot \dot{W}_{pump} + \dot{Z}_{18}$ $c_{Wp_{kJ}} = c_{Wt_{kJ}}$

2.6 Investment and O&M costs

In order to determine the investment and O&M costs ($\dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM}$) of the two proposed power plants, an economic analysis was carried out. The first step was the calculation of the components costs, which was done following the

methodology proposed in (Turton, et al., 2003). The components costs were determined from a standard mathematical relationship, which was subsequently improved with correction factors accounting for component class, working pressure and equipment materials. Finally, the obtained value was actualized to the reference year (2015) through the CEPCI (Chemical Engineering Plant Cost Index) inflation index(Chemical Engineering, 2015).

The Operation and Maintenance costs (O&M) of each component were determined as a fraction(1.5%) of the Purchased equipment costs (PEC), as suggested by Schuster (Schuster, A., et al. 2009).

The calculation of the Total Capital Investment cost (TCI) is presented in detail in Appendix A. Once the TCI was calculated, knowing the total yearly working hours of the power plant, it was possible to determine $\dot{Z}$ in €/s. In this case, we assumed 7446 [h/year] working time, which is a realistic value for geothermal power plants (Shokati, et. al., 2015).

The final outcome of the exergo-economic analysis is the cost of the produced kWh (c€/kWh).

3. Results

3.1. Power Cycles Optimization

The main parameters affecting the performance of the KC are the maximum and minimum temperature and pressure at evaporator and condenser outpu tand the ammonia mass fraction in the rich solution at the separator inlet. Therefore, a sensitivity analysis to these fundamental parameters was done, in order to maximise the thermal efficiency of the power plant and minimize the unit cost of the produced energy, for both high and low temperature case studies. For each reference case, a comparison with optimised ORC solutions was also carried out.

In the Mt. Amiata case study, figure 3 (a, b and c) displays the KC efficiency and produced energy unit cost vs. maximum cycle temperature (i.e. at evaporator exit) for three different ammonia mass fractions and condenser pressures. Due to the fixed upper temperature level, the cycle is improved at lower condenser pressure, thus the efficiency is higher and the energy unit costs are reduced.

With 0.8 ammonia mass fraction (base solution upstream the separator),the highest values of thermal efficiency are achieved. By the way, lower ammonia concentrations allow the exploitation of higher maximum temperature levels. On the other hand, higher ammonia concentrations give better performance with lower temperature heat sources. For these reasons, even the lowest unit energy cost is found at 80% ammonia mass fraction.

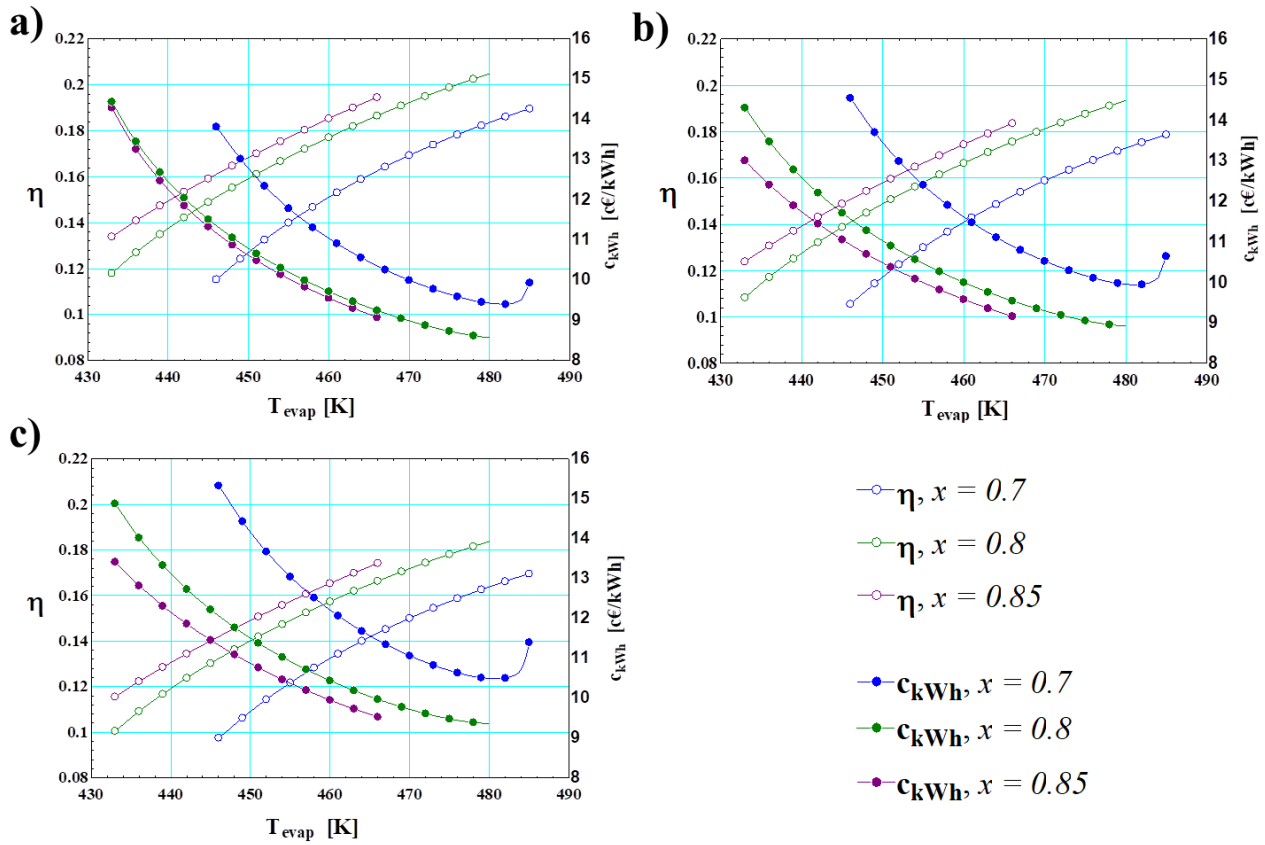
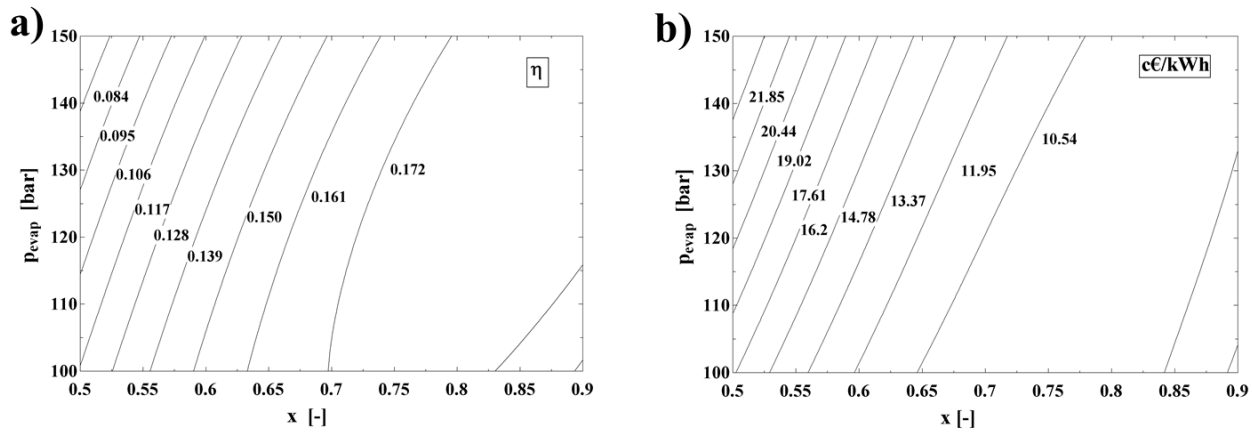


Figure 3 Thermal efficiency and produced power unit cost for KC Cycle, as a function of Evaporator temperature, ammonia mass fraction and condenser pressure. Evaporator pressure = 114 bar; Condenser pressure = 7 bar (a); 9 bar (b); 11 bar (c)

Figure 4showsthe contours of the KC efficiency (a) and produced energy unit costs (b) vs. evaporator pressure, at variable ammonia mass fraction. Higher values imply higher evaporator pressures, in order to achieve high efficiencies and low unit energy costs. The parametric analysis allowed, therefore, the determination of the optimal evaporator pressure to maximize the cycle efficiency and minimize the unit costs of produced energy.



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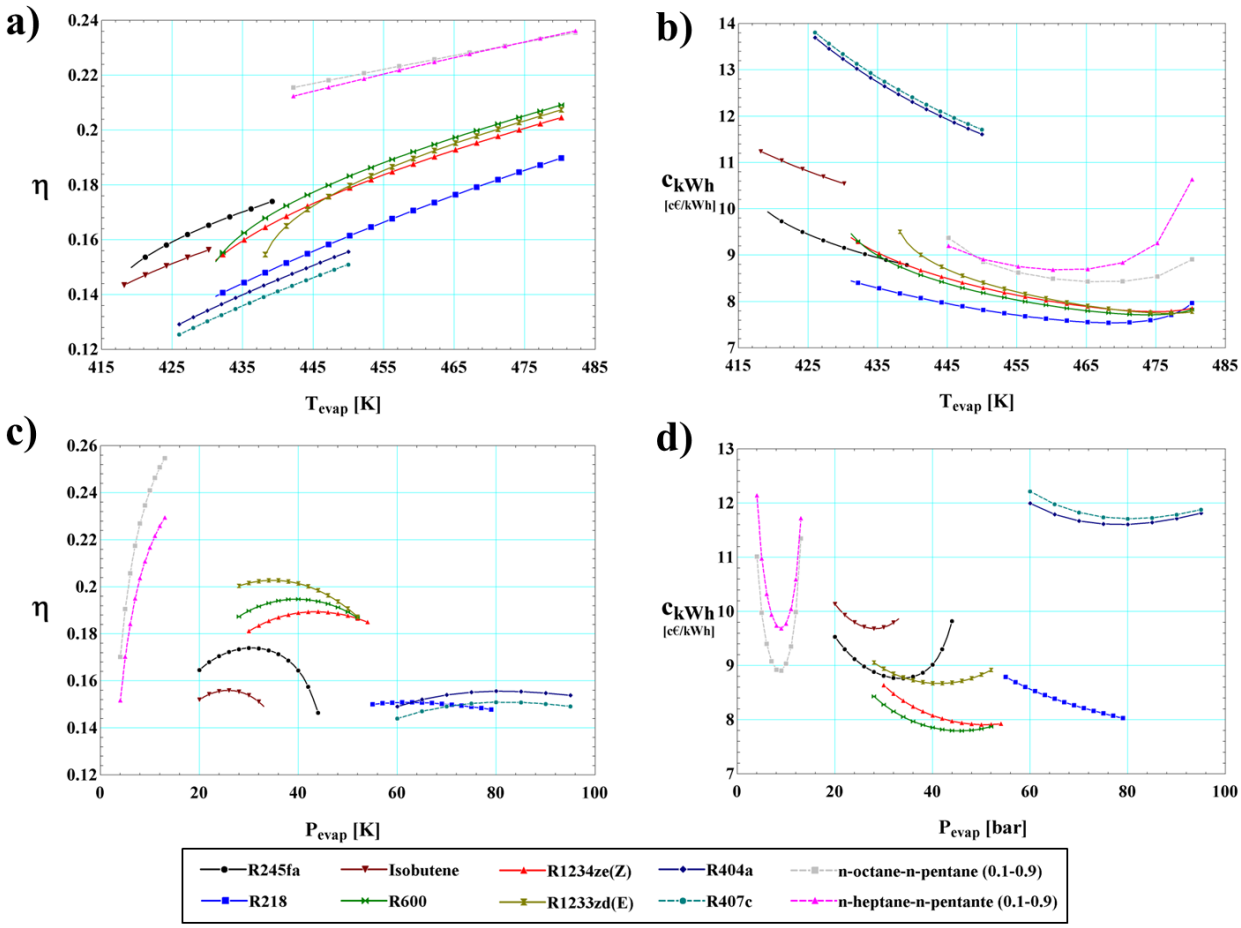
261 **Figure 4**Contours of Thermal efficiency (a) and produced energy unit cost (b, [c€/kWh]) for KC, vs. evaporator pressure and ammonia mass fraction.

262 Evaporator Temperature = 480 K; Condenser pressure = 9 bar



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264 **Figure5** ORCefficiency and produced energy unit cost as a function of Evaporator temperature (a-b) and pressure (c-d)

265 The same parametric analysis was carried out for the ORC. Figures 5 shows the efficiency and produced energy unit
266 cost of the ORC, as a function of evaporator pressure (a) and temperature (b) for several different working fluids, from
267 pure substances like R245fa or R600, to mixtures such as R404a or n-heptane/n-pentane (0.1-0.9). Specifically, the

selection and composition of the hydrocarbon mixtures proposed by Oyewumni, O.A., et al., 2017 was also considered here. Furthermore, the present work also includes the performance and cost analysis of CO_2cycle, under both trans and super critical conditions.Figure6 shows how the latter achieves higher efficiency, but has the disadvantage of a higher produced energy unit cost. Due to the fixed upper temperature level (which was selected as the maximum achievable temperature of the fluid), the cycle efficiency shows an optimizing pressure trend, which is strongly dependent on the fluid type. On the other hand, as it was expected, higher efficiency values and lower produced energy unit costs were obtained at higher maximum cycle temperature.

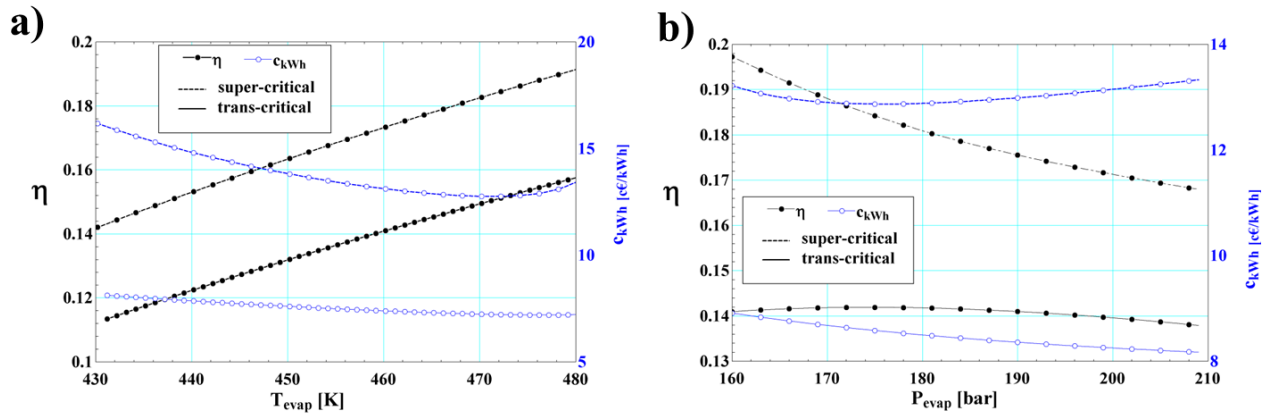


Figure6 Efficiency and produced energy unit cost for the ORC Cycle, as a function of the maximum temperature (a) and the higher pressure level(b) of the cycle. ORC Working Fluid = Carbon Dioxide

3.2. Exergy analysis: results

3.2.1. Mt. Amiata case study

The performance data of the considered power cycles for the high temperature case (Mt. Amiata) are summarized in table 4.In this site, the geothermal fluid is available at 212°C and it is re-injected at 150°C. The best matching thermodynamic cycle to the geothermal fluid resource is the one with super-critical CO_2, which, however, still has a worse matching than KC for a large field. With R1233zd(E) and the hydrocarbon mixtures (n-octane/n-pentane 0.1/0.9 mass fraction and n-heptane/n-pentane 0.1/0.9 mass fraction) as working fluids, the first law efficiency achieved values higher than 20%, which are reduced to about18 % when including the power consumed by the borehole pump.

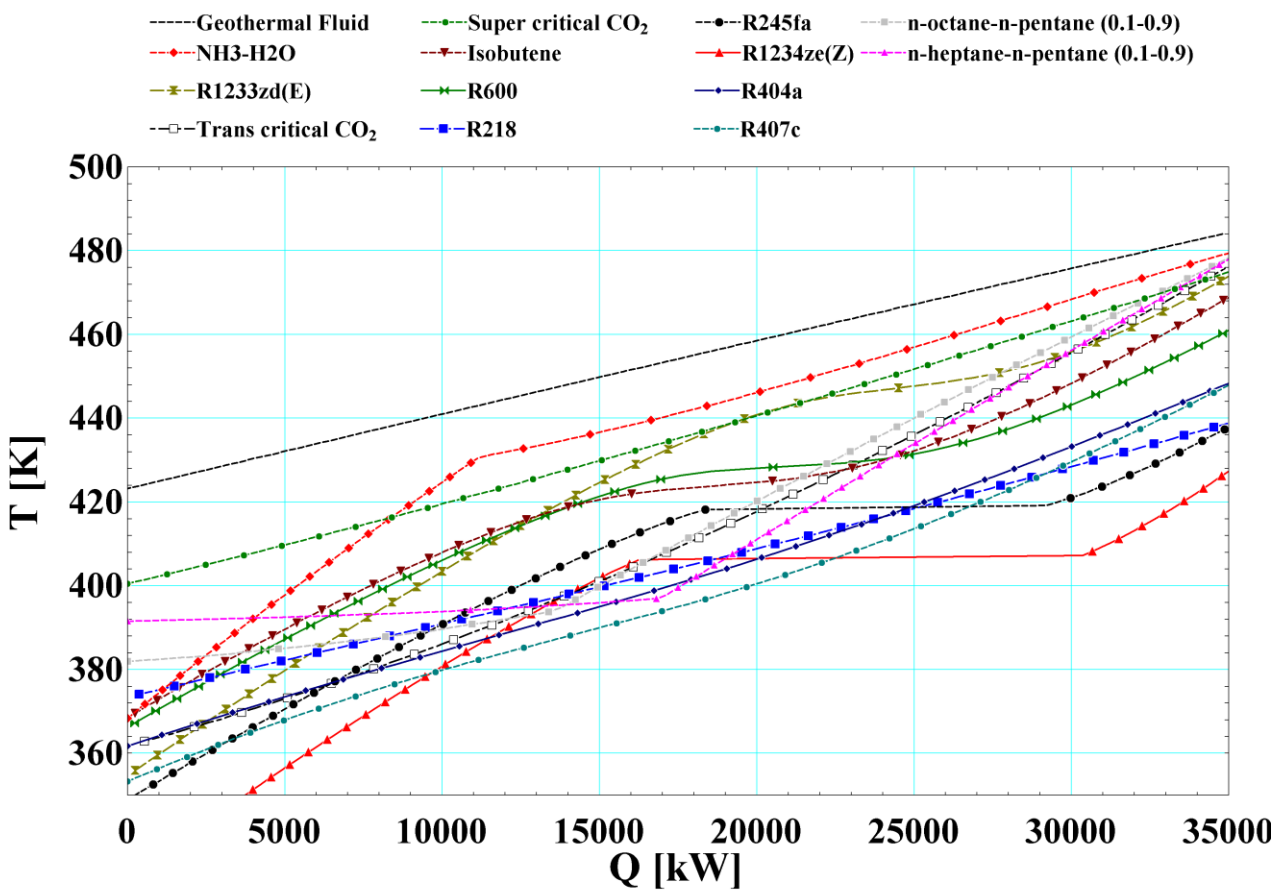
Considering the same amount of available geothermal heat input for all the thermodynamic cycles, the KC solution gives better efficiency than the ORCs working with R245fa, R218, trans critical and super critical CO_2, R404a, R407c and R1234ze(Z). On the other hand, the KC efficiency is lower compared to ORCs working with Isobutene, R600, R1233zd(E) and the investigated hydrocarbon mixtures , as shown in table 4.

Isobutene, R600, R404a, R407c and R1233zd(E) have a trans-critical behaviour, due to the fixed temperature and pressures inthe case study. These kinds of cycles allow a better matching of the curves at the evaporator, as shown in figure 7, where the behaviour of the cycle higher temperature side, allowing the highest thermal efficiency at fixed upper and lower temperature bounds of the heat sources (i.e. geothermal and environment), are considered. The good matching of geothermal and working fluid heat capacities grants limited irreversibility in heat transfer, thus allowinga better exploitation of the geothermal resource. Also the KC, due to the zeotropic NH_3-H_2O working fluid mixture and the hydrocarbon mixtures, which allow a non – isothermal vaporization behaviour, hold a good matching level with the geothermal fluid behaviour at the evaporator. It makes KC and ORC with hydrocarbon mixtures attractive compared to ORCs with pure fluids and isothermal vaporization behaviour.

R218, R404a, R407c and trans critical CO_2 cycles exhibit the worst cycle performance, because their thermodynamic efficiencies are heavily affected by the relatively high power demand of the recirculation pump: it requires 26.2% and 39%respectively of the total cycle power output. On the contrary, for all the other fluids (except super critical CO_2, which nonetheless achieves higher cycle efficiency),the recirculation pump power has a lower relative influence, variable between 6.5% and 8.9% of the overall turbine power output.R1233zd(E) presents one of the highest power plant performance and the lowest produced energy unit costs. Besides, this working fluid is a new generation organic fluid (HFO, derived from the common used R134a), having zero Ozone Depletion Potential (ODP) and very low Global Warming Potential (GWP) of 5. These favourable features suggest the R1233zd(E) selection for the high temperature case of Mt. Amiata.

310 **Table 4** Performance comparison between KC and ORC cycles for the High Temperature case (Mt. Amiata)

Performance Parameter			**KC**	**ORC**											
				R245fa	**Isobutene**	**R600**	**R218**	**Trans-critical Carbon Dioxide**	**Super-critical Carbon Dioxide**	**R1234ze(Z)**	**R1233zd(E)**	**R404a**	**r407c**	**n-octane n-pentane (0.1-0.9)**	**n-octane n-pentane (0.1-0.9)**
Heat Exchanged	Evaporator	[kW]	35528	35528	35528	35528	35528	35528	35528	35528	35528	35528	35528	35528	35528
	HT Recuperator	[kW]	1485	-	-	-	-	-	-	-	-	-	-	-	-
	LT Recuperator	[kW]	7936	1114	11052	10763	27077	13132	68975	2121	7260	15335	10127	39502	28545
	Condenser	[kW]	28648	29347	28533	28609	30169	30486	28847	30007	28394	30000	30166	28221	28292
Power	Turbine	[kW]	7458	6608	7682	7564	7257	8910	10309	5913	7723	7216	6609	7417	7368
	Recirculation pump/compressor	[kW]	578.1	427.1	686.1	645	1898	3472	3627	392.5	588.5	1688	1247	109.3	131.1
	Borehole pump	[kW]	897.5	897.5	897.5	897.5	897.5	897.5	897.5	897.5	897.5	897.5	897.5	897.5	897.5
First Law Efficiency		[-]	0.1937	0.174	0.1969	0.1948	0.1509	0.1545	0.1881	0.1554	0.2008	0.1556	0.1509	0.2057	0.2037
Global Power Plant Efficiency		**[-]**	**0.1684**	**0.1487**	**0.1716**	**0.1695**	**0.1256**	**0.1293**	**0.1628**	**0.1301**	**0.1755**	**0.1303**	**0.1257**	**0.1804**	**0.1784**



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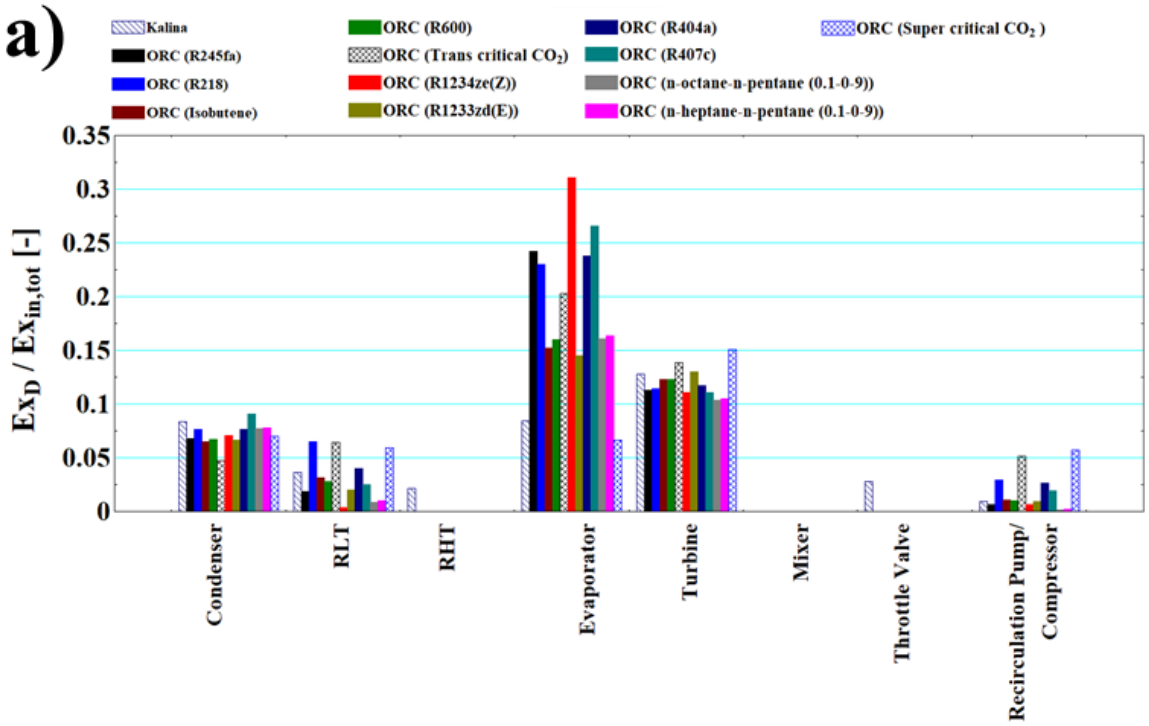
312 **Figure 7** Comparison of heat transfer temperature profiles inside the evaporator, for the Mt. Amiata case study. The dashed black line represents the
313 cooling curve of the geothermal fluid.

314 Figure 8showsthe non-dimensional exergy destruction of the components in the power cycles. The exergy input was
315 fixed at the same value for each thermodynamic cycle. As evident from figure 8, the highest exergy destruction source
316 both for KC and ORC cycles is the evaporator. Generally, trans-critical and super critical working fluids and -zeotropic
317 mixtures show a good matching with the heat transfer line of the geothermal fluid resource, thus generating relatively
318 moderate heat transfer exergy destruction. The second highest irreversibility source is the turbine. The only case where
319 the highest exergy destruction is in the turbine and not in the evaporator is for the super critical CO_2 cycle. This is
320 mainly due to the very good matching of the evaporator curves and the high power output of the turbine.

321 Depending on the thermodynamic cycle, the device allowing the increase of cycle pressure (namely the recirculation
322 pump or the compressor), strongly affects the overall exergy destruction. Indeed, as evident from figure 8, R218,
323 R404a, R407c and trans critical and super critical CO_2 cycles hold far higher exergy destruction than the other working
324 fluids. This is mainly due to the working fluids condition, which is transcritical (or supercritical in one case of CO_2),
325 therefore requiring higher compression power input.



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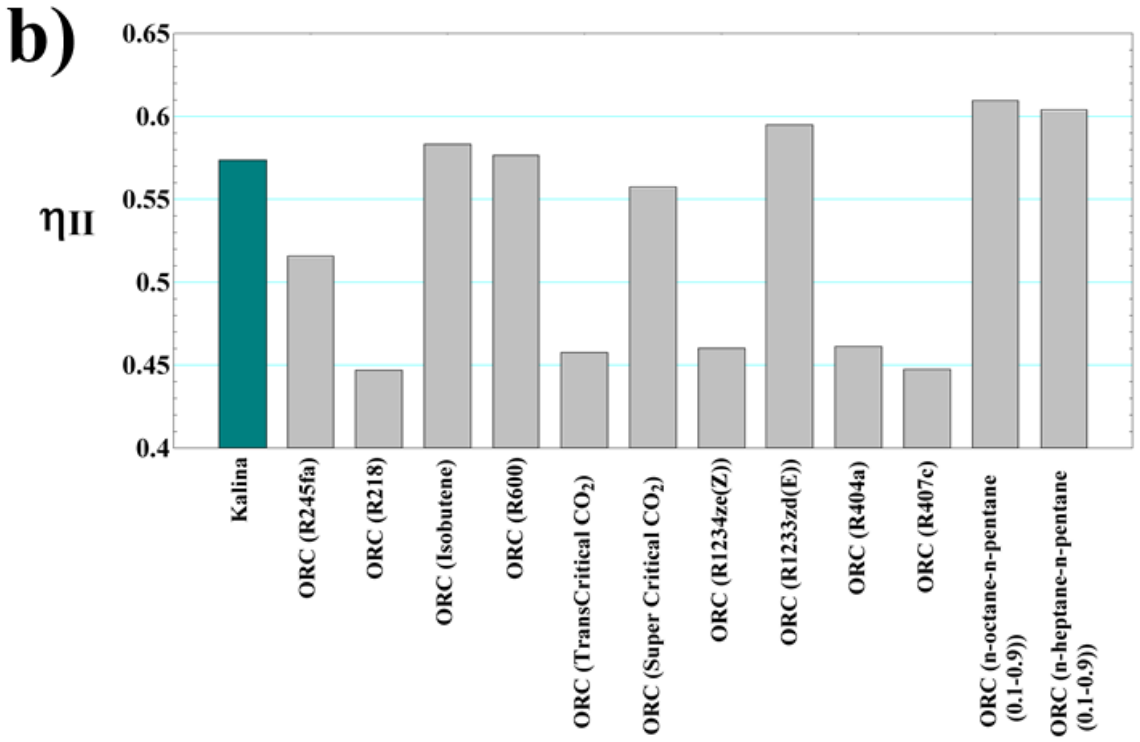

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328 **Figure 8**a) Component exergy destruction comparison between KC and ORCs; b) Second law efficiency comparison between KC and ORCs

329

330

3.2.2.Low temperature case study: Pomarance geothermal site

The performance data of the investigated cycles for the low temperature case study of Pomarance geothermal site are summarized in table 5.

In this site, where the resource is at the low 120°C temperature level and is released at 80°C, the best heat transfer matching between thermodynamic cycle and the geothermal fluid curve is the ORC working with super critical CO_2, nearly followed by the ORC with R218 and the KC. Nevertheless, the super critical CO_2cycle does not hold thehighest performance. This is mainly attributable to the high power required for the compression of the fluid upstream the high temperature heat exchanger. It reduces the efficiency of the power cycle, thus hindering the interesting thermal behaviour potential of this fluid, which, consequently, exhibited performance at the same level ofthe other working fluids.

As for the Mt. Amiata case study, R218, R404a, R407c and CO_2 cycle were trans-critical, differently from all the other ORC working fluids. The vaporization of the other ORC fluids was at constant temperature, thus not allowing a good matching of the evaporator curves to the geothermal fluid behaviour, as shown in figure 9.Nevertheless, the better cycle efficiency of the other fluids, generally more suitable to low temperatures, counterbalanced the higher matching features of the trans-criticalR218 and the super and trans critical CO_2.Onthe whole, the poor matching of the evaporator curves with subcritical cycles brought to moderate values of the first and second law efficiencies, thus the KC showed its far better potential(table 5 and figure 10). Due to the better matching of the heat transfer composite curves at the evaporator, the efficiency of the KC was found at 23 to 42% higher than that of the ORCs, for all the considered fluids including CO_2 cycles.

350 **Table 5** Performance comparison between KC and ORC cycles for the Low Temperature case (Pomarance)

Performance parameter			KC	ORC											
				R245fa	**Isobutene**	**R600**	**R218**	**Trans-critical Carbon Dioxide**	**Super-critical Carbon Dioxide**	**R1234ze(Z)**	**R1233zd(E)**	**R404a**	**r407c**	**n-octane n-pentane (0.1-0.9)**	**n-octane n-pentane (0.1-0.9)**
Heat Exchanged	Evaporator	[kW]	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
	HT Recuperator	[kW]	313.4	-	-	-	-	-	-	-	-	-	-	-	-
	LT Recuperator	[kW]	347.1	1044	927.4	1114	2015	909	9647	609	842	923.5	504.5	3731	2547
	Condenser	[kW]	4356	4521	4503	4529	4518	4627	4495	4517	4510	4541	4549	4567	4582
Power	Turbine	[kW]	674.3	492.3	520.8	488.8	636.4	712.1	900.2	497.5	502.7	589.6	546.3	437.4	423
	Recirculation Pump/compressor	[kW]	29.68	12.97	23.58	18	153.8	339.2	394.6	14.62	11.95	130.3	95.21	4.35	4.37
First Law Efficiency		[-]	0.1289	0.0958	0.0994	0.0941	0.0965	0.0746	0.1011	0.0966	0.0982	0.0919	0.0902	0.0866	0.0837

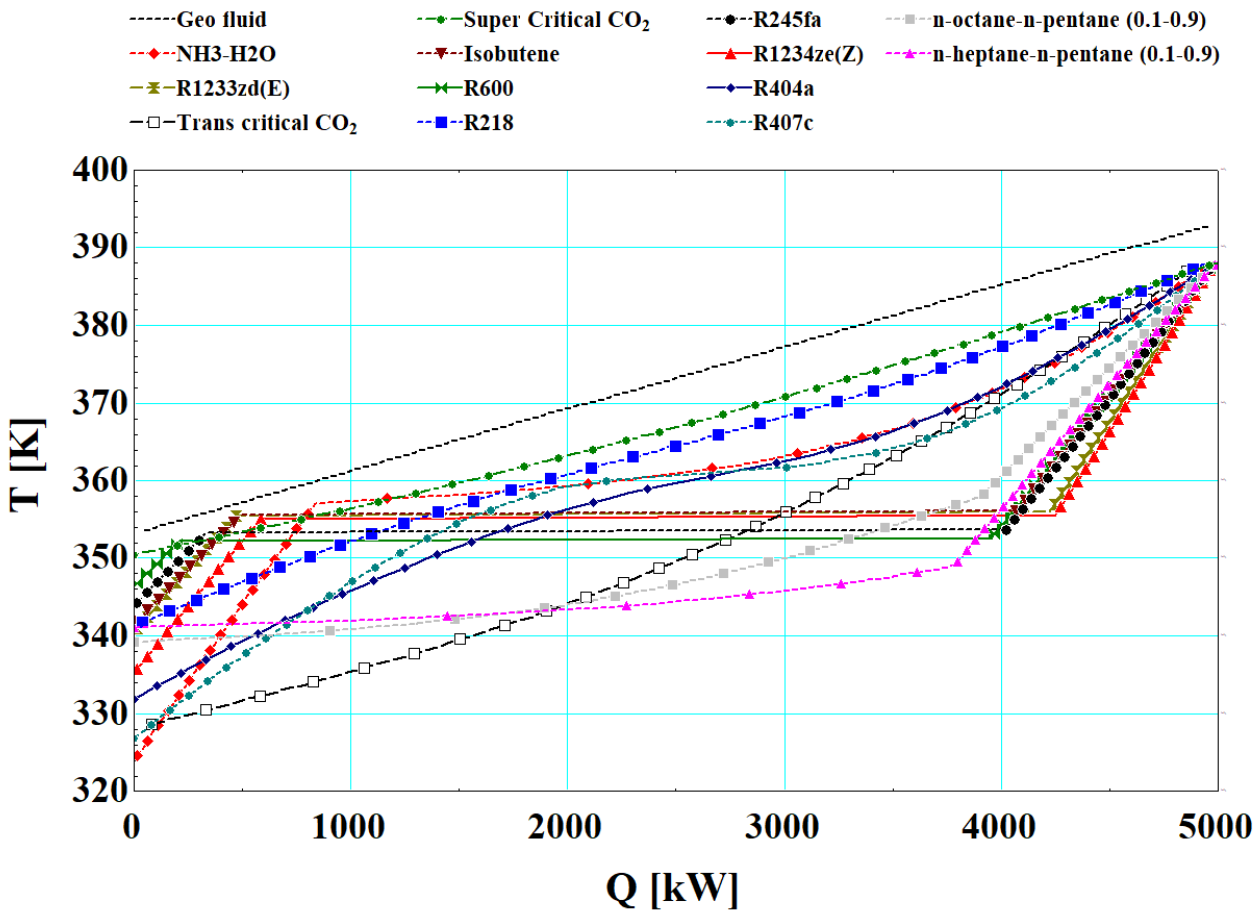
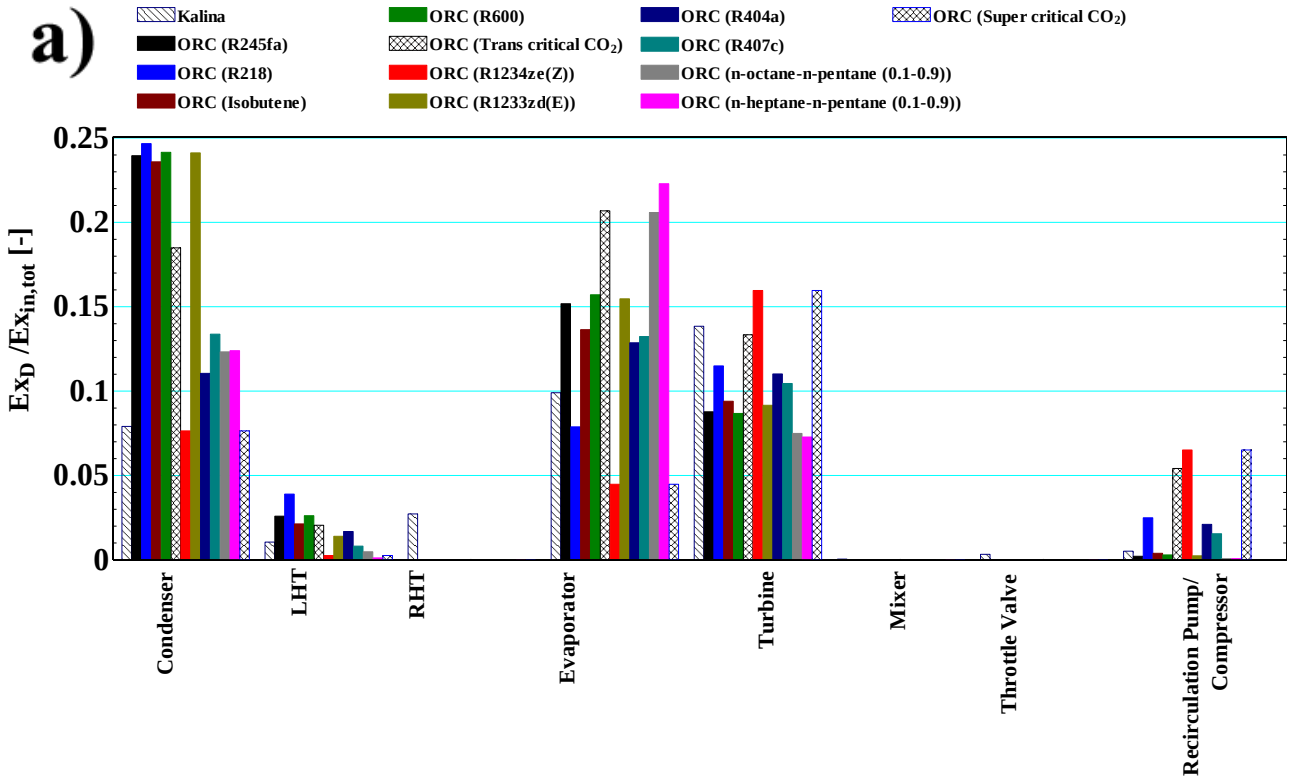


Figure 9 Thermal profiles comparison inside the evaporator, for the Pomarance case study. The dashed black line represents the cooling curve of the geothermal fluid

The main advantage of using a zeotropic mixture as working fluid is its variable phase change temperature, which allows low values of exergy destruction at the evaporator and, even more, at the condenser. It is clearly shown in figure 10a. In this case, this effect is dominant and, for this reason, the KC showed the best performance. The variable temperature phase change, both in vaporization and condensation, allows the achievement of a second law efficiency about 10 points higher than for the other ORCs (figure 10b). Compared to the ORCs, the overall exergy destruction of the KC case was reduced from 23 to 35%, as a result of the lower exergy destruction of the cycle components, with the only exception of the turbine, due to the higher enthalpy of the output flow. However, it is partially recovered in the low temperature recuperator (RLT, figure 1).



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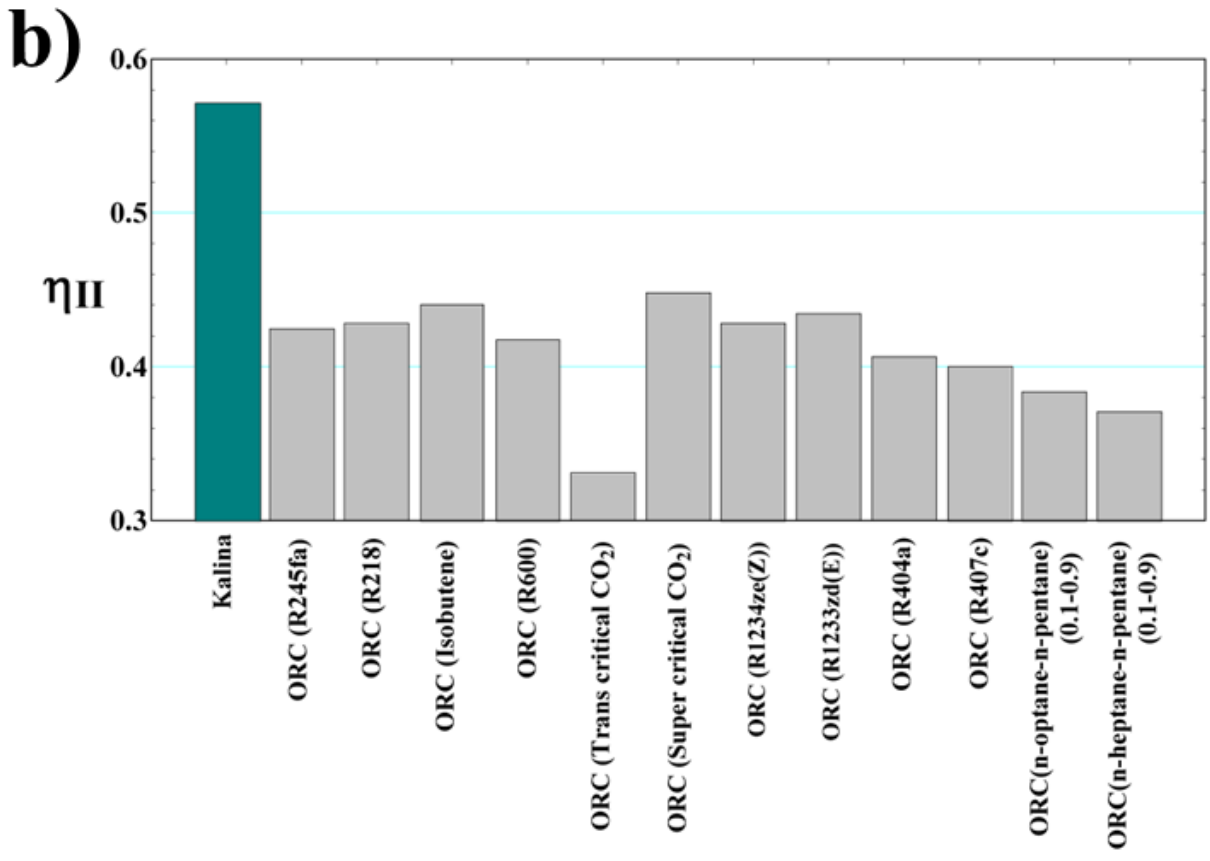

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365 **Figure 10**a) Comparison of components relative exergy destructions between KC and ORCs; b)Second law efficiency comparison between KC and

366 ORCs

367

3.3. Exergo-economic analysis: results

3.3.1.Mt. Amiata case study

The exergo-economic analysis allows the assessment of the cost of electricity generation of the proposed power cycles for the two different representative case studies in the Italian context. Currently, the average national electricity production cost in Italy from geothermal powerplants is about 9.5 c€/kWh in the range of 5 MW size and about 7.5 c€/kWh in the 20 MW size (AEEG, 2013).

In the here presented high temperature case study, the lowest electricity cost (8.85 c€/kWh) was achieved with the ORC with R1233zd(E) as working fluid. On the contrary, the highest electricity cost (12.90 c€/kWh) was calculated with the CO_2super critical cycle. Due to the well-matching of the heat transfer curves at the evaporator, the KC exhibited a moderate electricity cost (9.12 c€/kWh), in spite of the more complex power plant layout. Figure 11 summarizes the calculated electricity cost for all the analysed power cycles and working fluids: the KC showed values at the same level of the ORCs with the highest performing fluids.

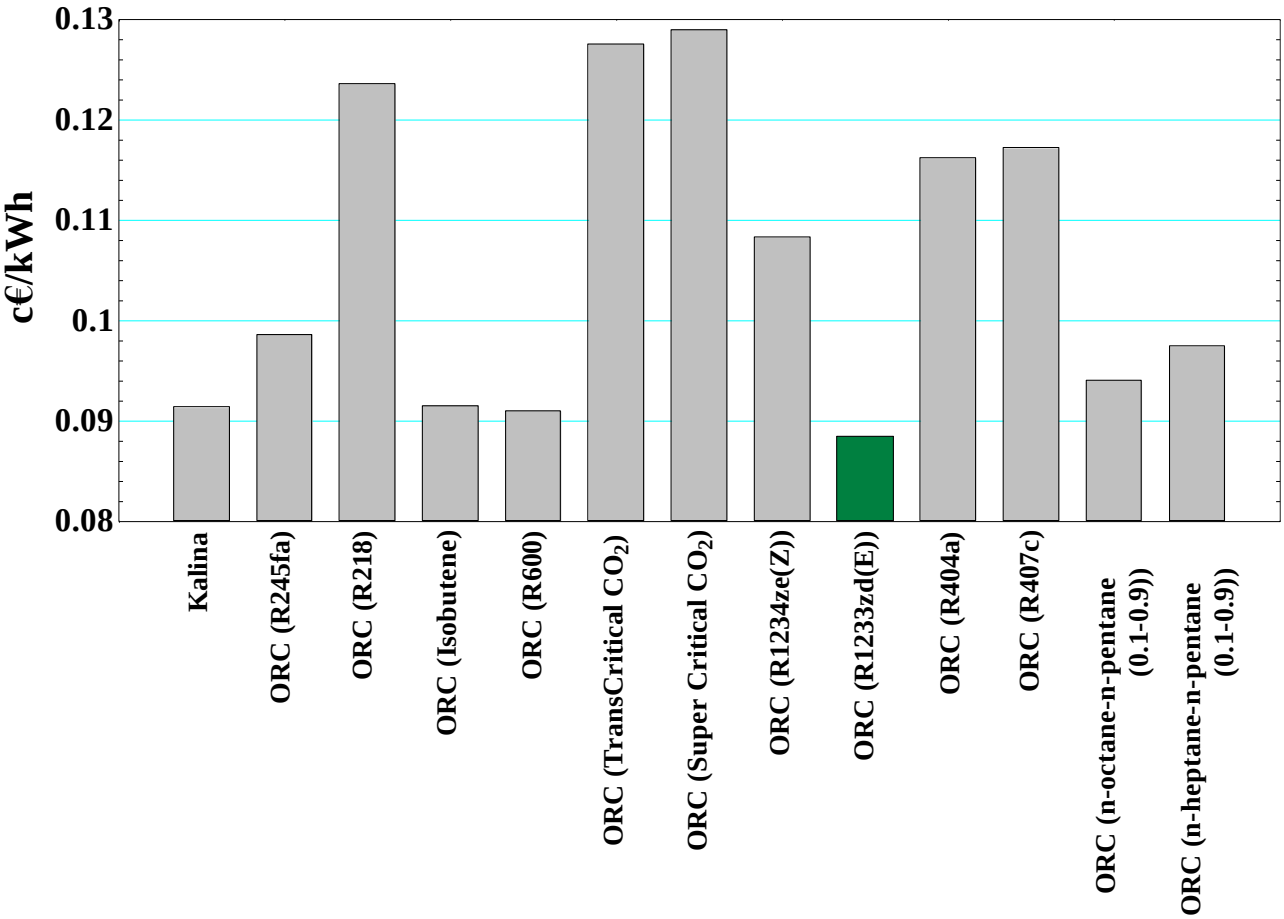

Figure 11 Comparison of electricity costs for the analysed power plants, Mt. Amiata case study.

3.3.2.Low temperature case study: Pomarance geothermal site

Figure 12 shows the results of the exergo-economic analysis for the Pomarance case study. The lowest electricity cost was achieved by the KC at12.53 c€/kWh. On the contrary, the trans criticalCO_2 cycle showed the highest electricity production costs (about 23 c€/kWh).On the whole, the total investment cost of KC resulted higher than R245fa, Isobutene, R600, R404a, R407c, R1234ze(Z) and R1233zd(E), n-octane/n-pentane and n-heptane/n-pentane ORCs by 8.96%, 9.65%, 4.22%, 3.96%, 10.65, 17.45%, 13%, 12.83% and 13.36%, respectively. Despite the higher capital investment cost, the higher power production due to the better cycle efficiency and the improved heat transfer matching at the boiler with the available geothermal resource (which brought to higher 2nd Law efficiency of the whole system) allowed the reduction of the electricity cost between 24% and 34%compared to the ORCs. This basically agrees with literature (Shokati, et. al., 2015), which addresses KC as one of the most economically viable solutions when dealing with low temperature resources, like Pomarance case study.

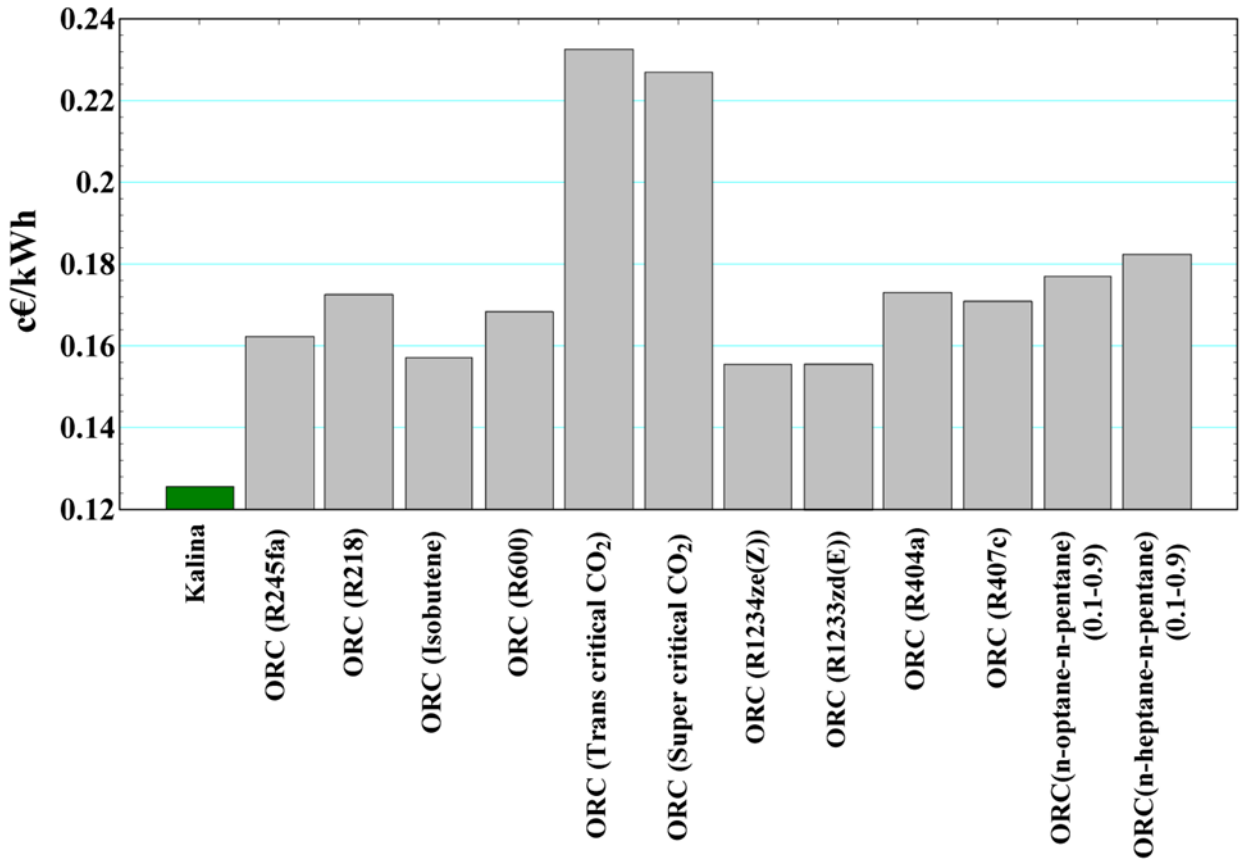

Figure 12 Comparison of electricity costs for the analysed power plants, Pomarance case study

4. Case studies results: comparison and conclusions

The main goal of this study was the comparison of KC and ORC binary cycles to exploit two different representative geothermal resources by the means of an exergo-economic approach.

The main results are summarized in table 6. Specifically, for the high-temperature resource case study (Mt. Amiata), the ORC with n-octane/n-pentane mixture (0.1-0-9 mass fraction) as working fluid shows the highest exergy efficiency (closely followed by the other hydrocarbon mixture and R1233zd(E)). In spite of the lower exergy destruction of the KC boiler, the higher number of components compared to the ORC leads, on the whole, to higher irreversibility and, consequently, to a lower second law efficiency. The higher number of components is also responsible for the larger investment cost of the power plant compared to the ORCs. Furthermore, the power output of the KC is lower than that of an ORC with R1233zd(E) and it holds the same figures of the hydrocarbon mixtures. For KC and R1233zd(E) working fluid, the turbine is the component with the highest exergy destruction. On the other hand, for the hydrocarbon mixtures, the evaporator was found to be the main responsible of the irreversibilities.

In the low temperature resource case study (Pomarance), the KC shows a notably higher efficiency than ORCs (from 22 to 40% depending on the fluid). Differently from the high temperature case study, the optimal ORC working fluid is R1234ze(Z), which anyhow shows lower performance levels compared to the KC. In particular, the power output of the ORC is far lower than that achieved with the KC, as well as the first and second law efficiency (by3 and 15 percentage points respectively). Differently from the high temperature case study, the higher number of components and thus of irreversibility sources for the KC is counterbalanced by their better performance, thus achieving, overall, lower electricity costs compared to ORCs. Like in the high temperature case, the most critical component of KC is the turbine. On the other hand, for the R1234ze(Z) cycle, the most critical components are the condenser and the evaporator. The reduced performance of the ORCs also entails an increase of the electricity cost by about 3 c€/kWh when compared to the KC.

Table 6Compariosn of results of Low- and High- temperature case

	Mt. Amiata case study (212°C)		**TLR Pomarance case study (120°C)**	
	KC	**ORC (R1233zd(E))**	**KC**	**ORC (R1234ze(Z))**
Power [kW]	5982	6237	645	483
First law efficiency	0.1684	0.1755	0.1289	0.0966
Second law efficiency	0.5731	0.5943	0.5709	0.4276

Critical component	Turbine	Turbine	Turbine	Condenser; Evaporator
TCI [k€]	8663	8483	2244	1852
Electricity cost	9.125	8.845	12.53	15.53

The achieved results confirmed that KC is a valuable solution as a binary cycle for the exploitation of low temperature geothermal resources, whereas in case of high temperature resources ORCs are preferable.

The most significant achieved results of the research are the costs of generated electricity by the adoption of binary power cycles from two deeply different geothermal resources:

- in the case of high temperature one, power plants in the 6 MW size range showed a cost of electricity production around 9 c€/kWh, with a modest 3% difference in favour of the best ORC over the KC;
- in the case of low temperature one, power plants in the 500 kW size range showed costs of electricity between 12 and 15c€/kWh, with a more remarkable difference of about 20% in favour of the KC over the best ORC.
- High thermodynamic performance were achieved with supercritical CO_2 cycle (which is a step ahead over the transcritical version) for the low temperature resource, and with hydrocarbon mixtures for the high temperature resource. However, when considering exergo-economics, their rank falls a bit down, especially for CO_2 cycles.

As a concluding remark, we can affirm that the exergo-economic analysis applied to the two case studies of high and low temperature geothermal resource showed competitive energy production costs of binary cycles in the field of medium size (5 – 6 MW, Mt. Amiata case) compared to the average national levels for geothermal resources. On the other hand, in the field of low 500 – 600 kW size, there are no real available data on energy production costs from geothermal resources. Anyhow, the achieved values of 12 – 15 c€/kWh make them competitive with those of other renewables in the same size range (*biogas and solid biomass* 17 – 25 c€/kWh, *landfill gas* 5 – 8 c€/kWh, *wind energy* 10 – 16 c€/kWh, *PV* 25 – 35 c€/kWh and *hydro*18 – 20 c€/kWh, (AEEG, 2013)).

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527

AppendixA

The Total Capital Investment (TCI) was evaluated from equation A.1 (Bejan, A., et al., 1996):

$$TCI = FCI + SUC + WC + LRD \quad \text{A.1}$$

Where:

- FCI = Fixed-Capital Investment
- SUC= StartUp Costs
- WC = Working Capital
- LRD = Costs of Licensing, Research and Development

FCI - Fixed-Capital Investment includes direct and indirect costs, which are needed to purchase and install the plant components, as well as the required infrastructure. Direct costs are composed by equipment, material and labour costs; indirect costs derive from the necessary operation for the completion of the powerplant, but will not become part of it.

The calculated direct costs, as suggested by (Lukawski, M., 2009), are listed below:

- Piping, assessed as 7% of PEC;
- Installation of equipment, which is composed by its transportation, insurance, labour, foundations, working fluid costs and all the other expenses related to a power plant construction. For small geothermal power plants, these costs are estimated to be 6% of PEC;
- Instrumentation, controls and electrical equipment, which are the electrical equipment costs; in case that the powerplant is near the electricity network, this value can be estimated to be 4% of PEC;
- Cost of Land –together with civil and structural work, are the "offsite cost"; this cost can be neglected if compared to the other costs;
- Civil and structural work – assessed as 7% of PEC.

The calculated indirect costs, still as suggested by (Lukawski, M., 2009), are listed below:

- Engineering and supervision – which is composed by planning and design of the plant costs, as well as supervision costs; this cost was estimated to be 6% of PEC;
- Construction: which is composed by temporary construction cost and contractor's profit; was assessed as 3% of PEC;

- Contingencies: include unexpected events that may occur during transportation or construction of the powerplant. The cost can range between 5% and 20% of FCI, depending on the complexity and peculiarity of the powerplant. The assessed case is a rather standard configuration; therefore the cost was estimated as 8% of FCI.

Other TCI costs include:

- Start Up costs (SUC) – assessed as 1% of FCI.
- Working capital (WC) – which is the capital invested to cover the operating expenses before financial return derived from the sale of electricity to the grid. It was assumed as 3% of PEC.

Geothermal power plants operation and maintenance costs are usually low when compared to the initial investment. They were estimated as 1.5% of the TCI, as suggested by (Schuster, A., et al. 2009).

In order to extend the validity of the economic analysis, it is necessary to take into account that money flows occurs at different time periods. Therefore, we actualized these cash flows at a specified year by the following classic relationship:

$$F = P(1 + i_{eff})^n \quad \text{A.2}$$

Where:

- P is the actualized value of money
- F is the money value after n years.

In order to determine the annual instalment of the TCI, a capital recovery factor, as suggested by Bejan (Bejan, A., et al. 1996), was adopted.

$$A = TCI * CRF = TCI * \frac{i_{eff} \cdot (1 + i_{eff})^n}{(1 + i_{eff})^n - 1} \quad \text{A.3}$$

Where:

- CRF – capital recovery factor
- i_{eff}–effective interest rate = 10%, as suggested by(Dorj, P., 2005)
- n –power plant lifespan = 20 years

The Total powerplant Cost is the sum between the annual instalment of the TCI and the Operation and Maintenance costs (O&M).

$$\text{Total Powerplant Cost} = \text{A} + \text{O\&}M = TCI * CRF + TCI * \ 0.015 \qquad \text{A.4}$$

577 Assuming the total operating time of the power plants at7446 h/year (Shokati, N., et al. 2015), for each k-th component,
578 the capital investment was determined.

$$\dot{\text{Z}}_{\text{k}}[€/\text{s}] = \frac{(\text{Total Plant Cost}) * \text{PEC}_{\text{k}}}{\text{PEC}_{\text{totale}} * 7446 * 3600} \qquad \text{A.5}$$

579 The powerplant components exergy destruction cost is defined as the inlet flux cots times the component exergy
580 destruction.

$$\dot{\text{Cost}}_{\text{dis}_{\text{k}}}[€/\text{s}] = \text{cost}_{\text{fuel}_{\text{k}}} * \dot{\text{Ex}}_{\text{dis}_{\text{k}}} \qquad \text{A.6}$$

581 The Total Capital Investment per installed kW was thus defined.

$$\text{TCI}_{\text{kW}}[\frac{€}{\text{kW}}] = \frac{\text{TCI}}{\text{W}_{\text{t}}} \qquad \text{A.7}$$

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