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Energy, Exergy and Exergo-economic analyses of supercritical CO_2 cycles for the exploitation of a geothermal resource in the Mt. Amiata region

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Abstract:

An alternative powerplant layout to the commonly applied flash technology is proposed for the geothermal location of Monte Amiata, Italy. The reservoir conditions correspond to a pressurized brine field, with relevant contents of CO_2, acid gases/contaminants, and dissolved salts. The present solution avoids flashing the brine stream, proposing instead to install a borehole pump capable of maintaining pressurized conditions. By applying this solution, the amount of non-condensable gases released when reaching the ground level with reduced pressure can be conveniently limited; the gas stream is recovered, compressed and reduced in liquid conditions, suitable for complete reinjection into the reservoir. The necessity of a gas treatment section is thus completely avoided. The heat recovered from the hot brine, placed at ground level, is transferred to the supercritical CO_2 cycle. Different CO_2 cycle configurations were considered. Exergy and exergo-economic analyses of the whole system are carried out. The optimal calculated exergy efficiency of 45.5% was achieved for the recuperative cycle with intercooling and reheat configuration and the lowest obtained produced cost of electricity was 7.4 c€/kWh for the recuperative cycle configuration. Furthermore, the influence of the pressure losses to the heat exchanger has been assessed, allowing evaluating of the loss in efficiency for each cycle.

Keywords:

Geothermal energy; binary cycle; sCO2; Exergo Economic; Electricity production cost

1. Introduction

The energy demand has increased exponentially in recent years due to the strong increase in economic development and population growth. This led to an increased concern on sustainability issues and environmental deterioration [1]. The exploitation of renewable energy technologies has therefore bloomed, allowing an increase in the efficiency of the conversion systems. Among renewables, geothermal energy has the advantage of having the highest resource availability, not depending on the weather conditions. Geothermal energy systems exploit the heat content of the earth's interior, as the earth is slowly cooling down. The total global output of the Earth's heat flow is over $4x10^{13}$ W [2], which is four times higher than the actual energy consumption; however, only a small part of this heat flux can be exploited. Geothermal power plants can be categorized in shallow geothermal and deep geothermal. The first exploits low temperature heat sources at the surface, with a maximum of well drilling in the range of 250 m and are suitable for low temperature heat generation. On the other hand, deep geothermal is considered when wells are drilled deep, from 1 to 5 km within the Earth, or even deeper with the newest drilling technologies. Deep geothermal allows reaching higher temperature, which enables the conversion of the geothermal heat in electricity. Another way to categorize geothermal power plant is to classify it on the enthalpy content of the flow: low, medium or high enthalpy. Medium and high enthalpy resources are the most common exploited and have almost reached its maximum potential, while low or moderate enthalpy fields are still yet to be fully utilized. Typical power plant for the exploitation of medium high temperature fields are single, double and triple flash power plants (for a water dominant reservoirs) and direct steam power plants (for vapor dominant reservoirs). These power plants have several advantages, such as relatively high conversion efficiencies, several years of operation which led to a solid know-how, well-known safety measures which are not critical thanks to low pressure and temperatures involved, and economic feasibility. On the other hand, they present a significant disadvantage when considering the environmental sustainability; indeed, a relevant documented issue is the release of non-condensable gases NCGs (mainly CO_2 plus several kind of contaminants) to the environment [3, 4]. The current solution to reduce the environmental impact of geothermal power plant is the utilization of AMIS

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technology in Italy, developed by ENEL GP [5]. This allows reducing the Hg and SO_2 content from the NCGs stream, and thus the environmental impact of the power plants. Several studies have been developed on the environmental sustainability of geothermal energy conversion systems though the application of life cycle assessment [6]. In [8] a 20 MW single flash power plant is evaluated and compared with similar size power plants operating with wind and solar. It was found that the geothermal power plant, which includes the AMIS technology, performs well against other renewables, and has only a slightly higher environmental footprint, due to larger values of the global warming category (Recipe 2016 Midpoint). In [9] enhanced geothermal systems (EGS) were considered, estimating several design scenarios and compared to other renewable energies environmental impacts. The results indicated that EGS power plant environmental footprint is in the same range of other renewables and it was confirmed that the highest contribution to the environmental impact comes from the drilling of the wells, in particular by the diesel burned in the drilling process. In [10], the environmental impact of a combined heat and power double flash geothermal power plant was estimated. Their studies confirmed that the drilling process is the main responsible for most of the impact category results. However, it was also found that the global warming and acidification category are significantly affected by the operation phase. Indeed, during the operational lifetime of the power plant, continuous emissions of CO_2 and H_2S provide a significant environmental impact. In [11] the definition of harmonized LCA guidelines for the comparison of geothermal power plant have been drought. Particularly, the aim of their study was to increase the comparability of the results of LCA studies on geothermal system, by proposing a consistent methodology with several indications of the critical aspects of the analysis.

From the above mentioned studies, it seems that only the use of binary cycles (like ORCs, Kalina or trans-critical and super critical CO_2) coupled to the complete reinjection of NCGs could give a valuable answer to the improvement of sustainability of geothermal power plants, particularly in the operational phase [12]. ORC and Kalina cycles work with novel and environmentally friendly fluids (low GWP), which are adapt for the exploitation of low temperature resources. Several studies on the coupling of ORC or Kalina cycles with low temperature or medium-high temperature [13-17] geothermal resources have been performed. These studies involved the optimal selection of the working fluid [18], including zeotropic mixtures [19], the optimal configuration of the power plant [20, 21], as well as thermo-economic analysis [22]. In [23] an energy and exergy analysis is carried out for a dual fluid ORC. Isobutane and Isopentane were selected as working fluids, allowing a production of almost 3.5 MW of electricity, almost equally shared between the high temperature isopentane cycle and the low temperature isobutane cycle. The most critical components for this power cycle configuration were found to be the low and high pressure vapor generators, due to the not optimal match of the heat curves. An interesting study on the profitability of geothermal electricity production from several ORC configurations have been carried out in [24]. In their study, an optimization of cycle configurations, working fluid selection and thermodynamic conditions was carried out in order to investigate the most performing configuration, based on levelized cost of electricity, return of investment and payback period. They performed the analysis taking into account for the economic calculation the corporate tax rates and the average electricity prices of 20 countries and found that is the country with the highest return of investment due to the high electricity price. A focus on the design and optimization of the evaporator for ORCs for low temperature geothermal application has been developed in [25]. In their study a Pareto front solution has been found in order to assess the proper compromise between costs and pressure drop in the heat exchanger; finally evaluating the performance of the ORC.

While several studies on ORC and Kalina cycle for geothermal applications have been developed, on the other hand, few studies on the coupling of super critical CO_2 cycles with geothermal energy resources have been carried out. In [26] a trans critical power cycle for low temperature geothermal power plants has been investigated, with a particular focus of the influence of the recuperator performance in both design and off-design operation. It was found that the recuperator allows an improvement in the off-design performance of the system, particularly enhancing the performance of the CO_2 pump.

In [27], an innovative supercritical CO_2 cycle configuration was evaluated, and its performance compared to a ORC working with R245fa or R1233zd(E). The cycle configuration exploits the thermosiphon concept, therefore utilizing the CO2 both as heat medium in the reservoir and as the working fluid in the power cycle. The results obtained indicated that the ORC cycle with R245fa as working fluid allowed the highest power production for one year of operation (8% more than the sCO_2 thermosiphon cycle). In [28] a low temperature geothermal case study, the Sidirokastron field in Greece was studied with the objective of coupling a super critical CO2 power plant. Particularly, the maximum temperature achieved by the geothermal fluid is of 75°C, which is a very low value, hindering the thermodynamic efficiency. In these conditions, the sCO_2 cycle achieved a maximum thermal efficiency of over 6%. Another interesting study by [29] deals with the thermodynamic analysis of a low temperature geothermal power plant utilizing a mixture of SF_6 and CO_2 as working fluid. The maximum achieved efficiency of the binary geothermal cycles was found to be 15% with a 20% SF_6-80% CO_2 composition, with a resource temperature of 160°C. The results therefore indicated that the utilization of zeotropic CO_2 mixtures could allow to increase the thermal efficiency of the sCO_2 power plants for geothermal applications.

While few studies were focused on the coupling of super critical CO_2 cycles with low temperature geothermal application, on the other hand several studies are available in literature dealing with high temperature applications, like solar power generation [30], coal fired power plants [31] or waste heat recovery [32,33]. This is due to the very good behaviour of the CO_2 for high temperature applications, nonetheless, it seems that further studies are needed to provide a clear assessment on the application of CO_2 cycle to low temperature resource. Indeed, the selection of CO_2 as working fluid is a due to its main characteristics, such as non-toxic, non-flammable, not suffering any thermal degradation at high temperature (unlike ORCs fluids) and optimal environmental traits, with a nil ODP and a GWP of 1. Furthermore, in the supercritical region, the high density of the CO_2 allows a smaller and more compact design of the components, which could allow a "miniaturize" design of geothermal power plants. Finally, for variable temperature heat source, super critical CO_2 allow a better match of the profiles, guaranteeing a higher efficiency of the heat exchange and thus reducing the exergy destructions in the heat exchanger.

1.1. A Case study for a sustainable Geothermal Energy power plant (Mount Amiata, Italy)

The properties of the geothermal resource are variable depending on the location in terms of pressure, temperature, state of the fluid, and amount and composition of NCGs as well as of dissolved mineral salts. The nature of contaminants released by GECS usually includes H_2S, NH_3, CH_4, and in some cases Hg [34 – 36]. Each potential location deserves careful study, possibly leading to different issues when selecting the best available technology.

The area of Mount Amiata, Italy, represents a significant challenging application. This region of Southern Tuscany is historically one of the reference sites for the development of geothermal conversion systems; currently, about 120 MW of geothermal electricity are installed there. The Amiata reservoir is water-dominant type [37]; the current conversion technology applies single or double-flash power plant layouts, in one case also combined to an ORC to recover the energy content in brines. The composition of the geofluid includes relevant amounts of NCGs (CO_2, H_2S, NH_3, CH_4), mercury sulphide, HgS and dissolved salts (mainly stibnite and silica salts). The reservoir is located at 3000–3500 m depth, thereby determining supercritical pressure conditions ($p > 250$ bar); however, the fluid is not in critical conditions, since the reservoir temperature is in the 300–350 °C range. Consequently, flashing in the well takes place at a depth between 600 and 1500 m, with two-phase flow in the upper section. In the current technology, a throttling valve/separator assembly is located at the wellhead [38, 39]. Despite the attractiveness of the region in terms of energy generation potential, local opposition is present in the area against further development of geothermal energy. The main concerns of the opponents are long-term sanitary effects (mainly traceable to Hg and H_2S emissions, even after the introduction of catalytic gas treatment [5]), as well as the water balance and the greenhouse gas emissions. Within this context, even if the resource can be classified as high-enthalpy and therefore traditionally converted using flash power plant solutions, it makes sense to explore different possible options, investigating the potential to mitigate these specific issues.

1.2. Reference case

As a specific reference case, the available data from the Bagnore 3 power plant were considered. A flow rate of 122 kg/s is assumed to be available at an enthalpy level of 1200 kJ/kg, corresponding to about 275 °C at 250 bar, which are the estimated reservoir conditions for the deep reservoir in the Mt. Amiata region at a depth $z > 3000$ m. The CO_2 content of the brine is evaluated at 2% mass fraction [40]. The current power plant applies a wellhead separator set at 20 bar, determining a saturated steam flow rate of 36 kg/s (with 7% CO_2 content), while a hot brine (enriched with salts causing considerable scaling problems) of about 86 kg/s is directed to reinjection. The power plant is a single-flash unit equipped with an ORC recovery section on a secondary (low-pressure) flash of the brine, providing a total power output of about 23 MWe (actually, at present 3 MWe less because a smaller ORC unit is installed, with incomplete heat recovery from the reinjection brine). The separator setting determines the flash conditions inside the well, which take place at a depth of about 600 m. The considerable amount of CO_2 in the flash steam is accompanied by minor contaminants (H_2S, Hg and NH_3 with minor traces of CH_4); while the steam is condensed in the steam cycle, the NCGs are discharged to the atmosphere; however, before the final release, the emissions treatment is applied, with extensive capture of H_2S, Hg and NH_3. The following emissions levels were calculated: $e_{CO2} = 396$ g/kWh; $e_{H2S} = 1.21$ g/kWh; $e_{Hg} = 1.3$ g/kWh; these figures correspond to measurements taken by the pollution control authority. It should be underlined that the CO_2 emissions are of natural origin; however, they are of similar level to those obtained by the most advanced fossil fuel power plants and could be avoided if the resource was not extracted from the reservoir.

For the above reasons, a number of improved solutions were developed, leading finally to identifying guideline the complete reinjection of NCGs in the reservoir as a possible best practice to exploit this geothermal resource [40].

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To summarize, the literature review and the analysis of the presented case study has indicated a significant gap in the study of supercritical CO_2 cycle for the exploitation of geothermal resources.

Specifically, in the present study a relatively simple solution is proposed, inspired by the guideline of completely avoiding the practice of flashing the geothermal stream by the means of a borehole pump located at suitable depth, coupled to an advanced (supercritical) binary cycle.

The aim of this study is therefore to **evaluate the energy, exergy and economic performance** of the proposed advanced CO_2 power plant, which guarantee a relevant step ahead in the environmental behaviour of the geothermal powerplants, but they could result into a not economically viable options if compared to the current single and double flash technologies.

The main goal of this study is, therefore, the investigation and comparison of optimized solutions adopting supercritical CO_2 cycles configurations to the selected case study, in order to assess the *most suitable ones to compete with the current single flash +ORC power plant,* either from thermodynamic and exergo-economic points of view. Figure 1 presents the schematic of the current power plant and table 1 summarizes its main performance parameters.

Table 1. Bagnore 3 single flash + ORC power plant performance parameters

Parameter	**Value**
First Law efficiency η	0.19
Second Law efficiency η_{II}	0.46
Net power output W_{net}	20
Cost of energy €/kWh	0.04

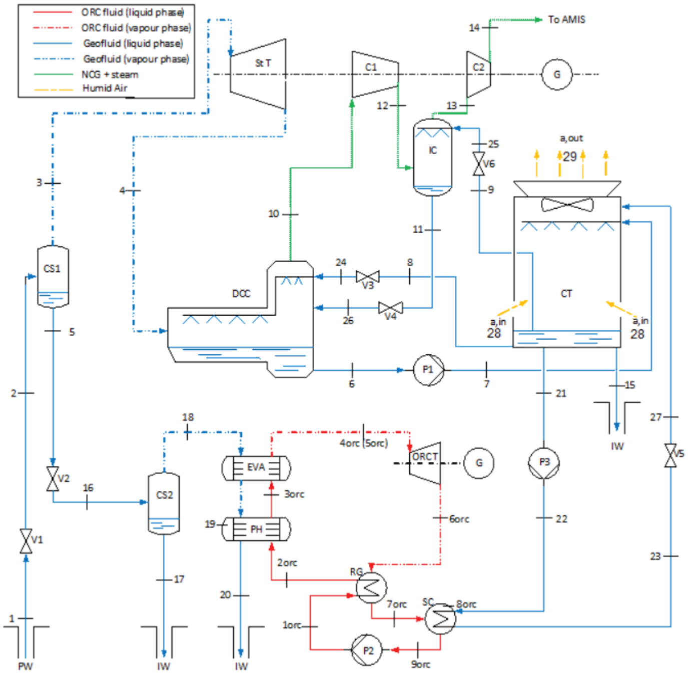

Figure 1. Schematic of Bagnore 3 power plant [40]

2. Methodology

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 located inside the well at 800 m depth from the ground level 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. 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. A guideline applied in this research is to maintain the geothermal fluid under pressurized liquid conditions: this includes the modelling of the well thermo-fluid dynamics and of the borehole pump. A model was thus developed in EES [41] in order to calculate the heat transfer and pressure losses, while the fluid (geothermal brine in liquid conditions) is ascending the well duct. A steel cladding is included only in the first 500 m from the surface. Once the geometry is fixed, the head losses, which must be overcome by the borehole pump in order to maintain the geothermal fluid in liquid phase were calculated; the same was done for the heat losses. The Colebrook formula for the calculation of the friction factor was utilized. The temperature of the ground is assumed to vary linearly with a gradient of 50°C per km of depth, from the starting value of the ambient temperature of 285 K.

Table 2 and Figure 2 show the main thermodynamic and performance parameters and the configuration of the borehole pump respectively.

Table 2. Main borehole pump parameters

Parameter	**Value**
η	0.8
$\mathbf{W_{bp}}$	0.87 [MW]
$\mathbf{T_{inBH}}$	273 [C]
$\mathbf{P_{inBH}}$	5758 [kPa]
$\mathbf{T_{outBH}}$	274.6 [C]
$\mathbf{P_{outBH}}$	10258 [kPa]

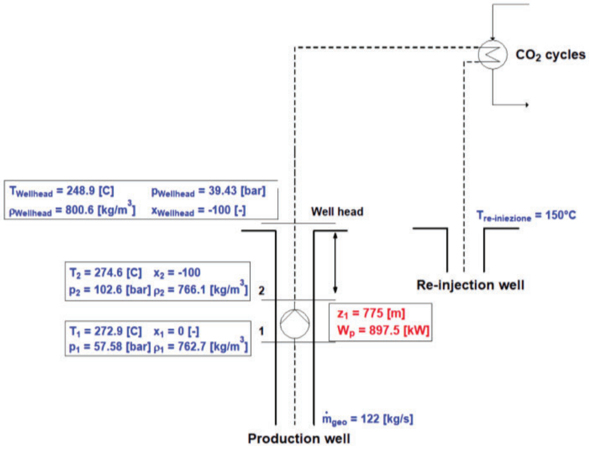

Figure 2 Borehole Pump schematic

2.1. Power plants schematic

In these work several power plant configurations were considered in order to evaluate the optimal power plant layout to be applied to the investigated medium temperature geothermal resource. Clearly, it is general for many different aspects, so that it may be representative of many other cases of exploitation of medium – high temperature geothermal resource with trans and supercritical CO2 binary cycles. Figure 3 shows the analysed configurations and figure 4 represents the corresponding temperature-entropy diagrams. Particularly, the assessed configurations comprehend a recuperative cycle, a recuperative cycle with reheating, a recuperative cycle with reheating and intercooling, a precompression cycle, a recompression cycle with two recuperation and a recompression cycle with one recuperator.

For each developed power plant, it was assumed that: (i) the cycles work in steady state conditions; (ii) the geothermal fluid is modelled as pure water; (iii) the difference in kinetic and potential energy between the input and output of turbomachines and heat exchangers is ne-glected; (iv) the isentropic efficiency of turbomachines is fixed.

The real fluids thermodynamic properties were evaluated from EES internal libraries [41].

For each component, mass end energy balance equations were applied, as displayed in Eqns. (1)-(2).

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \qquad (1) \qquad \dot{W} + \dot{Q} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \qquad (2)$$

The first law efficiency was then defined, as shown Eq. (3).

$$\eta_I = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \qquad (3)$$

2.2. Exergy and exergo-economic analysis

Exergy is the ability of a system, a flow of matter or an energy interaction (such as heat, work or potential energy) to produce work as a result of interaction with the environment. For a completely reversible system, the maximum obtainable work is equal to the total exergy of the initial thermodynamic state.

Exergy is, therefore, the combination of the First and Second Laws of Thermodynamic, which allow to properly assess the energy efficiency of a system and to correctly identified the associated irreversibilities [42].

Exergy analysis is considered as one of the most robust method for the design and assessment of energy systems [43]. Indeed, the concept of exergy allows to estimate the effective thermodynamic values of energy flows. In the present work, the exergy is calculated at each point of the system by Eq (4).

$$\dot{Ex}_j = \dot{m}_j[(h_j - h_o) - T_o(s_j - s_o)] \qquad (4)$$

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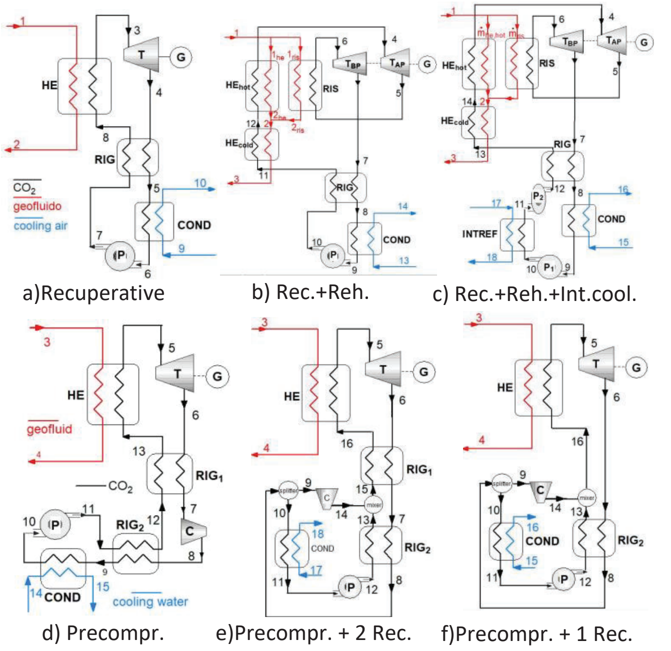
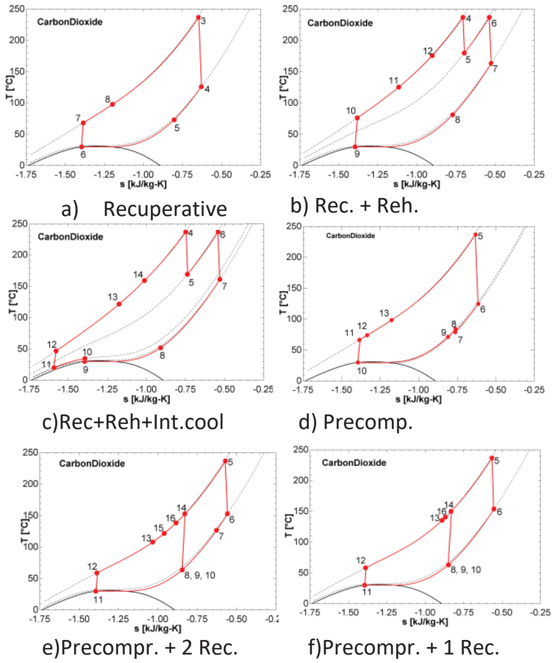


a)Recuperative b) Rec.+Reh. c) Rec.+Reh.+Int.cool.

d) Precompr. e)Precompr. + 2 Rec. f)Precompr. + 1 Rec.

Figure 3 Schematic of super critical cycles



a) Recuperative b) Rec. + Reh.

c)Rec+Reh+Int.cool d) Precomp.

e)Precompr. + 2 Rec. f)Precompr. + 1 Rec.

Figure 4 T-s diagram of super critical cycles

Combining the economic and exergy analysis (e.g. exergo-economic methodology) allows providing an efficient evaluation of the power plant and components cost-effectiveness, by introducing the costs per exergy unit [44]. The exergo-economic approach outlined in [45] was applied in this work by defining, for each component k, a cost balance equation, expressed in the following equations (5).

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k$$

$$c_{P,k}\,\dot{E}x_{P,k} = c_{F,k}\,\dot{E}x_{F,k} + \dot{Z}_k \qquad (5)$$

Where:

$\dot{C}_{P,k}$ and $\dot{C}_{F,k}$ are the cost rates associated with exergy products and fuels respectively

$c_{P,k}$ and $c_{F,k}$ are the costs per unit of exergy of product or fuel respectively.

$\dot{Z}_k$is the sum of cost rates associated with investments and O&M for the k-th component.

In order to determine the investment and O&M costs ($\dot{Z}^{CI}_{tot} + \dot{Z}^{OM}_{tot}$) of the two proposed power plants, an economic analysis was carried out. The cost functions applicable to the system components were obtained from [46, 16]. Costs were actualized to 2019 values, by using the CEPCI indexes [47]. The Operation and Maintenance costs (O&M) of each component were determined following the best practises in literature [48, 16].

Finally, Table 2 summarizes the exergo-economic balances and the auxiliary equations [44], which are logic statements that allow defining the missing number of conditions to solve the cost equations applied to each component for the recuperative cycle.

Table 2. Exergo-economic balance equations of power plant components for the recuperative configuration

	Recuperative
Borehole pump	$c_{21}\cdot\dot{E}x_{21} = c_{20}\cdot\dot{E}x_{20} + c_{Wp_{kJ}}\cdot\dot{W}_{BHpump} + \dot{Z}_1 \qquad c_{Wp_{kJ}} = c_{Wt_{kJ}} \qquad c_{20} = c_{fuel_{kJ}}$
Condenser	$c_6\cdot\dot{E}x_6 + c_{10}\cdot\dot{E}x_{10} = c_5\cdot\dot{E}x_5 + c_9\cdot\dot{E}x_9 + \dot{Z}_2 \qquad c_9 = 0 \qquad c_{10} = c_9$
Recuperator	$c_8\cdot\dot{E}x_8 + c_5\cdot\dot{E}x_5 = c_7\cdot\dot{E}x_7 + c_4\cdot\dot{E}x_4 + \dot{Z}_3 \qquad c_4 = c_5$
Heater$_{geo}$	$c_2 * \dot{E}x_2 + c_3 * \dot{E}x_3 = c_1 * \dot{E}x_1 + c_8 * \dot{E}x_8 + \dot{Z}_4 \qquad c_1 = c_{21} * \frac{\dot{E}x_{21}}{\dot{E}x_1} \qquad c_1 = c_2$
Turbine	$c_{Wt_{kJ}}\cdot\dot{W}_T + c_4\cdot\dot{E}x_4 = c_3\cdot\dot{E}x_3 + \dot{Z}_5 \qquad c_4 = c_3$
Compressor	$c_7\cdot\dot{E}x_7 = c_6\cdot\dot{E}x_6 + c_{Wp_{kJ}}\cdot\dot{W}_{pump} + \dot{Z}_6$

3. Results

3.1. Power Cycles Optimization

The main parameters influencing the cycles efficiency are the maximum pressure and temperature. Specifically, a very wide range of maximum cycle pressures was investigated, with a wider range for the recuperative cycle with reheating and intercooling, in order to assess the optimal configuration of the power plants. On the other hand, the maximum temperature of the cycle was defined by the geothermal source at 249 °C, therefore the ΔT approach was varied in order to investigate its influence on both efficiency and cost.

Figure 5 shows the behaviour of the first law efficiency and unit electricity exergo-economic cost at variable maximum pressure (a and b) and ΔT approach (c and d) of the investigated power cycles configurations reported in figures 3 and 4. The figures clearly show that the recuperative configuration with reheating and intercooling is the highest efficiency one, followed by the recuperative and reheating configuration. For all the proposed cycles, an optimizing efficiency range of maximum pressure exists. It is essentially due to the variable shape of the cycles at different p_{max}, which is rather remarkable in the range of 15000 to 30000 kPa. On the other hand, the First Law efficiency and unit energy cost are less sensitive to ΔT approach, with the costs monotonically decreasing with increasing ΔT, due to the dominant effect of heat exchanger cost on the slightly improved performance at low ΔT. The efficiency of the cycles also shows a slight optimization at ΔT in the 3 to 8 degrees, because of the increase of the compressors work for very low ΔT approach due to the increase of the exchange area (and therefore of the pressure losses) of the heat exchanger.

Conversely to the efficiency behavior, the lowest exergo-economic cost is achieved from the less efficient configuration which, however, is also the simplest one, namely the recuperative layout. This was expectable, as the other configurations allow indeed improved performance, but not so high to counterbalance the increased costs due to the additional required equipment. This is more remarkable for the recompression configurations, allowing a modest increase of efficiency at the price of much larger exergo-economic costs. Another interesting feature of the recompression configurations, is their optimal efficiency at lower maximum pressures, while the recuperative and the precompression layouts require higher maximum pressure in order to achieve high cycle efficiencies and low exergo-economic costs.

The performance data of the optimized power cycles are summarized in table 4. The considered configuration allows a 249°C geothermal fluid temperature at the inlet of the main HE, also considering the temperature increase given by the pumping process. The geothermal fluid is re-injected at 150°C in order to avoid the precipitation of stibnite while guaranteeing, at the same time, a correct management of the geothermal field. The best performing thermodynamic cycle is the recuperative with reheating and intercooling, which achieves an efficiency, even including the pumping power from the borehole pump and the heat losses of the ascending geothermal fluid in the well close to that of the currently installed single flash unit (19%). However, the maximum achievable power is much lower than the reference case, with a dramatic 40% reduction in power output. Indeed, all the configurations loose an amount of power output between 40 and 50% when compared to the traditional flash solutions.

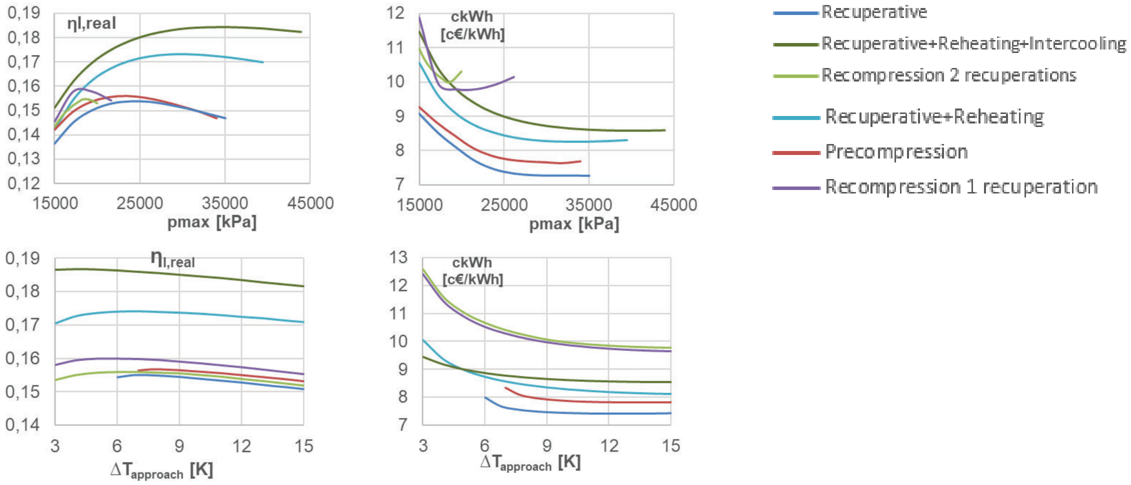


Figure 5 Efficiency and produced energy unit cost as a function of max pressure and $\Delta T_{approach}$ with geothermal fluid

The largest gross power production was achieved with the recompression cycles. However, these layouts have the main drawback of requiring the highest compressor power, exceeding 12 MW, which is almost double than all the other configurations. These ones, however, guarantee the lowest maximum pressure of the cycle at 18.9 and 18.6 [MPa] respectively, for the configurations 1 and 2 with recuperation.

Finally, the recuperative cycle is the one generating the lowest amount of power, and therefore it is also the less efficient one. It should be remarked that the considered overall power plant efficiency takes into account the heat losses in the ascending well pipe. If the analysis was carried out from the well-head input, the overall efficiency would be closer to the cycle efficiency, and therefore higher than the reference case with flash.

Table 4 Performance comparison of each supercritical CO_2 cycle configuration

Performance Parameter	**Recuperative**	**Recuperative with reheating**	**Recuperative with reheating and intercooling**	**Precompression**	**Recompression with 2 recuperations**	**Recompression with 1 recuperation**
Turbines [kW]	17605	20053	20151	18138	23339	23926
Compressors [kW]	6401	7545	6887.9	6784.7	12048	12371
Borehole pump [kW]	873.2	873.2	873.2	873.2	873.2	873.2
Net Power [kW]	10331	11635	12390	10480	10418	10682
Maximum Pressure [kPa]	24931	30661	35171	23670	18976	18611
CO_2 Cycle Efficiency [-]	0.2162	0.2414	0.2559	0.2191	0.2179	0.223
Global Power Plant Efficiency [-]	**0.1539**	**0.1733**	**0.1845**	**0.1561**	**0.1552**	**0.1591**

3.2. Exergy analysis: results

Figure 6 shows the non-dimensional exergy destruction and losses of each components of the power cycles. The exergy input from the geothermal resource, was fixed at the same value for each thermodynamic cycle. As it is evident from figure 6a, the highest exergy loss comes from the production well (29%). Indeed, this loss is common to all the considered cycles and cannot be avoided. On the other hand, the exergy losses at the condenser to the environment, are not the main contributors to the inefficiency of the cycles, as they are in the range of 2%. These levels of losses are clearly related to the largely different exergy value of the two heat losses.

The source of highest exergy destruction is differently located for the considered cycles: for example, in the recuperative and precompression cycles the highest values belong to the main heater (HE). Furthermore, the exergy destructions in the condenser represent the second main contributor to the inefficiency of the cycles, with values higher than 7.5% for all the configurations except the recuperative one with reheat and intercooling, as it allows a further heat recuperation from the exhaust stream of the turbine.

From the sum of the exergy destructions, it is possible to address the best and worst performing power cycles configurations. The highest exergy efficiency (45.4%) belongs to the recuperative cycle with reheat and intercooling, as clearly shown on figure 6b. As clear from the comparison of the exergy destruction sources in the different cycles, this is mainly due to the lower values found in the heaters and the condenser. Moreover, the good coupling of the fluids heat capacities (water and CO_2) allows achieving a satisfactory value of exergy efficiency in the main HE for this power plant layout. On the contrary, for the same reason (e.g. the weak coupling of heat capacities in the main HE) the recuperative cycle configuration shows the lowest overall value of exergy efficiency.

3.3. Exergo-economic analysis: results

The cost of electricity generation for the proposed power plant configuration can be obtained from an exergo-economic assessment. The levelized cost of electricity for geothermal power plants project installed (or in progress) between 2007 and 2021 varies depending on technology and size. Particularly, for binary cycle configuration the cost of electricity varies between 4 c€/kWh for very big power plants (>300 MW), to values close to 14 c€/kWh for power plants with a nominal capacity of 1 MW. The mean range value of electricity production from geothermal power plants is between 6 and 10 c€/kWh [49].

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In the here presented power plant case studies, the range of installed power is between 10 and 15 MW. These lead to a relatively high cost of electricity for some of the investigated configurations (recompression), but still very close or in line with the expected electricity production values. Particularly, the lowest electricity cost (7.42 c€/kWh) was achieved with the recuperative configuration. On the contrary, the highest electricity cost (9.98 c€/kWh) was obtained for the recompression cycle layout with one recuperation level. The configuration achieving the highest efficiency (recuperative with reheating and intercooling) achieves electricity production at 8.6 €/kWh, which is a proper value for this power range. However, if we compare the obtained electricity costs with the reference power plant (Bagnore 3, single flash + ORC), the costs are doubled and the power produced is lower. This kind of power plants can be nonetheless attractive, as they can achieve an almost zero environmental impact configuration during the operation phase. Figure 7 summarizes the calculated electricity cost for all the analysed power cycles.

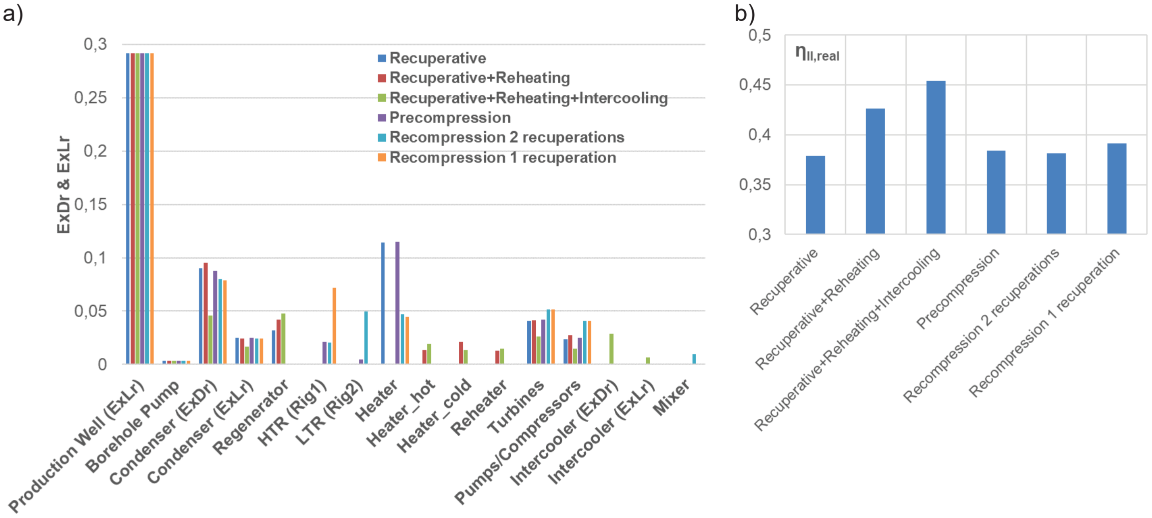

Figure 6 a) comparison of components exergy destruction of the different configurations overall; **b)** comparison of overall Second Law efficiency of the different configurations

3.4. Influence of heat exchangers pressure losses on cycles performance and electricity cost

Finally, given the primary importance of the heat exchangers performance, size and cost on the cycle efficiency and electricity cost, the influence of the pressure losses of the heat exchangers was carried out. In fact, when dealing with heat exchangers network in power cycles, the counteracting effects of their efficiency, generally enhanced with high specific area per unit volume with the induced enhanced pressure losses, negatively affect the cycle performance. Indeed, here the recent very efficient and compact Printed Circuit Heat Exchangers (PCHE, [50 – 52]) were considered, so deserving an accurate addressing of the pressure losses against their high heat transfer performance. The results presented so far included the evaluation of the pressure losses within the circuit, calculated through the developed model of the heat exchangers. The influence of the heat exchangers pressure losses is, on the whole, not negligible, as they reduce the efficiency in a relevant amount, especially for the recompression cycles where the efficiency drops by almost 5 percentage points, as clear from Figure 8.

The drop in efficiency is directly related to the increase of the produced electricity cost. Indeed, as can be grasped from Figure 9, the associated increase of the produced electricity cost is more remarkable for the recompression cycles, because of the relevant decrease in efficiency due to friction pressure losses, leading to an increase of costs higher than 1 c€/kWh. On the other hand, the lowest increase in electricity cost due to HX pressure losses belongs to the recuperative cycle configuration, as it is the simplest one from this point of view.

Conclusions

In this study an exergo-economic assessment of different supercritical CO_2 power cycles configurations for the exploitation of water dominant geothermal resources in place of traditional flash based technologies was carried out by the means of energy, exergy and exergo-economic analysis. The proposed power cycle configurations adopted the efficient PCHE which, on the other hand, may negatively affect the cycle performance due to their possible relevant pressure losses. The results confirmed that the supercritical CO_2 cycles may be valuable binary cycles solutions for the exploitation of low temperature geothermal resources, as the produced cost of electricity is in line with the existing binary cycle costs [49].

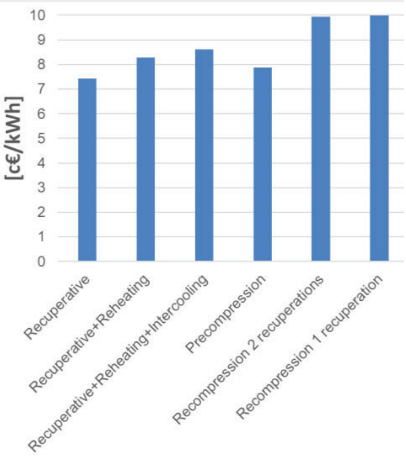

Figure 7 Comparison of electricity costs for the analysed power plants

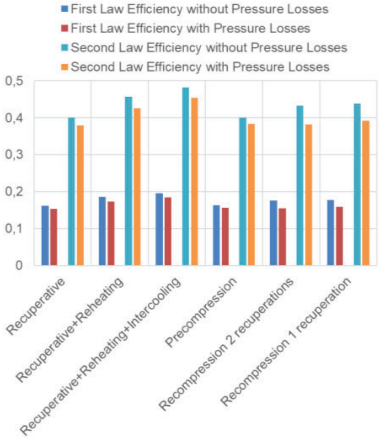

Figure 8 Sensitivity of first and second low efficiencies of the proposed cycles to the pressure losses in the heat exchangers (bars with and without considering them).

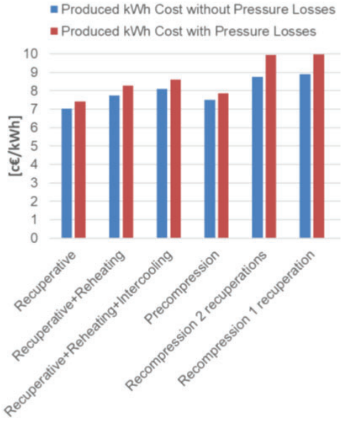

Figure 9 Sensitivity of electricity cost of the proposed cycles to the pressure losses in the heat exchangers (bars with and without considering them)

The most remarkable outcomes from the present research are the costs of electricity related to the adoption of supercritical power cycles under six different configurations, exploiting the same fixed geothermal resource:

- The lowest cost of electricity was achieved for the simplest recuperative cycle configurations, at 7.4 c€/kWh, which is in line with the level of current geothermal binary cycles.
- The configuration allowing the highest thermodynamic efficiency was the recuperative with intercooling and reheating, which gave First and Second Law efficiencies of 18.5% and 45.4% respectively. However, due to the increase in complexity of the power plant configurations, especially related to the “heavier” heat exchangers network, the cost of electricity becomes slightly higher (8.092 c€/kWh), even though still competitive with that of current binary cycles.
- The recompression configurations are hindered by the high required compressors work, having therefore the highest produced electricity costs and the lowest efficiencies. Nonetheless, it should be remarked that these configurations guarantee the lowest maximum cycles pressures (around 190 bar).
- All the binary configurations show lower performance when compared to the currently adopted single flash +ORC power cycle, with a reduction of the power output in the range of 40-50% and an almost doubled cost of the electricity. On the other hand, these CO_2 power plants could guarantee an almost zero environmental impact during the operation phase.

As a concluding remark, this analysis well addresses the importance of including the effect of pressure losses in the heat exchangers, also considering the fact that the high efficiency and compact PCHE were adopted, where this issue may be typically relevant. It is shown, here, that this aspect might lead to a significant increase of the produced electricity costs, related to the entailed drop of power cycles efficiency, especially in the most complex configurations.

The results of this research introduce, in the context of known configurations of CO_2 based binary cycles to exploit geothermal resources, the novelties related to two main aspects which are missing in literature:

1) The accurate evaluation and comparison of electricity production costs by the means of exergo-economic methodology;
2) This methodology was applied to cycles equipped with PCHEs, which is a novel proposal in these applications, particularly for the aspects addressing the influence of the related pressure losses on the cycle's performance.

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