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Integrated Geothermal Energy Systems for Small-Scale Combined Heat and Power Production: Energy and Economic Investigation

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Featured Application: A geothermal integrated energy system for combined heat and power production in a commercial centre is proposed. The suggested apparatus can be adopted for several small-scale applications (e.g., industries, dwellings, smart communities) to improve their global energy, economic and environmental performance.

Abstract: In recent years, an increasing interest in geothermal energy has been registered in both the scientific community and industry. The present work aims to analyse the energy performance and the economic viability of an innovative high-efficiency geothermal-driven integrated system for a combined heat and power (CHP) application. The system consists of a heat exchanger (HEX) and a transcritical organic Rankine cycle (ORC) that work in parallel to exploit a high-temperature geothermal source (230 °C) and satisfy the energy demand of a commercial centre located in Southern Italy. The ORC and HEX sub-units can operate at partial load to increase the system flexibility and to properly react to continuous changes in energy request. A lumped model was developed to find the proper operating conditions and to evaluate the energy production on an hourly basis over the whole year. In particular, a multi-variable optimisation was implemented to find the most suitable configuration and a 101.4 kW_{el} ORC was selected while the HEX nominal power was 249.5 kW_{th}. The economic viability of the integrated system was evaluated in terms of net present value and payback period and different operating strategies were compared: thermal-driven, electric-driven, and a mixed strategy. The latter turned out to be the best solution according to both energy and economic criteria, with electric and thermal self-consumptions larger than 90%, with no heat dumping and a payback time close to five years.

Keywords: CHP; economic viability; efficiency; emissions; geothermal; heat exchanger; operating strategy; ORC; parallel; transcritical

1. Introduction

Combined heat and power (CHP) generation presents several advantages in terms of lower costs, emissions, fuel consumption, and higher decentralised generation share as compared to conventional separate electric and thermal production [1–3]. During the last few years, the research community and the industry have been focusing increased attention on renewable sources, sustainability and global efficiency [4–6]. In this framework, geothermal energy represents an interesting resource and, due to its not intermittent availability, an attractive solution for lowering fossil-fuel dependence and their environmental impact [7–9]. Furthermore, geothermal sources are slightly dependent on the season, climate and local conditions, presenting the advantages of different viable technologies [10] with

direct (e.g., heat production for industrial and domestic users) and indirect applications (i.e., electricity generation at large, medium and small scales).

In geothermal applications, a geo-fluid transports the heat stored underground to the users through wells drilled into the geothermal reservoirs (up to 200–300 °C) [10]. The installed capacity of geothermal power has been increasing rapidly in the last few years [11] (from 6.8 GW in 1995 to an estimate of 21.4 GW for 2020 [12]). On the other hand, the direct use of geothermal sources is one of the first, most flexible and common methods to exploit geothermal potential [13].

A worldwide review of published data shows that the average electric conversion efficiency of geothermal systems is about 12%, while the highest values reach 21% [14]. For this purpose, it is worthy noting that several factors influence the system efficiency, including the conversion technology (i.e., dry steam, single, double and triple flash, binary and hybrid systems), the desired output (e.g., electricity production, combined heat and power generation, polygeneration), the size (large, medium, small, micro-scale), the ambient conditions, the temperature, the flow rate and the physic–chemical properties of the geothermal source [14].

In particular, several technologies can be adopted for geothermal power extraction, which depend on the thermodynamic state of the resource. At high temperatures, dry steam systems are usually adopted [12]. They represent a well-established technology and account for 23% of the global geothermal capacity. Furthermore, single and double flash steam power systems are the most diffused technology (42% for single flash and 19% for double flash) [12].

Finally, binary cycles represent the most recent solution that accounts for the remaining 16% of the total installed capacity in operation [15]. In this context, binary organic Ranking cycles (ORCs) play a crucial role [10,16–18]. ORCs represent an attractive and flexible technology for small applications owing to their capability to convert low enthalpy heat sources (i.e., waste heat [19–23] and renewable sources [24–26]) to electricity. Specifically, lower maintenance costs, better partial load performance, faster start-up and stop procedures, and higher safety and lifetime (up to 30 years) with respect to conventional installations are guaranteed [7,27]. Furthermore, a geothermal ORC does not need an intermediate thermal oil circuit, as usually present in other ORC applications [28,29] with a significant advantage in terms of performance, cost and architecture complexity [30]. The electric efficiency of the system can reach values up to 20% for the sole power generation [31]. Specifically, several factors affect the performance of ORC units: the thermal level of the external source, the working fluid, as well as the type of expander and operating conditions; therefore, the system architecture can vary significantly with the specific application and a standard setup is not completely established [11,32]. Moreover, the electric power of current geothermal systems is usually larger than 200 kW_{el} with values also higher than 50 MW_{el} [14,15,33,34]. On the other hand, few examples on small-scale ORCs are present, owing to higher specific costs and lower electric production [16,35]. As a consequence, further investigations are required to improve their performance [12,36]. Many scientific works concern geothermal ORC systems for electricity production. Ahmadi et al. recently provided a comprehensive review on this topic [7]. At the same time, the flexibility of geothermal-driven CHP systems based on ORCs has been receiving great attention from both the scientific community and industry [37–41]. In particular, a great amount of energy and techno-economic analysis and optimisation approaches are usually proposed for medium and large-scale geothermal power plants (electric power higher than 200 kW_{el}) and for different system arrangements [37,42,43]. The objective functions combine energy parameters (i.e., first and second law analysis [44–46], electric power [41], heat exchanger areas [44,47], etc.) and economic purposes (e.g., specific cost of investment and levelized cost of energy, energy production cost [48–50]).

In this work, an innovative transcritical geothermal-driven ORC system for small-scale applications was investigated. To this purpose, the ORC unit is coupled with a traditional geothermal heat exchanger for the direct production of thermal energy. The sub-systems work in parallel to satisfy the electric and thermal demand of a small commercial centre. In a parallel arrangement, the heat is delivered to both the thermal user and the ORC at a high temperature and at a lower flow rate [43,51]. In a series design,

the same geothermal flow passes through the ORC and subsequently through the heat exchanger [43,51]. As a consequence, the ORC unit significantly limits the thermal level of the heat generation in series arrangements [52,53]. According to the literature [43], the parallel configuration is the most suitable solution for supply and return temperatures higher or close to 80 and 60 °C [43], respectively, typical of space heating applications [7]. On the other hand, the series configuration is recommended for applications with lower temperatures (supply and return temperature close to 50 °C and 30 °C [25,30,43]) suitable for soil warming, swimming pools, de-icing, etc. [7]. Furthermore, the parallel configuration guarantees better ORC electric performance, owing to the lower condensation temperatures compared to series arrangements and higher flexibility. An innovative high-energy geothermal CHP demonstrator in parallel configuration is developing within the Fongeosec project [54,55]. Specifically, the geothermal source will be used to feed a 5.5 MW_{el} subcritical ORC and a 15 MW_{th} district heating network in Alsace (France) [56]. Parallel arrangements are also available in Bavaria (Germany) with Traunreut and Oberhaching geothermal plants. The global electric and thermal power is equal to 8.4 MW_{el} and 52.0 MW_{th}, respectively, while the net electric process efficiency ranges between 8.9% and 13.1% [57].

A lot of research effort is currently focused on organic Rankine cycles for CHP applications operating in subcritical conditions and driven by relatively low-temperature sources. The novelty of this work consists in the adoption of a transcritical ORC configuration with superheated conditions at the expander inlet. Transcritical systems show, in fact, higher performance compared to subcritical configurations [33,58] and provide a more efficient thermal exchange between the geofluid and organic fluid and lower irreversibility and exergy destruction [59]. Another benefit is the component downsizing due to the higher density of fluid. However, transcritical configurations present higher investment costs than subcritical arrangements owing to their higher operating pressures and larger size of some components (turbines, pumps and evaporators) [60,61]. Nevertheless, transcritical ORCs appear a promising technology to also exploit geothermal sources from an economic perspective [60–62]. Song et al. compared different ORC configurations (subcritical and transcritical, saturated and superheated, simple and regenerative cycles) with different organic fluids (isobutane, isopentane, R134a, R245fa, R1233zd, and R1234yf) for the exploitation of a 40 kg/s geothermal source at 180 °C [60]. A bi-variable optimisation was adopted based on the exergy efficiency maximisation and payback period minimisation. The comparison between optimised configurations demonstrated that transcritical systems present a lower payback period compared to subcritical arrangements for all the investigated working fluids, with decrease up to 90%. Furthermore, the authors demonstrated that when the payback period is fixed, the transcritical ORCs provide higher net power, larger long-term economic profit, and lower specific investment cost compared to subcritical systems. The advantages of transcritical configurations were also confirmed for geothermal source temperatures between 140 and 200 °C. Similar results were found by Preißinger et al., who observed a significant increase in the gross power and a noticeable decrease in the payback period comparing transcritical and subcritical power plants with geothermal source temperatures between 100 and 190 °C and different working fluids [61]. Furthermore, Astolfi et al. highlighted that transcritical systems guarantee lower specific costs with respect to subcritical ORCs when the ratio between the critical temperature of the organic fluid and the geothermal source thermal level ranges between 0.8 and 0.9 due to the higher energy production and efficiency that overcomes the larger investment costs. Furthermore, the investigation demonstrated that supercritical ORCs offer better energy and economic performance for high geothermal sources [62]. Nevertheless, to the best of the authors' knowledge, few works are present in the literature concerning geothermal transcritical configurations.

The proposed unit is able to work at partial loads to fulfil the energy demand of the final users, to increase the system flexibility and to respond efficiently to load variations [30]. It is worthy to note that most of the papers present in the literature do not focus on off-design performance [63]. The internal regeneration has been considered to maximise the electric power and achieve higher efficiency with respect to the mean value of typical geothermal plants (close to 12%) and isobutane has been selected as working fluid owing to its good performance and low specific costs, according

to the literature [64–67]. In particular, isobutane is considered one of the organic fluids with zero ODP (ozone depletion potential), suitable for supercritical ORC applications [33]. Even though the relatively high pressures lead to higher operating costs, the integrated system reaches higher global efficiency for high thermal level geothermal sources. Maloney et al. found that high pressure values are more appropriate for high expander inlet temperatures to maximise the system efficiency [68]. The authors show that only a few investigations are focused on working fluid temperatures larger than 180 °C. Despite this, in the range of temperatures 180–240 °C isobutane revealed good energy performance in transcritical ORCs. In particular, the authors showed that the best isobutane cycles are supercritical for the highest values of temperature of the geofluid investigated (180 °C and higher). Toffolo et al. confirm that isobutane represents one of the most effective fluids for the exploitation of high-temperature geothermal sources through a comprehensive screening of organic fluids [69] and similar results are found in the literature [70,71]. Furthermore, many researchers recommend isobutane as a suitable fluid for supercritical conditions from an energetic and exergetic point of view [72,73] and claim that it is a cost-efficient working fluid [74].

A lumped thermodynamic model has been developed to select the suitable ORC system and the corresponding operating conditions, and to calculate the energy production on hourly basis over the whole year. The proper system configuration has been defined adopting a multi-variable optimisation and different operating strategies (i.e., thermal-driven, electric-driven and mixed-mode) have been compared [2,75,76]. Finally, the economic viability of the proposed technical solution has been investigated through the estimation of the cost of the single sub-units. The payback period and net present value were compared for the different operating strategies.

2. Materials and Methods

Figure 1 highlights the scheme of the geothermal-driven system used to satisfy the energy requests of a commercial centre located in Southern Italy. In particular, the investigated area refers to the Phlegraean Fields where high temperature geothermal aquifers are present at a very shallow depth [77,78]. The system consists of an organic Rankine cycle (ORC) for the electric production and a heat exchanger (HEX) able to provide the thermal energy. The two components work in parallel and simultaneously and the total geothermal mass flow rate can be arranged between the ORC and HEX units according to the user energy demand. To this purpose, the geofluid is pumped to the two components from the geothermal reservoir and afterwards is reinjected into the ground.

The adopted parallel configuration guarantees high flexibility to the CHP system, owing to the possibility to split the geothermal mass flow rate in the ORC and HEX units, depending on the hourly user energy request [52]. Furthermore, the parallel arrangement permits one to meet the high temperature heat demand for the space heating and also when the ORC condensation temperature is set to low values to maximise the electric power and efficiency [43,52].

The integrated system was able to exchange the electric energy with the grid and a traditional natural gas packaged firetube boiler was adopted to meet the thermal load when the geothermal production was not sufficient.

In particular, the system can operate adopting a thermal-driven, an electric-driven or a mixed strategy. In the first two cases, the priority is given to the fulfilment of the heat and electricity request, respectively; as a consequence, the geothermal mass flow rate is divided between HEX and ORC sub-systems on the basis of the privileged load. In the mixed operation, the thermal-driven strategy is adopted when the heat demand is present in order to minimise the heat dumping. On the other hand, the geofluid is completely exploited in the ORC apparatus when the thermal request is absent to maximise the electric efficiency and production.

Figure 1. Simplified scheme of the integrated geothermal-driven CHP system.

The global performance of the combined system is expressed in terms of electric efficiency (η_{el}), energy utilisation factor (EUF) and marginal efficiency of electric production (η_{mar}) [28,79], as follows:

$$\eta_{el} = \frac{P_{el}}{\dot{m}_g (h_{g,in} - h_{g,out})} \quad (1)$$

$$EUF = \frac{P_{el} + P_{th}}{\dot{m}_g (h_{g,in} - h_{g,out})} \quad (2)$$

$$\eta_{mar} = \frac{P_{el}}{\dot{m}_g (h_{g,in} - h_{g,out}) - \frac{P_{th}}{\eta_{th,ref}}} \quad (3)$$

where P_{el} is the ORC electric power, $\dot{m}_g$ corresponds to the geothermal mass flow rate, $h_{g,in}$ and $h_{g,out}$ represent the enthalpy of the geothermal fluid at the entrance and exit of the integrated apparatus, respectively, and $\eta_{th,ref}$ is thermal reference efficiency, based on the European harmonised efficiency reference value for separate heat production [80].

2.1. Organic Rankine Cycle (ORC) Unit

Transcritical organic Rankine cycles (ORCs) were selected for the investigation, owing to their high performance, low payback period and efficient heat exchange with low and medium-temperature heat sources [60,81–84]. In fact, organic fluids present usually low critical pressures and, as a consequence, transcritical configurations are very attractive, owing to the possibility to guarantee proper performance without operating into extreme and dangerous conditions [16].

The main components of an ORC are a pump, an evaporator, a turbine, and a condenser (Figure 2a) [85,86]. The pump increases the pressure of the organic working fluid to the maximum value (1-2 process) then the evaporator is adopted to obtain the superheated vapour (2-3) that expands in the turbine (3-4) to provide the mechanical work that is converted into electricity by an alternator. Finally, the working fluid is condensed (4-1). An internal heat exchanger (IHE) is often used to improve the system efficiency [87]. To this purpose, the energy content of the organic fluid at the exit of the turbine is exploited (4-4*) to preheat the liquid before the entrance in the evaporator (2-2*). Specifically,

centrifugal pumps, radial turbine and shell and tube heat exchangers were selected, according to the literature [19,88–90]. Figure 2b depicts the different processes in the T-s diagram.

Figure 2. Typical system layout (a) and T,s diagram (b) of an organic Rankine cycle (ORC) with internal regenerator (IHE) and transcritical conditions.

The performances of the geothermal-driven ORC were characterised by adopting a thermodynamic model developed by the authors in the last years [16,29,91]. The model is general and refers to the ORC unit alone (pump, evaporator, turbine, regenerator and condenser). It is capable of characterising the behaviour of ORC systems in both nominal and partial load operations independently of the energy source. The model includes an intermediate thermal oil circuit when high-temperature sources are adopted. Since this component is not necessary for geothermal application, the algorithm considers only a single heat exchanger that transfers the heat input from the geofluid to the organic fluid directly. The model integrates the Refprop database to define the working fluid properties [92], whereas steady state conditions were imposed [93] and pressure losses in the ORC components were neglected [94], in line with the literature.

The behaviour of the geothermal organic Rankine cycle system at full and part loads has been defined in terms of electric power and efficiency.

The electric power P_{el} is evaluated as:

$$P_{el} = \eta_{em,t} P_t - P_p / \eta_{em,p} - P_{p,geo} / \eta_{em,geo} - P_{p,cool} / \eta_{em,cool} \quad (4)$$

where P_t and P_p represent the ORC turbine and pump power, respectively, while $\eta_{em,t}$ and $\eta_{em,p}$ are the corresponding electro-mechanical efficiencies. $P_{p,g}$ and $P_{p,cool}$ denote the power request of the pumps used to drive the geofluid and the cooling water, whereas $\eta_{em,g}$ and $\eta_{em,cool}$ are the corresponding electro-mechanical efficiencies.

The electric efficiency of the ORC system $\eta_{el,ORC}$ is:

$$\eta_{el,ORC} = \frac{P_{el}}{\dot{m}_{g,ORC} (h_{g,ORC,in} - h_{g,ORC,out})} \quad (5)$$

where $\dot{m}_{g,ORC}$ is the mass flow rate of the geothermal source exploited in the ORC unit while $h_{g,ORC,out}$ represents the enthalpy of the geofluid at the exit (out) of the ORC evaporator.

An iterative procedure has been implemented to take into account the variation of temperature and pressure at the turbine inlet when the system operates at partial loads, by using the Stodola's ellipse approach. The algorithm evaluates the off-design variation of the turbine, pump and heat exchanger performance. More details on ORC partial load operations are available in a previous

work of the authors [28]. The ORC model has been validated in previous works and more details are reported in the literature [16,28].

2.2. Heat Exchanger (HEX) Unit

A traditional geothermal heat exchanger (HEX) has been used to satisfy the thermal request of the commercial centre. To this purpose, a shell and tube unit in carbon steel has been considered, owing the high compatibility with geothermal and organic fluids [88]. The thermal power P_{th} is evaluated as:

$$P_{th} = \eta_{th,HEX} \dot{m}_{g,HEX} (h_{g,HEX,in} - h_{g,HEX,out}) \quad (6)$$

where, $\eta_{th,HEX}$ represents the HEX thermal efficiency, $\dot{m}_{g,HEX}$ is the geothermal mass flow rate used in the heat exchanger, $h_{g,HEX,out}$ is the enthalpy of the geofluid at the exit of the HEX sub-system. In particular, the geothermal mass flow rate for heating purposes $\dot{m}_{g,HEX}$ is:

$$\dot{m}_{g,HEX} = \dot{m}_g - \dot{m}_{g,ORC} \quad (7)$$

The area of the heat exchanger has been calculated as:

$$A = \frac{P_{th}}{U \Delta T_{lm}} \quad (8)$$

U represents the global heat exchange coefficient and ΔT_{lm} is the logarithmic mean temperature difference, defined as follows:

$$\Delta T_{lm} = \frac{(T_{h,out} - T_{c,in}) - (T_{h,in} - T_{c,out})}{\ln \left(\frac{T_{h,out} - T_{c,in}}{T_{h,in} - T_{c,out}} \right)} \quad (9)$$

where T is the temperature, the subscripts h and c refer to the hot and cold fluid, respectively, while the subscripts in and out correspond to the inlet and outlet fluid sections.

The global heat transfer coefficient is:

$$U = \frac{1}{\frac{d_o}{h_i d_i} + \frac{R_{f,i} d_o}{d_i} + \frac{d_o}{2k} \ln(d_o/d_i) + R_{f,o} + \frac{1}{h_o}} \quad (10)$$

where D is the tube diameter, H corresponds to the heat transfer coefficient, K is the thermal conductivity and R_f is the fouling factor. The subscripts i and o refer to the properties inside and outside the tubes. In particular, the Gnielinski equation [95] and the Kern method [96] were adopted to define H_i and H_o , respectively [88].

The same procedure was implemented to define the area of the other heat exchangers of the ORC sub-system (i.e., condenser, evaporator and internal regenerator). In particular, for the sole evaporator, the Krasnoshchekov et al. correlation was adopted to characterise the heat transfer coefficient in supercritical conditions [97,98]. The correlation is based on the Krasnoshchekov and Protopopov rule and the Petukhov and Kirillov equation [98,99]. To this purpose, it is worthy to note that a universal accepted law for the heat transfer coefficient in supercritical regimes is still not available [98,100,101]; however, the adopted rules are among the most accurate correlations available in the literature for supercritical fluids [98,102–104].

2.3. Operating Conditions

The performances of the integrated energy systems have been investigated. To this purpose, 1 kg/s of geothermal water at 230 °C was considered as energy input [16]. The geofluid was used to

drive both the ORC and HEX units depending on the energy request of the investigated users while the minimum reinjection temperature was fixed to 70 °C to prevent scaling and fouling problems within system components and pipes, according to the literature [82,105,106]. The thermal efficiency of the heating process from the geothermal source was fixed to 0.92 [80] and the minimum pinch-point temperature was considered equal to 10 °C [16]. This value was increased if the constraint on the minimum reinjection temperature was not fulfilled.

The analysis was carried out adopting transcritical ORC units with and without the internal heat regenerator (simple and IHE configuration, respectively) owing to their high performance with geothermal sources [16]. Isobutane was selected as organic fluid due to its thermal stability, low specific cost and attractive efficiency, according to the literature [67,107,108]. Furthermore, isobutane is suitable for supercritical ORC applications with high-temperature geothermal sources [33,68,69], as already pointed out in the introduction section. The ratio between the critical temperature of the working fluid and the geothermal source temperature was equal to 0.81, within the suggested interval (0.8–0.9) to minimise the specific investment cost and the levelized cost of energy [62]. ORC condensation temperature was fixed to 30 °C while the maximum pressure was set to 65.32 bar, corresponding to 1.80 times the critical value ($p_{crit} = 36.29$ bar). At part load operations, the maximum pressure can be reduced up to $1.03 p_{crit}$ depending on the energy request.

The temperature at the entrance of the turbine varies with the pressure and the maximum value was fixed to 220 °C, based on the geothermal source temperature.

For the investigation, the maximum turbine and pump efficiencies were imposed equal to 0.80 and 0.70 [109], respectively, while the electro-mechanical efficiencies were 0.95 [110]. The effectiveness of the internal heat exchanger was set to 95% and the vapour temperature at the IHE exit (*point 4**) was 10 °C higher than the condensation temperature [16,111]. The efficiency and head of the pump used for the cooling circuit were equal to 80% and 10 m, respectively, while the corresponding pinch point temperature was 5 °C [81,106]. Table 1 summarises the operating conditions and the main assumptions adopted for the analysis.

Table 1. Operating conditions and main assumptions.

Parameters		
Mass flow rate of geothermal fluid	(kg/s)	1
Temperature of geothermal fluid	(°C)	230
Minimum reinjection temperature	(°C)	70
Pinch-point temperature in geothermal circuit	(°C)	10
Geothermal heat exchanger efficiency	(-)	0.92
Geothermal pump efficiency	(-)	0.70
ORC configuration		Transcritical
ORC working fluid		Isobutane
ORC maximum temperature range	(°C)	140.0–220.0
ORC maximum pressure range	(bar)	37.38–65.32
ORC condensation temperature	(°C)	30.0
ORC condensation pressure	(bar)	4.05
Maximum ORC pump efficiency	(-)	0.70
Maximum ORC turbine efficiency	(-)	0.80
Electro-mechanical efficiency	(-)	0.95
Cooling pump efficiency	(-)	0.80
Head of cooling pump	(m)	10
Pinch-point temperature in cooling system	(°C)	5
Heat exchanger inner tube diameter	(mm)	10.92
Heat exchanger outer tube diameter	(mm)	12.70
Gas-fired auxiliary boiler efficiency	(-)	0.90
Natural gas lower heating value	(MJ/Sm ³)	34.54
Reference thermal efficiency	(-)	0.92

2.4. Electric and Thermal Demand

The integrated geothermal system was adopted to satisfy the energy request of a commercial centre in Southern Italy [112]. The yearly electric and thermal demands were equal to 533.1 MWh_{el} and 396.3 MWh_{th}, respectively. The electric load depended mainly on the lighting system and heating, ventilation, and air conditioning (HVAC) units, while the thermal demand was based on space heating and hot water request. The analysis was performed on an hourly basis and the electric and thermal loads during the year are depicted in Figure 3. The highest electric request (144.0 kWh_{el}) was registered in August when the thermal demand was absent or presented the minimum values. As expected, the maximum heat load (427.9 kWh_{th}) was noticed in winter, owing to the space heating demand.

Figure 3. Electric and thermal demand of the investigated commercial centre.

2.5. Economic Analysis

The economic viability of the integrated geothermal system has been evaluated. To this purpose, the costs of the different components were calculated, adopting the bare module equipment methodology, which takes into account direct and indirect costs [113]. In particular, the reference purchased cost C_j^0 (in US dollar) of the generic component j was evaluated according to the following equation:

$$\log C_j^0 = K_{1,j} + K_{2,j} \log S_j + K_{3,j} (\log S_j)^2 \quad (11)$$

where S is the size or capacity parameter of the component j and it corresponds to the area (in m^2) of heat exchangers or to the power (in kW) of pumps and turbines [113]. The superscript 0 refers to the base conditions with carbon steel material and ambient operating pressure, whereas the coefficients $k_{1,j}$, $k_{2,j}$ and $k_{3,j}$ vary with the selected sub-systems (Table 2).

Table 2. Equipment cost assumptions for bare module methodology.

Parameter	Heat Exchanger	Pump	Turbine
k_1	4.3247	3.3892	2.2476
k_2	−0.3003	0.0536	1.4965
k_3	0.1634	0.1538	−0.1618
c_1	0.0388	−0.3935	0
c_2	−0.1127	0.3957	0
c_3	0.0818	−0.0023	0
b_1	1.63	1.89	−
b_2	1.66	1.35	−
F_M	1.00	1.60	−
F_{BM}	−	−	3.5

The reference purchased costs of pumps and heat exchangers are corrected to take into account the adopted construction materials and operating pressures:

$$C_j = C_j^0 (B_{1,j} + B_{2,j} F_{M,j} F_{P,j}) \quad (12)$$

where the coefficients $b_{1,j}$ and $b_{2,j}$ depend on the equipment type, while $F_{M,j}$ and $F_{P,j}$ represent the material and the pressure factors of the generic component j . Specifically, the pressure factors are evaluated according to:

$$\log F_{P,j} = C_{1,j} + C_{2,j} \log p_j + C_{3,j} (\log p_j)^2 \quad (13)$$

where p_j is the operating pressure. The coefficients $b_{1,j}$, $b_{2,j}$, $c_{1,j}$, $c_{2,j}$, $c_{3,j}$ and the material factors $F_{M,j}$ are shown in Table 2 [19,88–90].

The turbine purchased cost was evaluated as a function of the corresponding reference cost [60,114,115]:

$$C_j = C_j^0 F_{BM,j} \quad (14)$$

where the corresponding bare module factor F_{BM} is in Table 2 [19,88–90].

Finally, the total cost (in euro) of the integrated geothermal system was calculated according to the following equation:

$$C = \frac{CEPCI_{2019}}{CEPCI_{2001}} \cdot e_{EUR/USD} \cdot \sum_{j=1}^N C_j \quad (15)$$

Here, the chemical engineering plant cost indexes (CEPCI) are used to account for inflation and update to 2019 the parameters of Table 2 (referred to as 2001). Specifically, CEPCI indexes correspond to 397.0 and 607.5 for 2001 and 2019, respectively [113,116,117]. Furthermore, the European Central Bank reference exchange rate ($e_{EUR/USD}$) from euro (EUR) to US dollar (USD) is adopted to express the total cost of the geothermal combined system in euros [118].

Other assumptions for the economic analysis are summarised in Table 3. In particular, the investment period has been set to 20 years and the interest rate to 2%. The electricity and natural gas prices are based on Italian tariffs for non-domestic users [119] and the maintenance costs of the integrated geothermal-driven system have been assumed to be equal to 2% of the initial investment [28]. The reference exchange rate from euro to US dollar is 1.12 €/€ (1 July 2020 value) [118].

Table 3. Further assumptions for the economic analysis.

Parameter	Unit	Value
Investment Period	(Years)	20
Interest rate	(%)	2
Specific revenue for the saved thermal energy	(c€/kWh _{th})	6.7
Specific revenue for the saved electricity	(c€/kWh _{el})	18.8
Specific value of the electricity injected into the grid	(c€/kWh)	10.0
Specific cost of the electricity withdrawn from the grid	(c€/kWh)	18.8
Specific cost of natural gas	(c€/kWh)	6.0
CEPCI ₂₀₀₁	(-)	397.0
CEPCI ₂₀₁₉	(-)	607.5
EUR/USD exchange rate	(EUR/USD)	1.12
Maintenance cost/Investment cost	(%)	2.0

3. Results and Discussion

The energy performance of a geothermal integrated system for combined heat and power (CHP) production was modelled and analysed. The geothermal source drives a transcritical organic Rankine cycle (ORC) unit and a heat exchanger (HEX) to satisfy the electric and thermal demand of a small commercial centre [112]. The available mass flow rate and thermal level of the geothermal source were fixed to 1 kg/s and 230 °C, respectively. Full and partial load operations were considered and the annual energy balances were evaluated on an hourly basis.

3.1. Performance of the Integrated Geothermal System

First, a parametric investigation was carried out, and the effect of the maximum temperature (T_{max}) on the ORC performance was analysed. The maximum pressure was fixed to 65.3 bar ($1.80 p_{crit}$) while the condensation temperature was set to 30 °C. As expected [29], a continuous increase in the ORC electric efficiency with the maximum temperature was noticed for both simple and regenerative configurations (Figure 4). The simple arrangement guarantees higher performance for temperature values lower than 165 °C and a plateau ($\eta_{el} \approx 13.4\%$) was reached for T_{max} higher than 200 °C. Conversely, the IHE configuration guarantees a significant raise in the electric efficiency when the temperature moves from 140 °C to 220 °C (6.7% to 18.7%, respectively) while the maximum electric power (102.3 kW_{el}) is registered when the temperature at the turbine entrance is equal to 195 °C.

Figure 4. Influence of the maximum temperature on ORC electric power and efficiency. Simple and IHE configurations.

A multi-variable optimisation was adopted to select the most suitable configuration of the ORC geothermal-driven apparatus, and the electric power and efficiency have been considered as objective parameters. Figure 5 highlights that a Pareto frontier exists and the “minimum distance” criterion was adopted to define the proper ORC arrangement according to the literature [120,121]. The method suggests selecting the system configuration that minimises the dimensionless distance to the ideal point (the red circle in Figure 5) that is characterised by the maximum ORC electric efficiency ($\eta_{el,ORCmax}$) and the maximum electric power ($P_{el,max}$), according to the following equation:

$$d = \min \left(\sqrt{\left(\frac{\eta_{el,ORCmax} - \eta_{el,ORCi}}{\eta_{el,ORCmax} - \eta_{el,ORCmin}} \right)^2 + \left(\frac{P_{el,max} - P_{el,i}}{P_{el,max} - P_{el,min}} \right)^2} \right) \quad (16)$$

The subscript k refers to the generic k^{th} ORC configuration that is characterised by the electric efficiency $\eta_{el,ORCk}$ and the electric power $P_{el,k}$, whereas $\eta_{el,ORCmin}$ and $P_{el,min}$ corresponds to the minimum ORC electric efficiency and power on the Pareto frontier, respectively.

Figure 5. Multi-objective optimisation for the selection of the proper system configuration.

In particular, the transcritical ORC with the internal heat exchanger (IHE) and temperature at the entrance of the turbine equal to 205 °C was selected as the most suitable configuration. The corresponding electric power and efficiency were equal to 101.4 kW and 17.4%, respectively. At full load, the geothermal mass flow rate (1 kg/s) was fully exploited in the ORC and the HEX thermal production is absent. At partial load the mass flow rate of the organic fluid was reduced and, as a consequence, a rate of the geofluid was used to drive the HEX sub-system. It is worth noting that a minimum geothermal flow is required for the proper operation of the HEX heat exchanger. For this reason, the integrated CHP system only produces electricity when the electric load is larger than 91.0%, corresponding to the purple area in Figure 6.

Figure 6a highlights the geothermal flow used in the ORC, the electric and thermal power of the integrated CHP system as a function of the electric load. Furthermore, the energy utilisation factor, the marginal efficiency, and the electric efficiency are plotted in Figure 6b. In particular, the minimum electric load is equal to 50%, owing to the constraints of the minimum pressure at the ORC turbine inlet ($1.03 p_{crit}$). The corresponding electric and thermal power are equal to 50.7 kW_{el} and 249.5 kW_{th}, whereas electric efficiency is 8.7%. A slight variation in the marginal efficiency is observed (from 16.0% to 17.7%) whereas *EUF* is more sensitive to the load and ranges between 25.2% and 50.9% (Figure 6b). The geothermal temperature at the exit of the evaporator ranges between 95.9 °C (at full load) and 70.0

°C (at minimum). For this purpose, it is worth noting that the adopted parallel arrangement permits to satisfy the high-temperature heat request for all the operating conditions.

Figure 6. Influence of the electric load on thermal power, electric power and geothermal flow at the entrance of ORC sub-system (a). Effect of the electric load on EUF , electric and marginal efficiency (b).

3.2. Influence of the Operating Strategy

The yearly electric and thermal productions of the geothermal-driven CHP system were evaluated on an hourly basis considering the electric and thermal request of a commercial centre [112] sited in the Phlegraean Fields area where geothermal sources at a temperature higher than 200 °C are present [77,78]. The energy system can operate according to a thermal-driven, electric-driven, or mixed strategy. Depending on the energy request of the final user, a variable operation is registered all over the year.

Figure 7 shows the comparison between the three operating strategies through the monthly energy balances of the CHP system. The electric demand presents a regular trend all over the year (around 44 MWh/month), while the thermal request variation is significant, ranging from 3.7 to 75.4 MWh/month (in August and January, respectively).

The thermal-driven and mixed strategies show a similar behaviour. Both operating modes guarantee no thermal dumping and a significant self-consumption during the winter period, ranging from 89.0% to 100.0%. Furthermore, the thermal-driven strategy satisfies 100% of the user heat request during the summer, whereas mixed-mode ranges from 64.8% to 88.9% in the same months. On the contrary, the mixed strategy significantly increases the electric self-consumption to values always higher than 87.6%, while thermal strategy never satisfies the electric request (the maximum self-consumption is 69.1%). In this case, a significant integration is necessary during summertime (up to 90% of the electric load).

The grid integration is present, although very small, when the mixed operation is adopted, despite the electric production always being larger than the energy demand. In fact, the electric and thermal loads are not simultaneous during the 24 h.

The electric-driven operation produces very high electric self-consumption and moderate excess to be injected into the grid. Conversely, noticeable thermal dumping is registered. In fact, the electric-driven strategy forces a homogenous operation of the apparatus, with a mean electric load equal to 68.1% for all the year, owing to the continuous electric request. The system operates with intermediate electric performance and significant thermal production, as well as when the thermal demand is absent.

Figure 7. Monthly electric and thermal balances for mixed (a,b) thermal- (c,d) and electric-driven (e,f) strategy.

On the contrary, the thermal-driven strategy guarantees a higher mean load (80.6%) with fewer operating hours (3692 h/year) because the thermal request is limited to the central hours of the day. This circumstance corresponds to lower equivalent operation hours (2977) as compared with the electric mode (6028). It is worthy to note that the mixed strategy reduces significantly the thermal dumping producing only electric energy at full load when the thermal request is absent. At the same time, the system operates in the high-performance range with 92.4% mean load and 8095 equivalent hours of operation. A slight excess of electric energy is noticed, due to the difference in the production and request timing.

Figure 8 shows the annual balance for the three operating modes. The mixed strategy satisfies both thermal and electric demand with small integration (4.7% and 9.3% of the thermal and electric load, respectively) with 59.2% electric surplus and no thermal dumping. If the heat-driven mode is used, the integrated CHP apparatus is able to satisfy up to 95.7% of the thermal demand, while the electric self-consumption drops to 47.5%.

Figure 8. Comparison of energy balance on yearly basis for mixed, electric-driven and thermal-driven strategy.

Furthermore, the economic viability of the integrated energy system was analysed and the different operating strategies were compared. To this purpose, the investment period was fixed to 20 years and the main assumptions for the economic investigation are summarised in Table 3. The cost of the integrated CHP system (ORC and HEX sub-systems) was evaluated equal to EUR 636,786 adopting the bare model cost [113]. Specifically, the initial investment for the selected supercritical ORC unit was evaluated equal to EUR 551,838, with a specific cost lower than 5500 €/kW_{el}, while the cost of the HEX sub-system corresponds to about EUR 85,000. The absolute and percentage costs of the different components are visible in Figure 9. The turbine revealed the highest rate (36.5% of the integrated system), whereas the share costs of the four heat exchangers were similar and ranged between 13.3% of the HEX unit and 18.0% of the condenser. The pumps costs correspond to about 4%.

Figure 9. Components cost of the integrated combined energy system.

The analysis reveals that the operating strategy has a noticeable impact on the economic performance of the integrated system when the same architecture is selected. To this purpose, the net present values (NPV) for the three operating modes are compared in Figure 10.

Figure 10. Influence of the operating strategy on the economic viability of the integrated energy systems.

The results highlight that the mixed strategy also guarantees better economic performance: the payback period is lower than five years (4.9 years) and the NPV at the end of the investment period is equal to EUR 1,617,456. A slight increase in the payback time (PBT) is registered when the electric-driven mode is adopted (6.1 years). On the other hand, the thermal-driven strategy is characterised by a significant PBT rise to 11.0 years, and the NPV reduces to less than EUR 430,000, owing to the noticeable electric integration from the grid (52.7%).

3.3. Hourly Energy Balance for the Selected Integrated System

The previous analysis demonstrates that the mixed operating strategy guarantees the best techno-economic performance for the investigated integrated energy system. To evaluate in more detail the behaviour of the geothermal-driven CHP apparatus, Figure 11 depicts the distribution of hourly global electric efficiency and *EUFI* index adopting mixed operations. The electric effectiveness ranges between 7.7% and 16.3%. As already observed, the maximum electric efficiency refers to full load operation with the sole electric production (Figure 6). It is worth noting that a concentration of high electric and low *EUFI* points is registered during the hot season due to the low thermal request during this period. In this case, most of the geothermal source is used for electric production at high electric load, with good electric efficiency and low thermal performance. Furthermore, in order to guarantee the complete exploitation of the geothermal source, the integrated unit produces the sole electric energy at full load when the thermal request is absent.

Figure 12 shows the hourly energy balances in typical winter and spring days (3 January and 3 April). The CHP unit is capable of fulfilling the thermal load almost completely in January and a negligible integration is needed at 7:00 h (0.5% of the daily energy demand), whereas no thermal surplus is registered. A slightly higher integration is necessary in April (3.7% of the daily demand) due to the thermal request at 15:00 h, lower than the minimum thermal power of the combined apparatus. As far as the electric production is concerned, a very high self-consumption is guaranteed for both reference days (89.3% and 96.2% in January and April, respectively) and integration is required during

the daytime, when the thermal request is present. Conversely, when there is no thermal demand, the whole geothermal source is used to produce electric energy. In this case, a higher electric surplus to be injected to the grid is noticed (39.1% in January and 47.6% in April).

Figure 11. Hourly electric efficiency (a) and energy utilisation factor (b) for the integrated geothermal energy system. Mixed strategy.

Figure 12. Hourly thermal and electric balance of the integrated energy system unit in January (a,c) and April (b,d) typical days. Mixed strategy.

The thermal demand decreases noticeably during the hot season (Figure 13) and it is present for a few hours per day. The thermal self-consumption is always higher than 94% and the system works at full load for 21 h in July, satisfying almost completely the daily electric request (values higher than 99% are found). The electric energy injected to the grid is 62.6% and 49.2% of the daily production in July and October, respectively.

Figure 13. Hourly thermal and electric balance of the integrated energy system unit in July (a,c) and October (b,d) typical days. Mixed strategy.

Table 4 summarises the yearly techno-economic performance of the integrated geothermal CHP system with mixed operation strategy. The global electric efficiency is equal to 13.4% and confirms that the parallel transcritical configuration guarantees high performance in line with medium and large-scale geothermal CHP systems [57]. The energy utilisation factor reaches 19.2% while the marginal efficiency of electric production is 14.4%.

Table 4. Optimised integrated geothermal CHP systems.

Parameter	Unit	Value
Maximum Electric Power	(kW _{el})	101.4
Maximum Thermal Power	(kW _{th})	249.5
Electric Production	(MWh _{el})	820.8
Thermal Production	(MWh _{th})	357.4
Electric Self-consumption	(%)	94.9
Electric Surplus	(%)	59.0
Electric Integration	(%)	5.1
Thermal Self-consumption	(%)	90.2
Thermal Surplus	(%)	0.0
Thermal Integration	(%)	9.8
Global Electric Efficiency	(%)	13.4
Energy Utilisation Factor	(%)	19.3
Equivalent Operating hours	(h)	8095
Natural gas consumption	(Sm ³)	4512.6
Natural gas saving	(Sm ³)	41,386.0
Initial investment	(k€)	636.8
Net present value	(k€)	1617.5
Payback period	(years)	4.90
Reduced CO ₂ emissions	(tCO ₂)	253.8
Reduced GHG emissions	(tCO _{2,eq})	309.9

As already observed, the thermal surplus is absent, whereas the electricity injected into the grid is about 315 MWh_{el}. The natural gas consumption reduces to 4512.6 Sm³ and corresponds to 9.8% of the quantity that should be used to satisfy the total thermal request of the commercial centre, adopting a traditional gas-fired boiler.

The significant fossil fuel saving, and the noticeable rate of electric self-consumption, have a positive influence on the environmental impact of the integrated energy system. For this purpose, the standard and LCA (life cycle assessment) methodologies have been used [122,123] to evaluate the carbon dioxide (CO₂) and greenhouse gas (GHG) emissions, expressed as tons of CO₂ (t_{CO2}) and tons of CO₂ equivalent (t_{CO2,eq}), respectively. According to the standard approach, the emission factor for the electricity generation in Italy is equal to 0.343 t_{CO2}/MWh based on the national energy mix with both renewable and non-renewable sources, whereas the emission factor for the natural gas combustion is 0.202 t_{CO2}/MWh. The corresponding factors are equal to 0.424 t_{CO2,eq}/MWh and 0.240 t_{CO2,eq}/MWh when the LCA method is considered [122,123].

The investigation highlights that geothermal exploitation in the suggested CHP system assures an annual decrease in the CO₂ and GHG emissions larger than 250 t_{CO2} and 300 t_{CO2,eq}, respectively, compared to the traditional methods to fulfil the user's energy request (electricity from the grid and thermal energy from a gas-fired boiler) and demonstrates that the integrated apparatus with the mixed operating strategy guarantees proper energy, economic and environmental performance. The proposed CHP geothermal system, developed for a commercial centre, can be easily extended and adapted to other applications (e.g., industries, dwellings, smart communities) owing to the high flexibility and the possibility to adopt different operating strategies depending on the user's energy requests. In this way, the distributed exploitation of renewable sources and local small-scale energy production can drive a faster and softer transition from fossil fuels and traditional technologies towards cleaner and more sustainable energy solutions.

4. Conclusions

A techno-economic analysis was carried out to investigate the energy performance and the viability of an innovative CHP system, based on a transcritical geothermal-driven ORC unit and a heat exchanger (HEX) for the exploitation of a high-temperature geothermal source (230 °C). The sub-systems operate in parallel to satisfy the energy request of a commercial centre. Depending on the energy demand, the geofluid drives both the ORC and HEX sub-units: at full electric load, the geothermal water drives the sole ORC and no thermal production is present, whereas at partial load a fraction of the geofluid feeds the HEX system.

A thermodynamic model was developed to predict the performance of the geothermal-driven integrated system at full and part loads. First of all, the influence of the maximum temperature on the ORC behaviour was evaluated through a parametric investigation for both simple and regenerative ORC arrangements and the proper system configuration was defined by adopting a multi-variable optimisation. To this purpose, electric power and efficiency were considered as objective parameters and the "minimum distance" method was used to find the most suitable apparatus. In particular, the optimised system consists of a regenerative 101.4 kW kW_{el} ORC unit with 17.4% electric efficiency and a geothermal heat exchanger that guarantees 249.5 kW_{th}.

As a test case, the application of the integrated CHP system to a commercial centre located in Phlegraean Fields (Southern Italy) was considered and the payback time was used to evaluate the economic viability. To this aim, the costs of the different components were estimated through the bare module cost methodology and three operating strategies were compared: electric- and thermal-driven and mixed strategies. For each operating mode, the yearly electric and thermal energy balances were evaluated on an hourly basis. The results highlight that mixed-mode represents the best solution according to both energy and economic points of view. Particularly, the integrated system provides an electric and thermal self-consumption higher than 90%, while thermal and electric strategies revealed lower performance (electric self-consumption lower than 50% for the thermal-driven mode and thermal

self-consumption less than 70% for the electric strategy). Furthermore, the mixed strategy assures no heat dumping and the highest equivalent hours of operation—i.e., 8095—whereas thermal- and electric-driven strategies show 2977 and 6028 h, respectively. Finally, the payback time lower than five years confirms that the proposed system represents a viable technical solution for small-scale and combined energy production, able to give a contribution in the transition towards cleaner and more sustainable technologies. Specifically, the geothermal exploitation in the suggested integrated apparatus provides a yearly CO₂ emission reduction of more than 250 tons and a greenhouse gas saving of more than 300 tons of CO₂ equivalent per year.

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Nomenclature

A	Area of heat exchanger (m ²)
b	Bare module coefficient (-)
C	Cost (€)
c	Bare module coefficient (-)
D	Tube diameter (m)
d	Minimum dimensionless distance (-)
$e_{EUR/USD}$	Euro/US dollar exchange rate (€/€)
F_M	Bare module factor (-)
F_M	Material factor (-)
F_p	Pressure factor (-)
H	Heat transfer coefficient (W/m ² K)
h	Enthalpy (J/kg)
K	Thermal conductivity (W/m K)
k	Bare module coefficient (-)
$\dot{m}$	Mass flow rate (kg/s)
P	Power (W)
p	Pressure (Pa)
R_f	Fouling factor (m ² K/W)
S	Size parameter (m ² or kW)
s	Entropy (J/kg K)
T	Temperature (°C)
U	Global heat exchange coefficient (W/m ² K)

Greek characters

Δ	Difference
η	Efficiency

Subscripts and superscripts

c	Cold
$cool$	Cooling system
el	Electric
em	Electro-mechanical
eq	Equivalent
g	Geothermal
h	Hot
i	Inside

<i>in</i>	Inlet
<i>j</i>	Generic component
<i>k</i>	Generic configuration
<i>lm</i>	Logarithmic mean
<i>mar</i>	Marginal
max	Maximum
min	Minimum
<i>o</i>	Outside
<i>out</i>	Outlet
<i>p</i>	Pump
<i>ref</i>	Reference
<i>t</i>	Turbine
<i>th</i>	Thermal
0	Base conditions

Acronyms

CEPCI	Chemical engineering plant cost index
CHP	Combined heat and power
EUF	Energy utilisation factor
GHG	Greenhouse gas
HEX	Heat exchanger
HVAC	Heating, ventilation and air conditioning
IHE	Internal heat exchanger
LCA	Life cycle assessment
ODP	Ozone depletion potential
ORC	Organic Rankine cycle

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