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Exergo-economic and Exergo-environmental analysis of an ORC for a geothermal application

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ABSTRACT

Novel geothermal power plant concepts have been flourished in the last years, due to the issues related to environmental concerns and particularly to the emission of Non-Condensable Gases (NCGs). Total rejection is one of the innovative solutions that are emerging. This technology is built upon the concept of closed-loop binary cycle, which exploits only the heat from the geothermal fluid and thus provide the potentiality of realization of a 'zero-emission' power plant.

In this manuscript, a throughout assessment of Castelnuovo power plant case study is presented. The analysis, starting from a thermodynamic approach, is extended to include Exergy, Exergo-Economic, Life Cycle Assessment and Exergo-Environmental aspects. The analysed case study represents an innovative geothermal power plant which includes an ORC working with R1233zd(E), and a specifically designed NCGs re-compression train.

The exergy, exergo-economic and exergo-environmental analyses are the optimal tools which allow identifying the components responsible for the largest inefficiency, as well as the contribution to the build-up of cost of electricity, and to the environmental cost. The calculated Levelized cost of Electricity for the case study is 7.15 c€/kWh and the obtained total environmental impact of electricity generation is 2.65 mPts/MWh.

1. INTRODUCTION

The possibility of utilizing geothermal energy is rising a particular interest in the last years, since it is an attractive 'renewable' natural energy which, depending on its characteristics, makes it possible not only to obtain heat for heating purposes and many other direct uses but also to produce electricity. Further advantages can also be obtained in the case of geothermal electricity production combined with the direct use of heat in cascades (combined heat and power production).

The traditional geothermal "cycle" for electricity production involves the use of the geothermal fluid (geothermal brine, from here on called geo-fluid) in the surface power plant (steam: dry steam power plants; pressurized hot water: single/double or triple flash power plants, from which steam is obtained by flashing (DiPippo, 2012)), from which the energy necessary to drive the turbines connected to the electric generators is derived. These cycles allow the best possible use of the thermodynamic energy of the natural fluid, maximizing efficiency. However, the non-condensable gases, extracted from the condenser with turbo-compressors driven by the main turbine, are released to the atmosphere after a dry/wet chemical treatment (in Italian power plants, contaminants are removed through AMIS ® technology, (Baldacci et al., 2005)) that reduces their H_2S and Hg content by more than 90%.

Most of the actual geothermal power plants are based on the flash steam cycles technology, but other promising technologies had a great development in recent years, such as Enhanced Geothermal Systems (EGS), and/or binary cycles technologies. Binary cycle technologies are becoming more and more utilized in geothermal applications, due to several advantages, such as the possibility of exploitation of low-medium temperature resources, as well as the potentiality to apply total reinjection. The Organic Rankine Cycle (ORC) technology is the most widespread plant, which takes advantage of a chemical substance or mixture that evolves in a close loop. The working fluid is heated by the geo-fluid in the evaporator in order to generate electricity (Fiaschi et al., 2017). The possibility of reinjecting all of the geo-fluid is of paramount importance, as it allows, not only to not release the Non-Condensable Gases (NCGs) to the atmosphere, but it also allows to maintain the original resource condition for a prolonged amount of time. Indeed, a significant improvement of the management of the resource has been testified by several cases, when applying only brine reinjection (Kaya et al., 2011; Rivera Diaz et al., 2016). Even of greater importance is the issue of NCGs. The majority of NCGs are Carbon Dioxide (CO_2), but also other very pollutant contaminants are present, such H_2S, CH_4, NH_3, and Boron or even heavy metals, (such as Hg) and salts (Zarrouk et al., 2014). The NCGs emissions bring a heavy score in terms of greenhouse emissions factor, especially in places, like Italy, where typical CO_2 levels within the geo-fluid are between 2 and 8%. This implies an emission factor in the range between 100 and 400 gCO_2/kWh (Sullivan et al., 2010). This is considered a "natural" emission, as it would probably reach the surface anyway because of natural fracture patterns (Bruscoli et al., 2015). Nonetheless, local utilization of geothermal energy develops a preferential pathway for the release of larger flow rates of CO_2 to the atmospheric environment (the upper values are close to those of advanced natural gas-fuelled power plants).

For the above reasons, a number of applications for research permits have been submitted to the competent authorities for the testing of pilot plants, albeit of modest unitary power, which aims to create systems with total re-injection of geothermal fluids and with "zero emissions", presenting product and/or process innovation, while guaranteeing the necessary feasibility and reliability.

2. THE CASTELNUOVO PROJECT

Castelnuovo project is centred on the development of an innovative operating scheme, which includes new technology for CO_2 reinjection (Shafaei et al., 2012). Particularly, the aim of the project is to demonstrate the possibility of complete reinjection of the resource (brine and NCGs) in the local geothermal reservoir. The defined pilot plant size is 5 MW (due to a limitation of the Italian laws), nonetheless, the Castelnuovo reservoir has a much higher capacity, therefore assuring the correct holding of the reinjected NCGs. The reinjection of the NCGs, which should be captured within permeable rocks or in local cavities, guarantees also the beneficial effect of maintaining the original reservoir pressure. Table 1 resumes the expected conditions of the resource, a saturated vapour with an 8% content of NCGs.

Figure 1 presents the scheme of Castelnuovo power plant. The power plant comprises of a subcritical recuperative ORC cycle and a NCGs re-compressor train. The ORC working fluid is R1233zd(E) and exploit the geothermal heat through a thermal exchange in the main heat exchanger (MHE). The geothermal brine is condensed, removed from the bottom and sent to the reinjection well. The NCGs, on the other hand, exits from the top of the MHE and are sent to the re-compression train.

Table 1: Resource conditions

Parameter	Unit	Value
Resource pressure	kPa	60-80
Resource temperature	°C	280
Resource depth	m	3500
NCGs	%	8

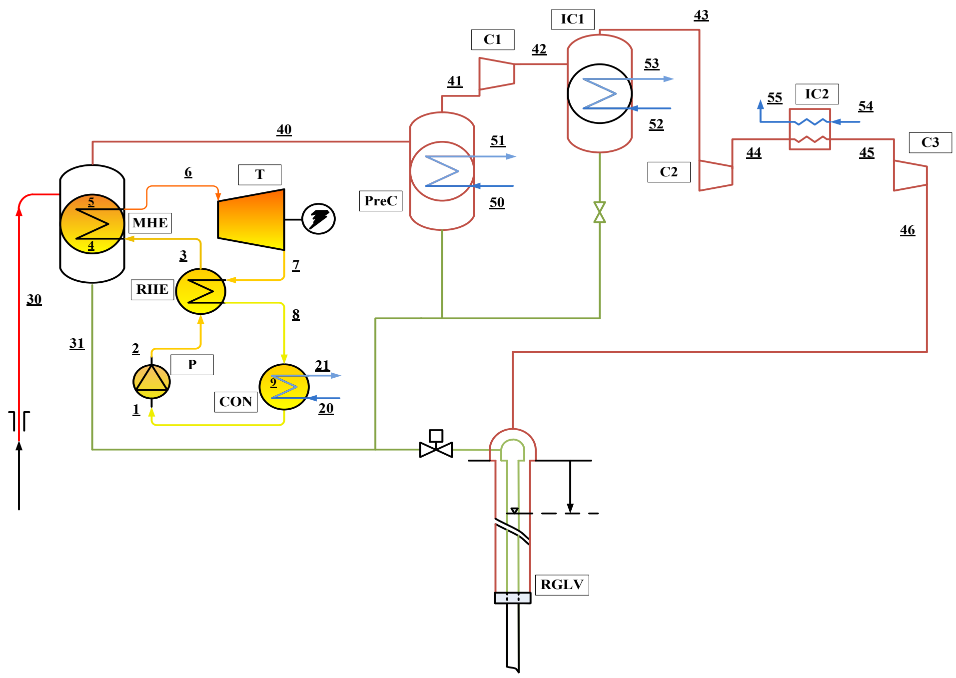

Figure 1 – Schematic of Castelnuovo power plants and wells/NCG reinjection arrangement MHE-Main Heat Exchanger; RHE-Regenerative Heat Exchanger; T- Turbine; CON – Air Cooled Condense; P-Pump; RGLV -Reverse Gas Lift Valve; PreC-Pre-cooler; C1-Compressor 1; IC1-Intercooler 1; C2- Compressor 2; IC2- Intercooler 2; C3- Compressor 3

3. POWER PLANT CALCULATIONS

In order to perform the thermodynamic calculations of the power plant, organic working fluid, and geothermal fluid accurate thermodynamic properties were needed. The working fluid properties were obtained from internal EES libraries (Klein & Nellis, 2012), which treat the properties of the fluids in terms of reduced Helmholtz energy. On the other hand, the geo-fluid properties have been computed through the development of ad-hoc models, as expressed in (Colucci et al., 2019). Table 2 resumes the assumed input data for the calculation, while table 3 displays the main obtained results.

Table 2: Assumed design input data for the Castelnuovo power plant

Parameter	Unit	Symbol	Value
Reference temperature	°C	T_0	15
Turbine isentropic efficiency	%	η_t	88
Pump isentropic efficiency	%	η_p	85
Geothermal fluid inlet temperature	°C	T_{30}	180
Geothermal fluid inlet pressure	kPa	P_{30}	1000
Net Power Output	kW	W_{net}	5000

Table 3: Main calculated performance parameters for the Castelnuovo Power Plant

Parameter	Unit	Symbol	Value
Geothermal mass flow rate	kg/s	$\dot{m}_{geo}$	11.09
CO_2 mass flow rate	kg/s	$\dot{m}_{CO_2}$	0.8869
Power plant efficiency	%	η	18.51
Heat input from Geothermal Fluid	kW	$\dot{Q}_{HE}$	26894

4. REINJECTION TRAIN CALCULATIONS

The calculation of the re-compression train performance was carried out starting from the available resource conditions (stream 30) and from the assumed depth of mixing between NCGs and water at 600 m from the surface. Particularly, the set mixing conditions of the reverse gas lift valve, impose the outlet pressure of the last compressor stage at 5841 kPa. Indeed, the re-compression train has been designed as a three-stage centrifugal compressor, comprising a pre-cooler and two-intercoolers. This configuration guarantees a drastic reduction of the necessary compression power. As for the ORC power plant, the computation was carried out assuming steady-state flow conditions. Table 4 shows the outcome of the calculation of the NCGs re-compression train.

Table 4: Calculated parameters for the NCG reinjection train

Point	Temperature [°C]	Pressure [kPa]
40	90	1000
41	65	1000
42	119.4	1801
43	60	1801
44	114.4	3243
45	60	3243
46	115.1	5841

Parameter	Unit	Symbol	Value
Heat Rate PreC	kW	$\dot{Q}_{PC}$	20.78
Power C1	kW	$\dot{W}_{C1}$	41.81
Heat Rate IC1	kW	$\dot{Q}_{IC1}$	51.53
Power C2	kW	$\dot{W}_{C2}$	39.88
Heat Rate IC2	kW	$\dot{Q}_{IC2}$	50.71
Power C3	kW	$\dot{W}_{C3}$	37.56

5. EXERGY AND EXERGO-ECONOMIC ANALYSIS

Exergy is defined as the maximum work that can be obtained by bringing the state of a system to equilibrium with that of the environment (Kotas, 1985). In the present study, the exergy analysis includes the detailed calculation of destructions and losses (1), of the exergy efficiency (3) and exergy destruction ratio (4) in each k-th component of the, as well as for the overall system. Based on the function of a component, appropriate costs can be allocated to the fuel (F), product (P), destructions (D) or losses (L). In general terms, the exergy balance is expressed as follows:

$$\sum \dot{Ex}_{F,k} = \sum \dot{Ex}_{P,k} + \sum \dot{Ex}_{D,k} + \sum \dot{Ex}_{L,k} \tag{1}$$

The physical exergy of each state point is considered as:

$$\dot{Ex}_i = \dot{m}_i[(h_i - h_o) - T_o(s_i - s_o)] \tag{2}$$

where m_i is the mass of substance under consideration; h_i, s_i are, respectively, the enthalpy and entropy of the considered stream of matter; h_0, s_0 are the enthalpy and entropy of this matter in equilibrium state with the environment at the reference temperature T_0 and pressure p_o. The exergy efficiency of each component is defined as:

$$\varepsilon_k = \frac{\dot{Ex}_P}{\dot{Ex}_F} \tag{3}$$

while the exergy destruction ratio is calculated as:

$$\chi_k = \frac{\dot{Ex}_D}{\dot{Ex}_{D,tot}} \tag{4}$$

The Exergo-Economic Analysis (EEA) combines the exergy and the economic analyses, in order to provide a clear and efficient evaluation of the cost effectiveness of each component of the power plant, introducing the costs per exergy unit (Bejan et al., 1996). Exergy accounting involves cost balances formulated separately for each component. The annual investment costs of the k-th component is calculated from:

$$Z_k^{an} = \frac{ir \cdot (1 + ir)^n}{(1 + ir)^n - 1} Z_k \tag{5}$$

Where: ir is the interest rate, which was here assumed at 10%, n is the year lifetime here assumed at 20 years, $\dot{Z}_k$ is the sum of the cost rates associated with investments and operation and maintenance for the k-th component.

Economic correlations are applied to obtain the investment, operation and maintenance (O&M) costs of each component. The methodology proposed in (Turton, 2013) was adopted in this case. The component cost was obtained based on construction materials, working pressure and type of component. The obtained equipment costs were updated to the reference year, 2019, through the CEPCI (Chemical Engineering Plant Cost Index) inflation index (CEPCI, 2020). As proposed by (Schuster et al., 2009), the O&M cost for each component were defined as a fraction (1.5%) of the Purchased Equipment Costs (PEC). The Total Capital investment cost was calculated following the methodology used in (Fiaschi et al., 2017). The yearly working hours of the plant were assumed to be 7446 h/yr, which is reported as a reference value for geothermal power plants (Shokati et al., 2015). The exergy cost balance applied to kth component is shown in (6):

$$\sum_{e}^{N_e} \dot{C}_{P,e,k} = \sum_{i}^{N_i} \dot{C}_{F,i,k} + \dot{Z}_k$$
$$\sum_{e}^{N_e} \left(c_{P,e}\dot{E}x_{e,k}\right)_k = \sum_{i}^{N_i} \left(c_{F,i}\dot{E}x_{F,i}\right)_k + \dot{Z}_k \tag{6}$$

Where $\dot{C}_{P,k}$ and $\dot{C}_{F,k}$ are the cost rates associated with the exergy product and fuel; $c_{P,k}$ and $c_{F,k}$ are the costs per exergy unit of product or fuel, respectively. If there are N_e exergy streams exiting the k-th component, we have N_e unknown and only one equation. Therefore, $N_e - 1$ auxiliary equations must be formulated and coupled to the system of the cost balance equations. Such an approach is accomplished with the Fuel and Product principles in the SPECO method (Lazzaretto & Tsatsaronis, 2006). The exergy destruction cost rate can be calculated by:

$$\dot{C}_{D,k} = c_{F,k} \cdot \dot{E}x_{D,k} \tag{7}$$

Finally, an exergo-economic factor, which associates the investment cost of the component to the sum of the investment cost and the cost of exergy destruction, can be calculated through:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{8}$$

The system considered in this work consists of 11 components and 27 streams. Therefore, 16 auxiliary equations were necessary to be applied and they are presented in Table 5.

Table 5 - Cost balance and auxiliary equations of each component

k	Component	Cost balance equations	Auxiliary equations
1	P	$c_2\dot{E}x_2 = c_1\dot{E}x_1 + c_{W_p}\dot{W}_p + \dot{Z}_p$	$c_{W_p}=c_{W_t}$
2	RHE	$c_3\dot{E}x_3 + c_8\dot{E}x_8 = c_2\dot{E}x_2 + c_7\dot{E}x_7 + \dot{Z}_{HE}$	$c_7 = c_8$
3	MHE	$c_6\dot{E}x_6 + c_{31}\dot{E}x_{31} + c_{40}\dot{E}x_{40} = c_3\dot{E}x_3 + c_{30}\dot{E}x_{30} + \dot{Z}_{HEgeo}$	$c_{30} = c_{31}$ $c_{40} = c_{30}$
4	T	$c_7\dot{E}x_7 + c_{W_t}\dot{W}_t = c_6\dot{E}x_6 + \dot{Z}_t$	$c_6 = c_7$
5	CON	$c_1\dot{E}x_1 + c_{21}\dot{E}x_{21} = c_8\dot{E}x_8 + c_{20}\dot{E}x_{20} + \dot{Z}_{cond}$	$c_{20}=0$ $c_{21} = c_{20}$
6	PreC	$c_{41}\dot{E}x_{41} + c_{51}\dot{E}x_{51} = c_{40}\dot{E}x_{40} + c_{50}\dot{E}x_{50} + \dot{Z}_{PC1}$	$c_{50}=0$ $c_{40} = c_{41}$
7	C1	$c_{42}\dot{E}x_{42} = c_{41}\dot{E}x_{41} + c_{W_{c1}}\dot{W}_{c1} + \dot{Z}_{c1}$	$c_{W_{c1}}=c_{W_t}$
8	IC1	$c_{43}\dot{E}x_{43} + c_{53}\dot{E}x_{53} = c_{42}\dot{E}x_{42} + c_{52}\dot{E}x_{52} + \dot{Z}_{IC1}$	$c_{52} = c_{50}$ $c_{43} = c_{42}$
9	C2	$c_{44}\dot{E}x_{44} = c_{43}\dot{E}x_{43} + c_{W_{c2}}\dot{W}_{c2} + \dot{Z}_{c2}$	$c_{W_{c2}}=c_{W_t}$
10	IC2	$c_{45}\dot{E}x_{45} + c_{55}\dot{E}x_{55} = c_{44}\dot{E}x_{44} + c_{54}\dot{E}x_{54} + \dot{Z}_{IC2}$	$c_{54} = c_{50}$ $c_{45} = c_{44}$
11	C3	$c_{46}\dot{E}x_{46} = c_{45}\dot{E}x_{45} + c_{W_{c3}}\dot{W}_{c3} + \dot{Z}_{c3}$	$c_{W_{c3}}=c_{W_t}$

In the above equations, the cost of the inlet fuel stream c_{30} (geothermal brine) is assumed as the investment cost of the production and re-injection wells system divided by the total exergy extracted from the well in its lifetime operation (20 years). The well cost was evaluated applying equation (9) (Dumas et al., 2013):

$$Well\ cost = n_{wells} * 2.5 * 1000 * D \tag{9}$$

Where n_{wells} is the total number of wells and D is the wells depth.

6. ENVIRONNMENTAL IMPACT AND EXERGO-ENVIRONMENTAL ANALYSIS

The environmental impact of the electricity produced in the geothermal power plant was analyzed using methodology developed by the European Commission to evaluate the environmental impacts of products and organisations (European Commission, 2013) called the Product/ Organisation Environmental Footprint (PEF/OEF or generically EF). The EF impact assessment is a multicriteria measure based on a life-cycle approach and is used to model the environmental impacts of the input and output flows and it is recommended to evaluate the environmental performance of geothermal systems (Parisi et al., 2020).

In this study, the evaluation is made using methodological framework EF 2.0 developed during the EF Pilot Phase. All relevant inputs and outputs (materials, energy and resulting emissions and wastes) associated with the product are considered from a cradle to grave perspective, means that the assessment includes the raw material extraction, processing, distribution, storage, use, and disposal or recycling stages. The EF impact assessment include two mandatory steps i.e. classification and characterization and may be complemented with two optional steps: normalization and weighting. The input and output flows are classified and characterized using the international reference life cycle data system (ILCD) midpoint method for 16 impact categories, that covers all relevant environmental issues related to the electricity production. Table 6 provides a list of EF impact categories and related assessment methods used in this study.

Table 6 – List of impact categories adapted in Environmental Footprint 2.0

Name	Unit	Model
Climate change (biogenic, fossil, land use and land use change)	kg $CO_{2\ eq}$	Radiative forcing as Global Warming Potential (GWP100. Version 1.0.5 (land use, land use change, biogenic), 1.0.8 (fossil), 4.0.16, IPCC 2013 (Stocker et al., 2013)
Ozone depletion	kg CFC-11 $_{eq}$	EDIP model based on the ODPs of the World Meteorological Organization (WMO) over an infinite time horizon Version 2.0.12, WMO 1999 (WHO, 1999)
Acidification	mol H^{+}_{eq}	Accumulated Exceedance model. European country-dependent. Version 1.3.9 (Seppälä et al., 2006) and (Posch et al., 2008)
Ecotoxicity, freshwater	CTU_e	USEtox™ consensus model. Version 1.02. and 1.03 (Rosenbaum et al., 2008)
Human toxicity, cancer	CTU_e	USEtox™ consensus model. Version 1.02. and 1.03 (Rosenbaum et al., 2008)
Human toxicity, non-cancer	CTU_e	USEtox™ consensus model. Version 1.02. and 1.03 (Rosenbaum et al., 2008)
Eutrophication, marine	kg N $_{eq}$	Fraction of nutrients reaching freshwater end compartment (P) using the EUTREND model as implemented in ReCiPe. European country-dependent. Version 2.0.10 (Struijs et al., 2012)
Eutrophication, freshwater	kg P $_{eq}$	Fraction of nutrients reaching freshwater end compartment (P) using the EUTREND model as implemented in ReCiPe. European country-dependent. Version 1.0.10 (Struijs et al., 2012)
Eutrophication, terrestrial	mol N $_{eq}$	Accumulated Exceedance model. European country-dependent. Version 1.2.9 (Seppälä et al., 2006) and (Posch et al., 2008)
Ionising radiation, human health	kBq U^{235}	Human exposure efficiency relative to U235 using the Human health model. Valid on global and European scale. Version 1.0.11 (Frischknecht et al., 2000)
Particulate Matter	Disease incidence	Human health effects associated with exposure to PM2.5 from the PM method recommended by UNEP. Version 2.0.11 (UNEP/SETAC, 2016)
Photochemical ozone formation - human health	kg NMVOC $_{eq}$	Tropospheric ozone concentration increases from LOTOS-EUROS as applied in ReCiPe 2008. Version 2.0.13 (van Goethem et al., 2013)
Land use	Dimensionless aggregated index	Soil quality index (biotic production, erosion resistance, mechanical filtration and groundwater replenishment) based on LANCA. Version 1.0.10 (Bos et al., 2016)
Resource use, fossils	MJ	ADP for energy carriers. Version 1.0.10 (De Oers et al., 2002) and (Guinée et al., 2002)
Resource use, minerals and metals	kg Sb $_{eq}$	ADP for mineral and metal resources. Version CML v4.8 (De Oers et al., 2002) and (Guinée et al., 2002)
Water use	m^3	AWARE 100 (based on UNEP 2016) User deprivation potential (deprivation-weighted water consumption). Version 3.0.14 (UNEP/SETAC, 2016)

After the characterization, optional steps i.e. normalization and weighting are applied. In order to obtain normalized EF values, results are multiplied by normalization factors (PEF standard normalization factors) that represent the overall inventory of a reference unit (e.g. a whole country or an average citizen). Normalized EF impact assessment results are dimensionless, and reflect the contribution of the examined system to the total impact potential without considering the importance of the respective impact. In order to provide the result that can be directly compared across impact categories, and also summed across impact categories to obtain a single value overall impact indicator, the normalized EF impact results are multiplied by set of weighting factors (PEF standard weighting factors).

An open-source software, OpenLCA (Ciroth et al., 2019) and the Environmental Footprint Secondary data database were used for the background data modelling and environmental assessment. In the present study, the component – related environmental impact $\dot{Y}_k$, was calculated including the following system boundary stages: 1) production of raw materials and manufacturing of components (CO), 2) operational and maintenance phase (OM) 3) end of life phase, that includes decommissioning and recycling or disposal of components (DI) and 4) transportation above mentioned stages.

$$\dot{Y}_k = \dot{Y}_{CO} + \dot{Y}_{OM} + \dot{Y}_{DI} \tag{10}$$

Concerning the definition of the system boundaries, a 1% cut-off was set (a value coherent with the exergo-economic analysis). The functional unit of the LCA was set at 1 MWh of output electricity. A 30 years lifetime was assumed. In the construction phase, geothermal deep well drilling, collection pipelines, power plant machinery and power plant buildings are considered. As far as operation stage is considered, consumption of lubricating oil and refilling and leakage of ORC working fluid are considered. The environmental impact of the working fluid leakage is taken into account assuming an annual loss rate of 0.5 % (Ding et al., 2018). With the present binary cycle, full reinjection is considered. Therefore, air emissions from geothermal fluid during the power plant operation are not included in the LCI. The End-of-life stage includes well closure. The detailed inventory data with the corresponding EF 2.0 compliant datasets are summarized in Table 7.

Table 7 Summary of equipment sizes and materials inventory for the 5 MW (net power) ORC.

Equipment/material - geothermal wells	Quantity	Unit	Environmental Footprint 2.0 compliant dataset
Geothermal well - Material requirements for wellhead equipment	3	well	Total length: 3500 m (CAS_P1); 3615 m (CAS_P2); 3670 m (CAS_I)
Fill	3800	m^3/well	Gravel, production mix, at plant, wet and dry quarry, drying, grain size 2/32 - EU-28+EFTA
Concrete	88	kg/well	Portland cement, production mix, at plant, raw material extraction, production of clinker, and cement grinding, CEM I 32.5 - EU-28+EFTA
Steel	71446	kg/well	Steel cast part alloyed, single route, at plant, electric arc furnace route, from steel scrap, secondary production, carbon steel - ROW
Stainless steel	78	kg/well	Stainless steel cold rolled, production mix, at plant, hot rolling, stainless steel – ROW
Aluminum	5971	kg/well	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+EFTA
Wells construction	10785	m	Total length: 3500 m (CAS_P1); 3615 m (CAS_P2); 3670 m (CAS_I)
Steel	100,200	kg/m	Steel cast part alloyed, single route, at plant, electric arc furnace route, from steel scrap, secondary production, carbon steel – ROW
Diesel	159,300	kg/m	Diesel combustion in construction machine, diesel driven – GLO
Portland cement	36,969	kg/m	Portland cement, production mix, at plant, raw material extraction, production of clinker, and cement grinding, CEM I 32.5 - EU-28+EFTA
Drilling fluid	10785	m	
Bentonite	7,449	kg/m	activated bentonite production, production mix, at plant, technology mix, 100% active substance – GLO
Barite	39,722	kg/m	barite production, production mix, at plant, technology mix, 100% active substance – GLO
Caustic Soda	0,248	kg/m	Sodium hydroxide production, production mix, at plant, technology mix, 100% active substance – RER
Poly_Plus RD	0,328	kg/m	polyacrylamide production, production mix, at plant, technology mix, 100% active substance – RER
Resinex e/o Rheomate	2,896	kg/m	Lignite mix, consumption mix, to consumer, technology mix - EU-27
Spersene CF	0,414	kg/m	basic chrome sulfate production, production mix, at plant, technology mix, 100% active substance – ZA
Water (in cement)	17,803	kg/m	-
Water (in drilling well)	11219,286	kg/m	-
Piping ORC - wells	390	m	115 m, 160 m, 115 m
Steel	6,767	kg/m	Drawing of steel pipe, single route, at plant, slab casting, rolling, pickling, thermal treatment, 1m length - ROW
INOX 316 L	0,556	kg/m	Stainless steel cold rolled, production mix, at plant, hot rolling, stainless steel - ROW
Mineral wool	2,577	kg/m	Glass wool, production mix, at plant, fleece, density between 10 to 100 kg/m3 - EU-28
Equipment/material - machinery	**Quantity**	**Unit**	**Environmental Footprint 2.0 compliant dataset**
Turbine	5409	kW	
Reinforcing Steel	56176	kg	Stainless steel cold rolled, production mix, at plant, hot rolling, stainless steel – ROW
Steel, low-alloyed	92530	kg	Steel cast part alloyed, single route, at plant, electric arc furnace route, from steel scrap, secondary production, carbon steel – ROW
Chromium steel 18/8	2017	kg	Stainless steel cold rolled, production mix, at plant, hot

			rolling, stainless steel – ROW
Copper	5452	kg	copper oxide production, production mix, at plant, technology mix, 100% active substance – RER
Aluminum	3094	kg	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+EFTA
Cast iron	1644	kg	Cast iron, single route, at plant, electric arc furnace route, from steel scrap, secondary production, > 2,06 % carbon content - EU-28+EFTA
Polyethylene, HDPE	1364	kg	HDPE granulates, production mix, at plant, Polymerisation of ethylene, 0.91- 0.96 g/cm3, 28 g/mol per repeating unit - EU-28+EFTA
Air cooled condenser	21775	kW	
Steel low-alloyed	10537	kg	Steel cast part alloyed, single route, at plant, electric arc furnace route, from steel scrap, secondary production, carbon steel – ROW
Chromium steel 18/8	687	kg	Stainless steel cold rolled, production mix, at plant, hot rolling, stainless steel – ROW
Aluminum	381	kg	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+EFTA
Polyethylene HDPE	1923	kg	HDPE granulates, production mix, at plant, Polymerisation of ethylene, 0.91- 0.96 g/cm3, 28 g/mol per repeating unit - EU-28+EFTA
Economizer + Evaporator	26894	kW	
Copper tube	5353	kg	Copper tube, single route, at plant, melting and mechanical treatment (fabrication), 8.92 g/cm3 - EU-28+EFTA
Cast iron	611	kg	Cast iron, single route, at plant, electric arc furnace route, from steel scrap, secondary production, > 2,06 % carbon content - EU-28+EFTA
Steel	86	kg	Steel cast part alloyed, single route, at plant, electric arc furnace route, from steel scrap, secondary production, carbon steel – ROW
Pump	290	kW	
Stainless steel	319	kg	Stainless steel cold rolled, production mix, at plant, hot rolling, stainless steel – ROW
Copper	106	kg	copper oxide production, production mix, at plant, technology mix, 100% active substance - RER
Recuperator	4044	kW	
Copper tube	805	kg	Copper tube, single route, at plant, melting and mechanical treatment (fabrication), 8.92 g/cm3 - EU-28+EFTA
Cast iron	92	kg	Cast iron, single route, at plant, electric arc furnace route, from steel scrap, secondary production, > 2,06 % carbon content - EU-28+EFTA
Steel	13	kg	Steel cast part alloyed, single route, at plant, electric arc furnace route, from steel scrap, secondary production, carbon steel – ROW
Compressors	41.8/39.9/37.6	kW	
Steel	164/159/159	kg	Steel cast part alloyed, single route, at plant, electric arc furnace route, from steel scrap, secondary production, carbon steel – ROW
Cast iron	123/119/119	kg	Cast iron, single route, at plant, electric arc furnace route, from steel scrap, secondary production, > 2,06 % carbon content - EU-28+EFTA
Copper wire	82/79/79	kg	Copper Wire Drawing, single route, at plant, wire drawing, 8.92 g/cm3 - EU-28+EFTA
Aluminum	57/56/56	kg	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+EFT
Precooler/Intercoolers	4.7/ 4.6/ 1.3/ 4.67/ 2.73	m^2	
Stainless steel	100.72/374.8/368.8/355.3/207.84	kg	Stainless steel cold rolled, production mix, at plant, hot rolling, stainless steel – ROW
Working fluid R1233zd	30 831	kg	Tetrafluoroethane (R134a) , production mix, at plant, estimation, 102.03 g/mol ; Melting point −103.3 °C;

			Boiling point −26.3 °C; - DE
Building			
Steel	49615	kg	Steel cast part alloyed, single route, at plant, electric arc furnace route, from steel scrap, secondary production, carbon steel – ROW
Concrete	2073450	kg	Concrete C20/25 (Ready-mix concrete) , production mix, at plant, technology mix, C20/25 - DE
Filling	3415	m^3	Gravel, production mix, at plant, wet and dry quarry, drying, grain size 2/32 - EU-28+EFTA
Operation and Maintenance	30	y	Lifetime
Lubrificating oil	1000	l/y	Lubricants at refinery, production mix, at refinery, from crude oil, 41.8 MJ/kg net calorific value - EU-28+3
Refilling working fluid	154.155	kg/y	Tetrafluoroethane (R134a) , production mix, at plant, estimation, 102.03 g/mol ; Melting point −103.3 °C; Boiling point −26.3 °C; - DE
Air emission (working fluid loss)	154.155	kg/y	
Wells closure	10785	m	
Diesel	6.68	kg/m	Diesel combustion in construction machine, diesel driven - GLO
Filling	1.7	kg/m	Gravel, production mix, at plant, wet and dry quarry, drying, grain size 2/32 - EU-28+EFTA
Portland cement	8	kg/m	Portland cement, production mix, at plant, raw material extraction, production of clinker, and cement grinding, CEM I 32.5 - EU-28+EFTA

The Exergo-Environmental Analysis (EEvA) represents the natural follow-up of the LCA: EEvA starts from the allocation of the LCI to all powerplant components, and analyzes the progressive build-up of the environmental costs along the processes (Meyer et al., 2009). The EEvA can be carried out similarly to the thermo-economic analysis replacing the environmental costs (EF 2.0 Pts) to the economic costs – still referring to the exergy unit. The environmental cost rates related to each j-stream $\dot{B}_j$ (Pts/s) are allocated to their exergy content $\dot{Ex}_j$ (kJ or kWh) to evaluate the specific environmental impacts b_j (Pts/kJ; or Pts/kWh referring to the final cost of electricty) through:

$$b_j = \frac{\dot{B}_j}{\dot{Ex}_j} \tag{11}$$

This methodology is based on the solution of impact balances performed for each k – th component, using (12):

$$\sum \dot{B}_{j,k,in} + \dot{Y}_k = \sum \dot{B}_{j,k,out} \tag{12}$$

Where $\dot{Y}_k$ (mPts/s) is the environmental impact rate associated with the construction, O&M and disposal phases. This parameter is clearly connected with the LCA results, which are expressed considering 1 MWh of electricity as a functional unit (Pts/MWh). In practice, the single score impact was multiplied by the yearly productivity; after that, an impact rate $\dot{Y}_k$ was achieved. The environmental costs per unit of exergy (Pts/MWh) of product $b_{P,k}$ and fuel $b_{F,k}$ were defined as in the case of EEA. This allows the evaluation of the environmental cost rate $\dot{B}_{D,k}$ (mPts/s) associated to the exergy destruction occurring inside each component through:

$$\dot{B}_{D,k} = b_{F,k} \cdot \dot{Ex}_{D,k} \tag{13}$$

An exergo-environmental factor $f_{d,k}$, representing the percentage contribution of $\dot{Y}_k$ compared to the total $\dot{B}_{D,k} + \dot{Y}_k$, can be calculated using (14):

$$f_{d,k} = \frac{\dot{Y}_k}{\dot{B}_{D,k} + \dot{Y}_k} \tag{14}$$

The relative difference of the specific environmental impacts for the k-th component is given in the following equation (15):

$$r_{d,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} \tag{15}$$

7. RESULTS

7.1 Exergy and Exergo-economic analysis

Figure 2 shows the non-dimensional exergy destruction for each component of the cycle. As shown, the highest relative exergy destruction comes from the geothermal heat exchanger. This result means that an improved matching of the heat capacity of the cold and hot sides of the MHE main heat exchanger can have a relevant effect on the system performance. After the MHE, the condenser exergy loss and the turbine exergy destruction represent the largest contributions compared to the remaining components.

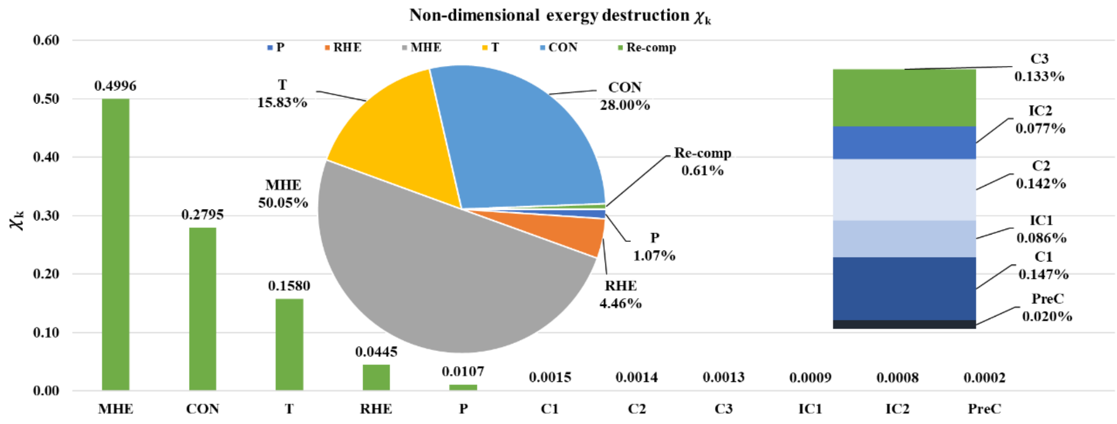

Figure 2 - Non-dimensional exergy destruction for each component

The calculated values from the EEA are represented in Table 8. In the economic analysis, the turbine and the MHE heat exchanger are most expensive powerplant components. As shown from this table, the sum of the capital cost rate and exergy destruction cost for these three components is larger than for other ones. The specific cost of the turbine output product represents the levelized cost of electricity (LCOE). In the present case, the obtained value of the LCOE is 0.0715 €/kWh, which is attractive for geothermal electricity compared to other renewables.

Table 8 – The exergoeconomic values of the cycle

Component	PEC (€)	$\dot{Z}_k$ (€/s)	$\dot{C}_{D,k}$ (€/s)	$\dot{Z}_k + \dot{C}_{D,k}$ (€/s)	$c_{F,k}$ (€/kWh)	$c_{P,k}$ (€/kWh)	f_k (%)
P	193464	0.001558	0.0008032	0.002361	0.07148	0.1056	65.99
RHE	438204	0.00353	0.00242	0.00595	0.05154	0.1009	59.32
MHE	2.920E+06	0.02352	0.009514	0.03303	0.01804	0.03419	71.2
T	2.651E+06	0.02136	0.008596	0.02995	0.05154	0.07148	71.3
CON	656282	0.005286	0.01634	0.02162	0.05538	0.2662	19.36
PreC	181662	0.001463	0.000003835	0.001467	0.01804	1.819	99.74
C1	126231	0.001017	0.0001109	0.001128	0.07148	0.1835	90.16
IC1	185022	0.00149	0.000053	0.001543	0.05869	0.8226	96.57
C2	120236	0.0009685	0.0001071	0.001076	0.07148	0.1837	90.05
IC2	219831	0.001771	0.00006767	0.001838	0.08384	1.008	96.32
C3	113008	0.0009102	0.0001005	0.001011	0.07148	0.1834	90.06

7.2 LCA and Exergo-environmental analysis

The annual single score environmental impacts and the contribution of the power plant components are presented in Figure 3. The total environmental impact of electricity produced in the analyzed binary power plant is 2.65 mPts/MWh. Furthermore, the highest impact value (2.29 mPts/MWh) is assigned to geothermal wells construction, that contributes for nearly 86 % to the total impact. This is mainly due to diesel combustion during drilling, as well as cement and steel consumption for the well casing. Significant contribution, almost 6 % to the total impact, is observed for operation and maintenance phase that includes working fluid refilling and it fugitive emissions as well as lubricating oil exchange . The overall contribution of the power plant components to the total associated environmental impact is rather small (below 5%). Regarding the machinery of the ORC power plant, the major contributor to the environmental impact is the turbine with generator accounting for almost 4.0 % of the total score (0.106 mPts/MWh), followed by the air cooled condenser whose impact is mainly due to steel, copper and aluminium for construction. The NCG reinjection train, consisting of the set of compressors and intercoolers, accounts for 0.07 % (0.002 Pts/MWh) of the total impact. Impact of working fluid and building were 0.037 and 0.026 mPts/MWh, respectively.

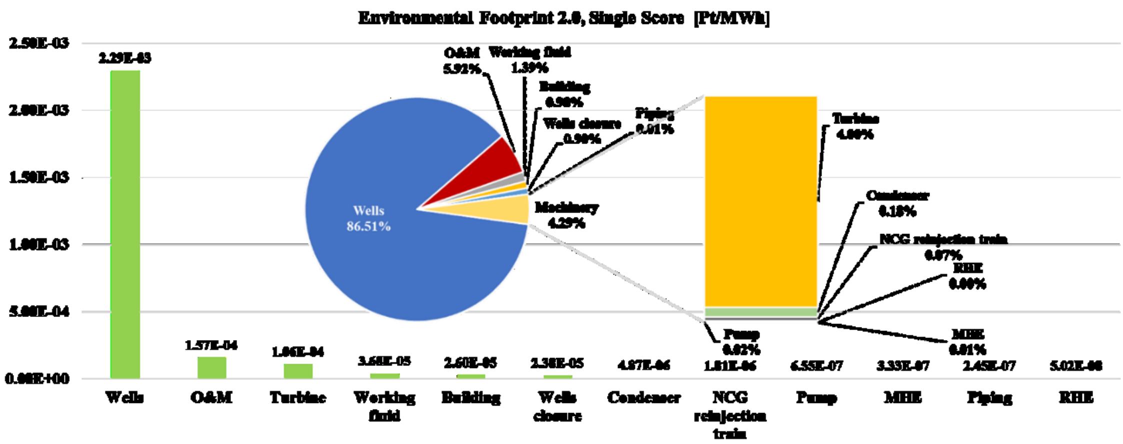

Figure 3 - Single Score environmental impacts of the analyzed systems.

Table 9 presents the results of the EEvA: the component-related environmental impact of a *k*-th component, the environmental impacts per exergy unit for product and fuel, the environmental impact rate associated with the exergy destruction within the *k*-th component, the exergo – environmental factor and the relative difference of the specific environmental impacts of fuel and product.

Table 9 – Summary of the exergo-environmental analysis

Component	$\dot{Y}_k$ (mPts/h)	$\dot{B}_{D,k}$ (mPts/h)	$\dot{B}_{D,k} + \dot{Y}_k$ (mPts/h)	$f_{D,k}$ (%)	$r_{D,k}$ (%)
P	0.018	0.118	0.136	13.0	18.7
RHE	0.016	0.111	0.127	12.5	30.6
MHE	0.625	2.534	3.159	19.8	33.6
T	0.782	1.460	2.241	34.9	18.2
CON	0.359	2.544	2.903	12.4	-
PreC	0.001	0.001	0.002	42.6	45.5
C1	0.002	0.015	0.017	13.3	17.8
IC1	0.003	0.006	0.009	33.5	67.2
C2	0.002	0.014	0.017	13.3	18.0
IC2	0.003	0.006	0.009	31.5	59.3
C3	0.004	0.014	0.017	21.0	19.7

The $f_{D,k}$ factor identifies the relevance of the impact coming from the exergy destruction of the k-th component. It is evident that for almost all of power cycle components (excluding geothermal wells) the environmental impact is mainly due to exergy destruction $\dot{B}_{D,k}$, whereas component construction $\dot{Y}_k$ contributes much less .
Concerning the total environmental impact ($\dot{Y}_k$+$\dot{B}_{D,k}$), the main heat exchanger is found to be the most impacting: among the power cycle machinery equipment, accounting for almost 36.5 % of the total environmental impact ($\dot{Y}_k$+$\dot{B}_{D,k}$), 20 % only of this total impact ($f_{D,k}$) is due to the environmental cost of component construction $\dot{Y}_k$, whereas 80 % is attributable to its exergy destruction ($\dot{B}_{D,k}$). In fact, the thermodynamic irreversibility in this component is the highest, as can be observed in Figure 2.
Another component significantly contributing to the environmental impact is the condenser (33.6 % total environmental impact ($\dot{Y}_k$+$\dot{B}_{D,k}$)), with a high relative environmental impact due to the exergy loss (88 %). In addition, a relevant environmental contribution to exergy destruction (1.460 mPts/h) is calculated for the turbine which sums to the largest contribution to the environmental cost of construction (0.782 mPts/h i.e. 26 % of the total environmental impact ($\dot{Y}_k$+$\dot{B}_{D,k}$).
The relative difference of specific environmental impacts $r_{D,k}$ is an indicator of the environmental quality of a component, allowing to assess the potential of reducing its environmental impact. As indicated in Table 8, precooler, intercoolers and heat exchangers represents a relatively high contribution which may address the possibility of an environmental impact reduction at low cost.

CONCLUSIONS

Total reinjection power plants are attracting a lot of interest in the last years, due to the increased attention toward environmental concerns. Total reinjection is possible when binary power cycles are utilized, exploiting the heat of the geothermal resource. The geo-fluid can therefore be completely reinjected thus avoiding the release of pollutants to the atmosphere. The investigation of this innovative technology is planned, under the cap of H2020 GECO Project. The presented case study represents a novel application in geothermal energy – a first-of-a-kind powerplant applying complete reinjection of non-condensable gases (NCGs).

The exergy, exergo-economic, LCA, and exergo-environmental analyses point out to the pathway of general performance improvement, identifying within the system, the components responsible for the largest irreversibilities, contribution to the build-up of cost of electricity, and to the environmental cost. Following the main achieved results:

- The largest exergy destructions source is the main heat exchanger (50%), followed by the ORC turbine (15%). The condenser is responsible for the highest exergy loss (28%).
- The exergo economic analysis showed the possibility of achieving an LCOE of 0.0715 €/kWh, which is attractive for geothermal electricity compared to other renewables.
- The yearly single score environmental impacts put in evidence that the total environmental impact of electricity generation (i.e. binary cycle) is 2.65 mPts/MWh. The highest impact is due to the well construction, with 2.29 mPts/MWh ; the overall contribution of the power plant components is relatively small (less than 5%).
- The exergo environmental analysis evidenced that highest impacting components, after the well, is the main heat exchanger, accounting for 36.5% of total power cycle machinery equipment impact, followed by the condenser (33.6 %) and turbine (26 %).

The results demonstrate that the powerplant is capable of producing electricity at an interesting cost and with sustainability indexes and may be competitive with the best renewable energy technologies.

NOMENCLATURE

$\dot{C}$	Cost rate associated with exergy transfer, $(€/s)$
c	Specific exergy cost, $(€/kJ)$
$\dot{B}$	Environmental cost rates, (Pts/s)
b	Specific environmental cost, (Pts/kWh)
D	Well depth, (m)
EEA	Exergo-Economic Analysis
$EEva$	Exergo-Environmental Analysis
$\dot{Ex}$	Exergy rate, (kW)
f	Exergo-economic factor
f_d	Exergo-environmental factor
h	Specific enthalpy, (kJ/kg)
ir	Interest rate
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
$LCOE$	Levelized Cost of Electricity, $(€/kWh)$
$\dot{m}$	Mass flow rate, (kg/s)
$NCGs$	Non-Condensable Gases
P	Pressure, (kPa)
$\dot{Q}$	Heat rate, (kW)
r	Relative difference of the specific environmental impacts
s	Entropy, (kJ/kgK)
T	Temperature, $(°C)$
$\dot{W}$	Power, (kW)
$\dot{Y}_k$	Environmental impact rate, $(mPts/s)$
Z	Capital cost of components, $(€)$
$\dot{Z}$	Capital cost rate of components, $(€/s)$
Greek	
η	Efficiency
ε	Effectiveness
Subscripts	
t	Turbine
p	Pump
geo	Geothermal
PC	Pre-cooler
C	Compressor
IC	Intercooler
HE	Heat exchanger
$Cond$	Condenser
L	Loss
D	Destruction
P	Product
F	Fuel
tot	Total
i	inlet
e	exit
0	Ambient

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