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Article

# Qualtra Geothermal Power Plant: Life Cycle, Exergo-Economic and Exergo-Environmental Preliminary Assessment

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**Abstract:** Qualtra, an innovative 10 MW geothermal power plant proposal, employs a closed-loop design to mitigate emissions, ensuring no direct release into the atmosphere. A thorough assessment utilizing energy and exergy analysis, Life Cycle Assessment (LCA), Exergo-economic and Exergo Environmental Analysis (EevA) was conducted. The LCA results, utilizing the ReCiPe 2016 midpoint methodology, encompass all the spectrum of environmental indicators provided. The technology implemented makes it possible to totally avoid direct atmospheric emissions from the Qualtra plant, so the environmental impact is mainly due to indirect emissions over the life cycle. The results obtained for the Global Warming Potential indicator is about 6.6 g CO<sub>2</sub>/kWh, notably lower compared to other conventional systems. Contribution analysis reveals that the construction phase dominates, accounting for over 90% of the impact in all LCA MidPoint categories. At the component level, a single score calculation incorporating normalization and weighting was executed. The resulting single score is then used into Exergo-Environmental Analysis (EEvA), highlighting the well system as the most impactful contributor, constituting approximately 45% of the total impact. Other substantial contributions to the environmental impact include the condenser (21%), the turbine (17%), and the HEGeo (14%). The Exergo-Economic analysis assesses cost distribution across major plant components, projecting an electricity cost of about 8.3 c€/kWh.

**Keywords:** geothermal power plant; closed loop; zero emission; life cycle analysis; exergy; exergo-economics; exergo-environmental analysis

## 1. Description of the QUALTRA Geothermal Project

QUALTRA is an innovative proposal of modern Geothermal Power Plant (GPP), applying for the first time closed-loop operation [1,2], that is, avoiding emissions to atmosphere. The technology applied relies on a binary cycle approach. As is shown in Figure 1, the geothermal resource (superheated steam at 10 bar and 180 °C is expected on this specific site, with a flow rate of 32.96 kg/s) heats the working fluid (R1233zd(E) in this specific case – a modern synthetic fluid with limited impact in case of release to the environment), which is then directed to the turbine of the Rankine cycle. An air-cooled condenser is applied to recover the condensate working fluid, which is then pressurized by a pump and sent back to the main heat exchanger (MHE). In this last condensation of the resource takes place at pressurized conditions (about 10 bars): in the process, the liquid brine is recovered, subcooled to preheat the working fluid and directed to reinjection in the reservoir. The NCG stream is collected at the dome of the MHE, and extracted using a set of intercooled compressors (water is recovered along the at the first intercoolers along the compressor line). The high-pressure NCG stream (mainly CO<sub>2</sub>) is directed to the innovative reinjection well. This operates following a new concept: two-phase flow reinjection (the liquid brine + the compressed NCG stream) is realized mixing the streams at substantial depths using a coaxial pipe arrangement and one or more reverse-gas-lift valves which allow the gas (which pass across the external annulus) into the inner pipe delivering the brine. The mixing conditions at depth take place at high pressure, and accurate two-



To achieve this objective, the Recipe 2016 method was employed. Additionally, a distinct Life Cycle Assessment (LCA) was executed for each primary component of the plant, enabling the calculation of individual single-score values for these components.

## 2.2. Life Cycle Inventory (LCI) for the QUALTRA Plant

In this section, the life cycle inventory referred to the Qualtra GPP is briefly reported (Tables 1 and 2).

**Table 1.** LCI - Main parameter.

Site-specific parameter	Unit	Value for QUALTRA
Reservoir		
Number of wells drilled	-	5
Total meters drilled	m	18520
Collection pipelines	m	1750
Power plant		
Net installed capacity-binary cycle	MW	10

**Table 2.** LCI - Geothermal Drilling and Well head.

Geothermal well	Unit	Amount
Drilling well		
Bentonite	kg/m <sub>wells</sub>	7.23
Barite	kg/m <sub>wells</sub>	38.55
Chemical, inorganic	kg/m <sub>wells</sub>	0.41
Chemical, organic	kg/m <sub>wells</sub>	3.22
Diesel	MJ/m <sub>wells</sub>	5534.10
Sodium Hydroxide	kg/m <sub>wells</sub>	0.37
Steel	kg/m <sub>wells</sub>	59.30
Water	m <sup>3</sup> /m <sub>wells</sub>	0.01
Well Head		
Steel	kg/well	1700

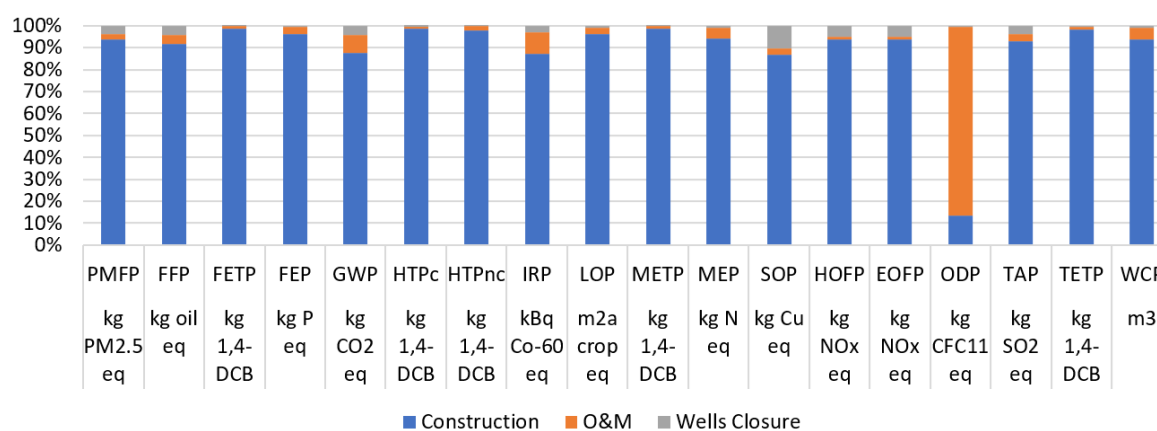
## 2.3. MidPoint Life Cycle Impact Analysis (LCIA) for the QUALTRA Plant

The LCIA was performed using OpenLCA [13], with secondary data sourced through the EcoInvent 3.6 database [14] and applying the ReCiPe 2016 midpoint methodology. The functional unit is the kWh produced by the Qualtra geothermal system, estimating a useful life of 30 years. The results obtained from the LCIA analysis are reported in the table below. Table 3 shows 18 different environmental impacts, reported as impact categories. Each unit is specific to its environmental indicator, and it is related to the functional unit, which, in this context, pertains to the production of one kilowatt-hour (kWh) of energy over a 30-year lifespan of the power plant. It is crucial to underscore that Qualtra power plant, as detailed earlier, employs a complete re-injection process for the geothermal fluid, leading to zero direct emissions into the atmosphere. Consequently, certain categories, such as GWP, TAP, HTPc, and HTPnc related to emitted gases, present results solely based on indirect emissions throughout the life cycle. The GWP indicator is highlighted as a reference point, with a fixed value of 6.56 g CO<sub>2</sub>/kWh. This indicator serves as a benchmark for assessing the environmental impact associated with greenhouse gas emissions, providing a standardized measure for comparative analysis within the specified context.

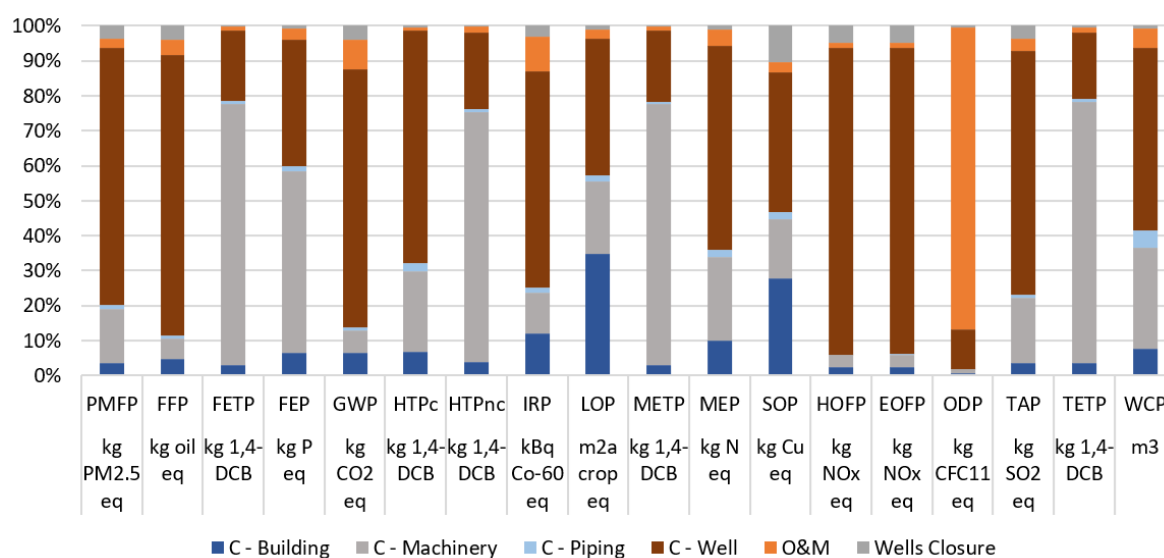
**Table 3.** QUALTRA Impact analysis table.

ReCiPe 2016 midpoint	Impact result	Impact result	Unit (refer to kWh)
<i>Fine particulate matter formation</i>	PMFP	1.80E-05	kg PM2.5 eq
<i>Fossil resource scarcity</i>	FFP	1.86E-03	kg oil eq
<i>Freshwater ecotoxicity</i>	FETP	1.10E-03	kg 1,4-DCB
<i>Freshwater eutrophication</i>	FEP	2.10E-06	kg P eq
<i>Global warming</i>	GWP	6.56E-03	kg CO2 eq
<i>Human carcinogenic toxicity</i>	HTPc	1.09E-03	kg 1,4-DCB
<i>Human non-carcinogenic toxicity</i>	HTPnc	1.14E-02	kg 1,4-DCB
<i>Ionizing radiation</i>	IRP	1.40E-04	kBq Co-60 eq
<i>Land use</i>	LOP	3.33E-05	m2a crop eq
<i>Marine ecotoxicity</i>	METP	1.40E-03	kg 1,4-DCB
<i>Marine eutrophication</i>	MEP	1.09E-07	kg N eq
<i>Mineral resource scarcity</i>	SOP	2.65E-06	kg Cu eq
<i>Ozone formation, Human health</i>	HOFP	5.72E-05	kg NOx eq
<i>Ozone formation, Terrestrial ecosystems</i>	EOFP	5.84E-05	kg NOx eq
<i>Stratospheric ozone depletion</i>	ODP	2.33E-08	kg CFC11 eq
<i>Terrestrial acidification</i>	TAP	3.60E-05	kg SO2 eq
<i>Terrestrial ecotoxicity</i>	TETP	5.71E-02	kg 1,4-DCB
<i>Water consumption</i>	WCP	1.49E-02	m3

An analysis of the contributions for each category of the ReCiPe midpoint 2016 methodology was performed. The contributions from the plant phases were highlighted: Construction, Operation and Maintenance, Wells closure. Figure 2 shows how for each category the main impact comes from the construction phase, in fact it exceeds 90% of the impacts for all categories excluding GWP, IRP, SOP and ODP. For GWP, IRP and SOP, it covers a very considerable percentage, about 85-87%, whereas for ODP it is restricted to 12%. Furthermore, for ODP there is a different trend, in fact the operation and maintenance phase is the most impactful phase, covering about 85% of impacts due to the use of organic working fluid. The well closure phase covers a very low percentage for all categories, reaching a maximum of 10% for SOP.

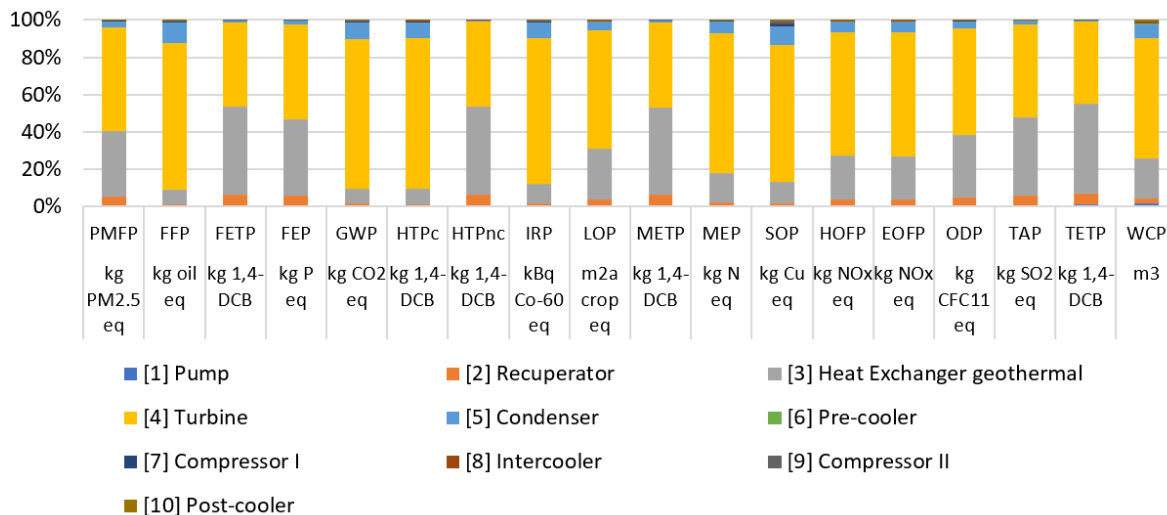
**Figure 2.** QUALTRA Contribution Analysis Macroprocesses (Phases).

Given the high impact of the construction phase, all processes involved in this phase were examined with more detail; a synthesis is presented in Figure 3. The general trend for each category, excluding ODP, is that the impact from the construction phase is mainly attributable to the construction of the wells and to the mechanical components of the power plant. In particular, the realization of wells causes the greatest impacts for categories HOFp and EOFp (87.5%), categories PMFP, FFP and GWP (73 - 80%), and categories HTPc, IRP, MEP and TAP (59-69%). Similarly, there are categories that are characterised by the impact of machinery, like FETP, HTPc, METP and TETP (71-74 %). For the FEP category power machinery covers about 52%, and for the other categories like HTPc, LOP, MEP, SOP, TAP and WCP 15-28%. Building is a process that does not produce important impact except for the IRP, LOP, MEP and SOP indicators where it accounts for respectively 12.2%, 34.8%, 10.1% and 27.8% of the impact. For all categories, the piping process is almost irrelevant, covering about 0.7-4.8% of the total impacts.



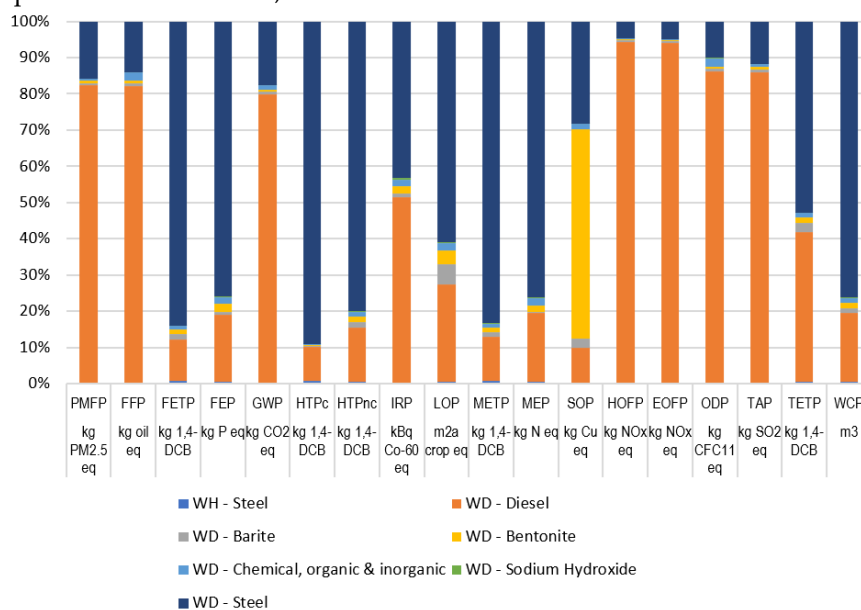
**Figure 3.** QUALTRA Contribution analysis in subprocess (C = Construction phase).

A contribution analysis was also carried out referring exclusively to the power cycle components of the system for all category indicators. Figure 4 shows that the main impact of machinery is the turbine, which is responsible of most of the impacts for all categories going for 90% for FFP, GWP and HTPc and about 82-85% for MEP and SOP. For all other indicators it covers more than 50% of the impacts except for FETP, HTPnc, METP, TETP for which it covers about 43-45 %. The second element in terms of environmental impacts is the main heat exchanger, which covers a significant percentage for the categories of PMFP, FETP, FEP, HTPnc, METP, ODP, TAP, TETP covering about 33-46%. The condenser also has a considerable impact - about 8-11% for some categories: FFP, GWP, HTPc IRP and SOP. Finally, the recuperator is responsible of 5-6% of the impacts for the categories of FETP, FEP, HTPnc, METP, TAP and TETP. All other mechanical elements have minimal impacts compared to the total.



**Figure 4.** QUALTRA Contribution Analysis – Power Equipment.

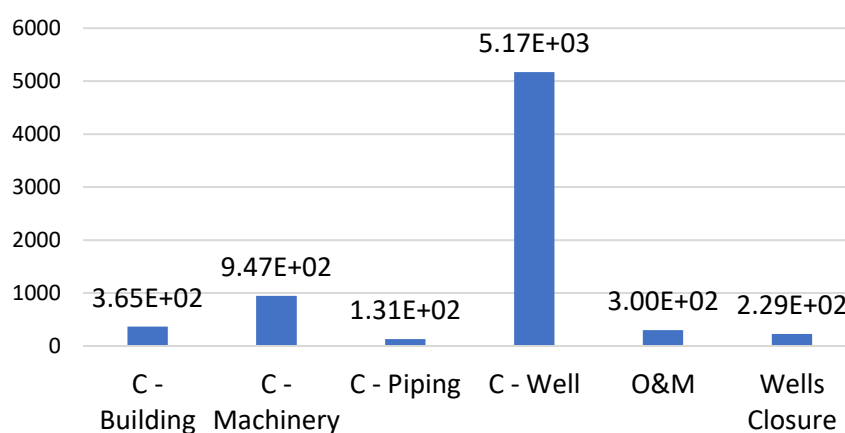
The analysis of the contributions of the well process was finally carried out to highlight how the environmental impact is distributed. Figure 5 shows two different well processes: Well Drilling (WD) and Well head (WH). First, it is shown that the materials used for WH cover a negligible percentage of impact for all categories. As a second fact, the picture shows us that the environmental impacts can only be attributed to two contributions, that of the casing steel and the diesel consumed in the drilling phase. In particular, diesel consumption has a substantial impact for the categories of PMFP, FFP, GWP covering about 80%, and even more considerably for HOFp, EOFP, ODP and TAP which impacts about 86-94%. For other indicators it covers smaller percentages such as 50% and 40% for IRP and TETP respectively, or even smaller but still considerable for LOP, WCP between 18 and 26%. In contrast, casing steel has a significant impact for the FETP, FEP, HTPc, HTPnc, METP, MEP and WCP categories for which it accounts for approximately 77-88 % of the impacts. For the categories of IRP, LOP and TETP it covers smaller but still considerable percentages between 45-58% of impacts. The only exception is shown in SOP, where bentonite covers about 58% of the total category.



**Figure 5.** QUALTRA Contribution Analysis Wells (WH = Well Head; WD = Well Drilling).

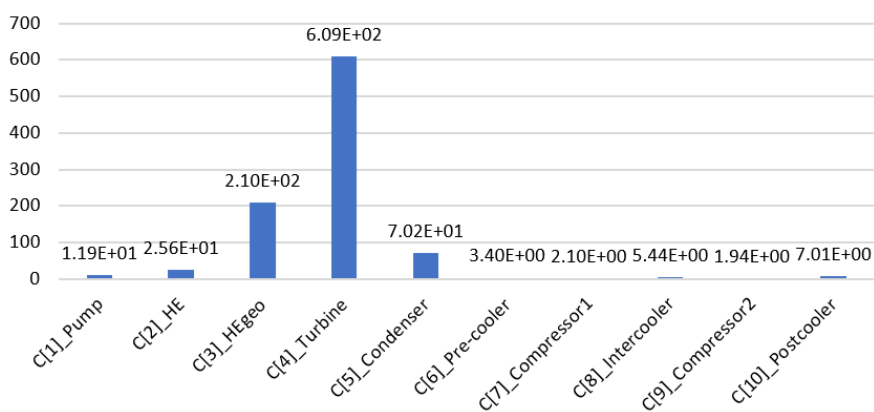
#### 2.4. Building the Single Score - QUALTRA

This step is not mandatory by the ISO 14040 and ISO 14044 standards, but it is necessary for the subsequent Exergo-Environmental analysis. To perform the calculation of the Single Score, the ReCiPe 2016 Endpoint methodology is applied. The results obtained from the impact analysis must be first processed with the normalisation and weighting sets. The resulting single score represents a global indicator representative of all environmental impacts. The following Figure 6 shows the single score split into the processes that constitute the whole Qualtra power plant. As the plant will operate on a completely closed loop and will need marginal flows of materials during operation (replacement of working fluid, lubricants,...), the Construction phase is dominating. The sum of all the processes for plant construction results in an overall lifetime impact of  $7.14\text{E}+3$  kPt. As is shown, the impact that dominates the single score is definitely the realisation of wells, which covers 72.4 % of the single score. The other processes cover much smaller percentages, such as Machinery and Building amounting to 13.3% and 5.1 % respectively; all others are below 5%.



**Figure 6.** QUALTRA Single score (Recipe 2016 Endpoint) Subprocess (C = Construction phase).

The power cycle components deserve a more detailed breakdown as they will be analysed in detail in the following exergo-environmental analysis. is the last result to be obtained from the LCA. The environmental cost expressed in kPt is shown in Figure 7: the highest environmental cost is attributable to the turbine (64.3% of the environmental cost of power machinery). Two other elements have a significant impact, the geothermal heat exchanger (HEgeo) and the condenser, which respectively account for 22.18% and 7.42%. All other elements have an environmental cost of no more than 2% of the total cost of machinery.



**Figure 7.** Single Score results – Power plant components.

### 3. Exergy Analysis

Exergy is employed as an indicator for the capability of a material or energy flow' to perform work through interaction with the external environment [15,16]. It has been used in numerous instances as a metric for geothermal energy systems that simultaneously produce heat and power [17]. To assess the most dissipative step in electricity generation from geothermal system, an exergetic analysis is performed under the assumption of steady-state conditions. The equation of physical exergy is the governing equation for exergy exchanges within the system and is defined for each stream as follows:

$$\dot{E}x_j = \dot{m}_j e_j = \dot{m}_j [(h_j - h_o) - T_o (s_j - s_o)] \quad (1)$$

where  $\dot{m}_i$  is the mass flow rate;  $h_j, s_j, h_o, s_o$  are, respectively, its enthalpy and entropy, at the stream  $j$ , or stream  $o$ . The latter represents the equilibrium state that is characterized by the reference temperature  $T_o$  and pressure  $p_o$ .

In exergy analysis, a component-level approach is applied [18,19]. The following balance states that the exergy of the fuel of a component  $k$  must be equal to that produced, plus all the destructions (D) and losses (L):

$$\dot{E}x_{F,k} = \dot{E}x_{P,k} + \dot{E}x_{D,k} + \dot{E}x_{L,k} \quad (2)$$

Furthermore, standard Key Performance Parameters indicating the system's performance are defined: the component exergy efficiency (3), the exergy destruction ratio (4), and the overall exergy efficiency of the entire system (5), which can also be re-checked using an indirect approach (6):

$$\varepsilon_k = \frac{\dot{E}x_{P,k}}{\dot{E}x_{F,k}} \quad (3)$$

$$y_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{F,S}} \quad (4)$$

$$\varepsilon_d = \frac{\dot{E}x_{P,S}}{\dot{E}x_{F,S}} \quad (5)$$

$$\varepsilon_{ind} = 1 - \frac{\sum \dot{E}x_{D,k} + \sum \dot{E}x_{L,k}}{\dot{E}x_{F,S}} \quad (6)$$

In the context of heat conversion and specifically in the case of geothermal energy, the primary exergy input into the system is the heat drawn by the fluid from the reservoir rock, characterized by its corresponding temperature level. This can be assessed by taking into account the Carnot factor based on the rock temperature:

$$\dot{E}x_{in Res} = \dot{Q}_{Res} \left( 1 - \frac{T_o}{T_{rock}} \right) \quad (7)$$

The proposed formulation in equation (7) for defining the exergy input suggests that the exergy destruction within the well encompasses pressure losses (across pipes and the porous reservoir) as well as the irreversibility associated with heat transfer between rocks and brine.  $\dot{Q}_{Res}$  is assessed from the enthalpy balance between the brine streams at re-injection and production wellheads, while  $T_{rock}$  can be determined as the temperature of the fluid at the origin of the production well.

#### Exergy Analysis Qualtra

Table 4 shows the list of components and their numbering (red numbers in Figure 1; streams are numbered in black).

**Table 4.** Components of Qualtra Power Plant.

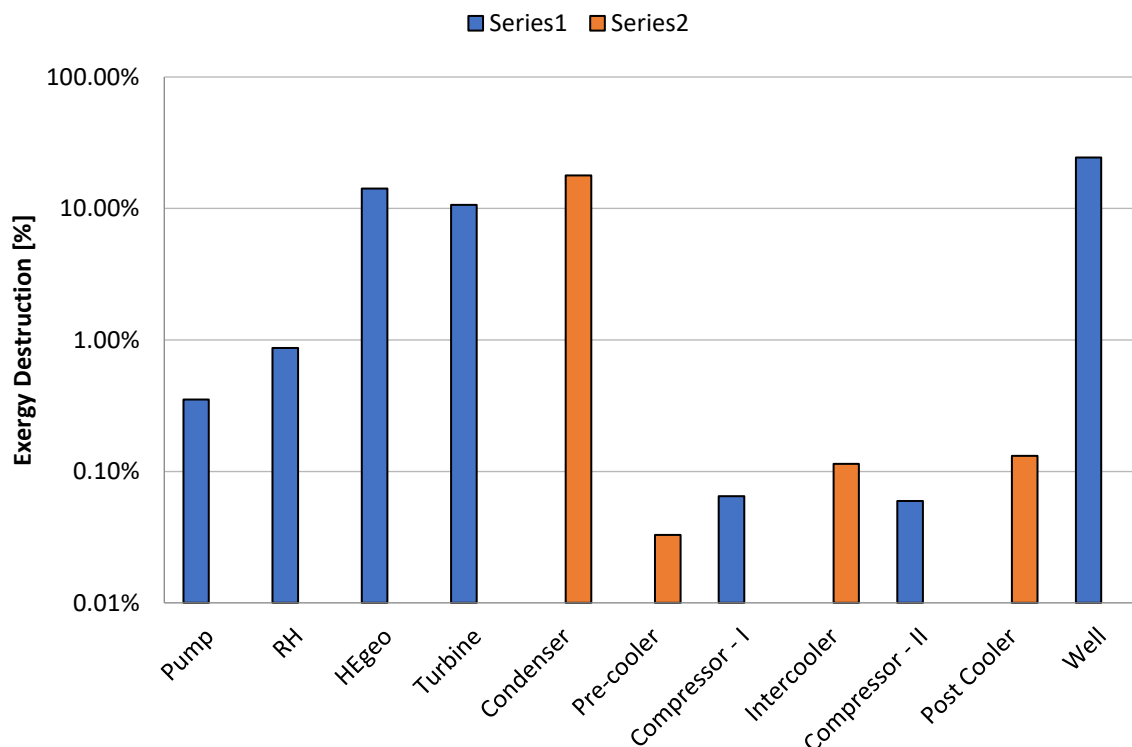
Component #	Component name	Component #	Component name
1	Pump	6	Pre-cooler
2	RHE	7	Compressor 1
3	MHE (Geo)	8	Intercooler
4	Turbine	9	Compressor 2
5	Condenser	10	Post Cooler

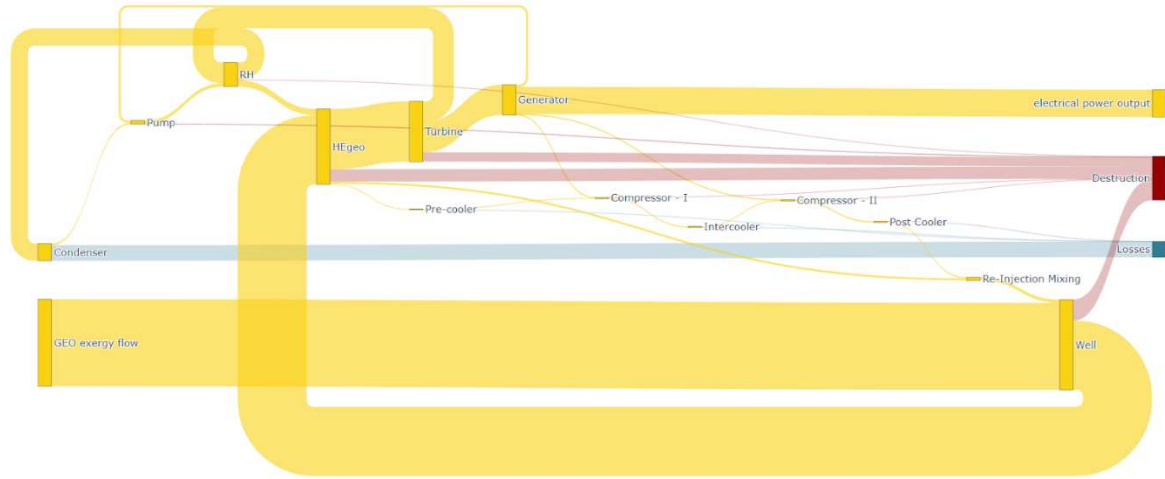
Figure 8 depicts the outcomes of the Qualtra power plant's exergy analysis. It reveals that the geothermal wells system stands out as the component causing the most exergy destruction. Other notable contributors to exergy losses are the HEGeo, turbine, and RH.

The total geothermal exergy input amounts to 36 MW, generating an exergy output of 10 MW in electricity. Consequently, the plant exhibits an exergy efficiency of 28%, with significant dissipation primarily linked to the wells. If the wells are excluded, the exergy efficiency of the overall plant reaches 37%.

From the Sankey diagram in Figure 9, it is possible to individuate the relative share of exergy conversion in electricity, destruction and loss. The cumulative exergy destruction of the power plant determines a large share of the plant inefficiencies, and there is also a relevant exergy loss at the condenser. A considerable part of the inlet exergy is recirculated to the geothermal reservoir through the reinjection wells, as a consequence of the prevention of environmental risks (micro-seismicity) and of avoiding scaling and corrosion.

## Exergy Destruction and Losses [%]

**Figure 8.** Exergy destruction and Losses for each component.



**Figure 9.** Sankey exergy conversion diagram. Colour Code: Yellow = standard exergy fluxes, Red = exergy destruction, Blue = exergy losses. The thickness of the connecting lines is proportional to the exergy flux (in kW)

#### 4. Exergo-Economic and Exergo-Environmental Analysis

The Exergo-Economic Analysis (EEA) is a method that evaluates the performance and economic efficiency of individual components. This is achieved through a cost balance that considers the costs associated with the exergy produced, the fuel utilized, and the overall investment. Auxiliary equations are introduced to handle the complexity arising from the number of exergy streams, and the cost of exergy destruction for each component is calculated [18]. The whole system must observe the cost balance of each component, taking into account the product cost and fuel of the  $k$ -th component and the total investment, according to the diagram in Figure 10.

Equations (8) and (9) describe the component economic balance:  $\dot{C}_{P,k}$  and  $\dot{C}_{F,k}$  are expressed in terms of €/s and represent the cost associated with the exergy of the component product and fuel, and they are calculated from the product of  $c_{P,k}$  and  $c_{F,k}$  (costs per exergy unit of product or fuel) by the respective exergy flows in kW. A mathematical model is formed where there are  $N_e$  unknowns, equal to the number of exergy streams, and composed of equations from the exergy balance and  $N_e - 1$  auxiliary equations (10) provided by the SPECO approach [19]. Moreover, additional parameters characterizing exergy performance can be established, such as  $f_k$  (11), which delineates the origin of the component's cost, distinguishing between exergy destruction and the cost of the investment itself. Similarly, the relative difference  $r_k$  in economic cost between the product and fuel flags a notable increase in cost across the component (12). An extensive description of this methodological approach can be found in [20].

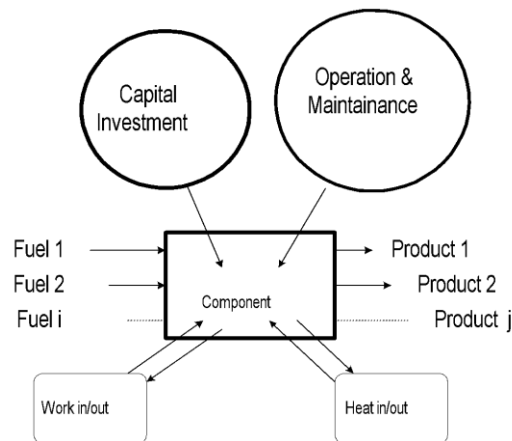
$$\sum_e^{N_e} \dot{C}_{P,e,k} = \sum_i^{N_i} \dot{C}_{F,in,k} + \dot{Z}_k \quad (8)$$

$$\sum_e^{N_e} (c_{P,e} \dot{E}x_{e,k})_k = \sum_i^{N_i} (c_{F,in} \dot{E}x_{F,in})_k + \dot{Z}_k \quad (9)$$

$$\dot{C}_{D,k} = c_{D,k} \cdot \dot{E}x_{D,k} = c_{F,k} \cdot \dot{E}x_{D,k} \quad (10)$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \quad (11)$$

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \quad (12)$$



**Figure 10.** Schematic of k-th component.

The Exergo-Environmental Analysis (EEvA) [21,22] employs an approach similar to that of Exergo-Economic Analysis, but replaces conceptually economic costs with a singular indicator of the component environmental performance. This approach requires detailed LCA calculations for each k-th component. From the point of view of LCA, EEvA necessitates the application of a normalized and weighted Single Score for each component, typically expressed in Ecopoints. This Single Score acts as a substitute for the Capital Cost in Exergo-Economic Analysis (EEA), taking into consideration the resource intensity inherent in each component.

EEvA allows for a comprehensive assessment of the environmental impact of each component within a system. The use of Ecopoints provides a standardized unit, facilitating the comparison of the environmental performance across various components. This approach not only enables the identification of components with the most significant environmental impact, but also allows for the prioritization of mitigation efforts. Further insights into this methodology can be found in [20].

#### 4.1. Exergo-Economic Results Qualtra

The overall specific investment cost for the power plant was calculated at 1398 €/kW. The final production cost of electricity is 9.4 c€/kWh, which is comparatively higher than other Geothermal Power Plants (GPPs) [21], but is justified by the smaller size and by the implementation of the total reinjection concept.

Table 5 summarizes the key exergo-economic parameters calculated for the Qualtra power plant. Notably, the components with a substantial economic impact, influenced by both exergy destruction ( $\dot{C}_{D,k}$ ) and the capital cost ( $\dot{Z}_k$ ) are the HEGeo and the turbine, whereas for the wells the capital cost  $\dot{Z}_k$  is the only contributor to the cost build-up.

The condenser emerges as the component with the highest exergy inefficiency and, consequently, the greatest economic impact ( $\dot{Z}_k + \dot{C}_{D,k}$ ), following the wells. The turbines also exhibit significant impact, constituting approximately 7% of the total economic impact. Within this, 22% is attributed to the capital cost ( $\dot{Z}_k$ ), while 78% is ascribed to exergy destruction ( $\dot{C}_{D,k}$ ).

The HEGeo significantly influences the economic cost, representing 12% of the overall economic impact ( $\dot{Z}_k + \dot{C}_{D,k}$ ). This substantial contribution is attributed predominantly to its elevated exergy destruction cost, which constitutes 63% of the total component impact cost. Thus, it becomes apparent that the power plant's most impactful components, in terms of economic impact, are the Wells, condenser, turbine, and HEGeo, contributing 70%, 5%, 7%, and 12%, respectively, to the total economic impact.

Figure 11 illustrates that the cost of the wells significantly influences almost all components of the power plant, with an external contribution exceeding 60% for all except the reinjection train components. Subsequent to the well's contribution, the HEGeo plays a substantial role in the cost structure of almost all components, while the contributions of other components prove negligible.

Table 5. Exergo economic results, main parameters.

k	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]	$f_k$ [%]	$r_k$ [-]
1	Pump	4.92E+05	3.7E-03	0.00340	0.00705	0.09467	0.13708	51.9	0.45
2	RH	9.00E+05	6.7E-03	0.00582	0.01251	0.06583	0.11275	53.5	0.71
3	HEgeo	4.82E+06	3.6E-02	0.06150	0.09730	0.04279	0.06098	36.8	0.43
4	Turbine	2.76E+06	2.0E-02	0.07126	0.09179	0.06583	0.09467	22.4	0.44
5	Condenser	1.84E+06	1.4E-02	0.11941	0.13305	0.06583	0.00000	10.3	-
6	Pre-cooler	1.06E+05	7.9E-04	0.00014	0.00093	0.04279	0.00000	84.7	-
7	Compressor - I	5.10E+05	3.8E-03	0.00062	0.00442	0.09467	0.24030	85.9	1.54
8	Intercooler	1.16E+05	8.6E-04	0.00124	0.00210	0.10653	0.00000	41.1	-
9	Compressor - II	4.71E+05	3.5E-03	0.00057	0.00407	0.09467	0.24160	86.0	1.55
10	Post Cooler	1.32E+05	9.8E-04	0.00186	0.00284	0.13951	0.00000	34.6	-
11	Well	4.63E+07	2.1E-01	0	0.21180	0.00000	0.04094	100.0	0.00
-	<b>Total Plant</b>	<b>5.84E+07</b>	-	-	-	-	-	-	-

## Stream Cost Composition

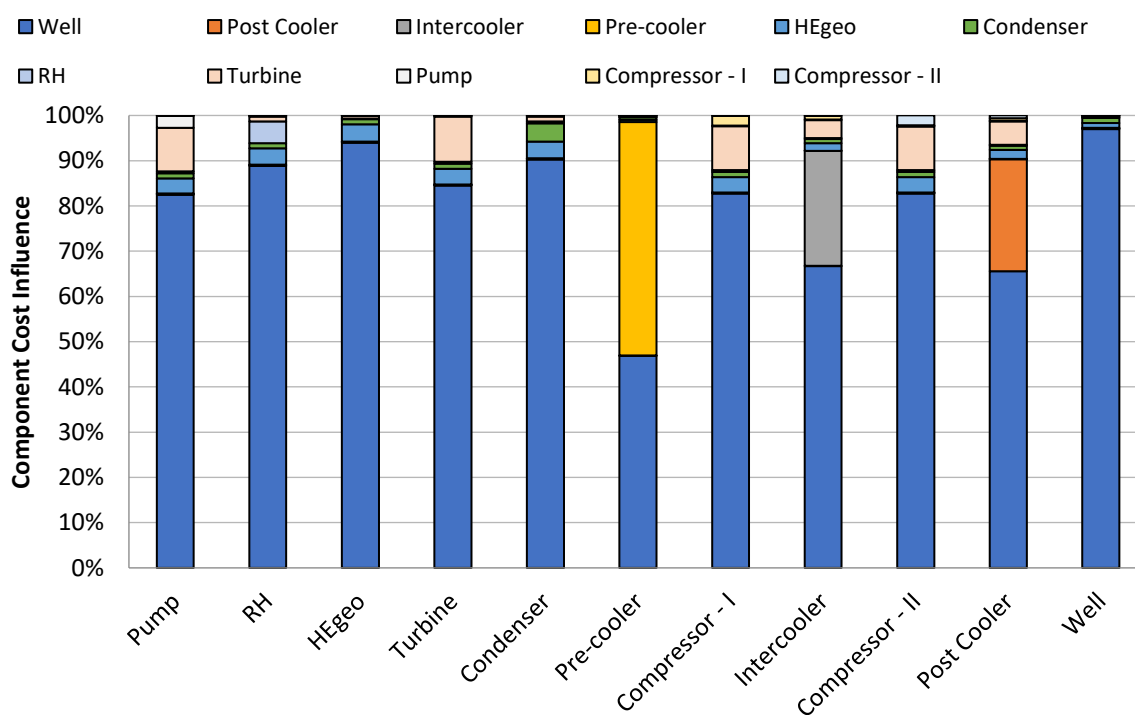


Figure 11. Economic stream Cost contribution for each component (self and share from all others).

#### 4.2. Exergo-Environmental Analysis Qualtra

The outcomes of the EEVA conducted for the Qualtra power plant are outlined in Table 6. When viewed from an environmental standpoint, the wells system stands out as the component with the most relevant impact representing approximately 45% of the total impact. Other noteworthy contributors to the environmental impact are the condenser (21% of the total), the turbine (17%), and the HEGeo (14%).

The turbine exhibits a relatively high value of  $r_{d,k}$  signifying that an accurate meticulous evaluation of this component is essential for potential marginal improvements in the plant's sustainability. The overall environmental cost associated with the electricity generated by the power plant was calculated at 8.3 cPts/kWhe. This notably low score is attributed to the complete avoidance of emissions (H<sub>2</sub>S, Hg, NH<sub>3</sub>, and CO<sub>2</sub>), facilitated by the fully closed-loop operation.

Furthermore, Figure 12 illustrates that, in a way similar to the economic analysis and consistent with other geothermal power plants, the wells contribute significantly, with contribution values surpassing 60% for all components except the condenser. The cost structure of the condenser is notably influenced by its own contribution as this is a terminal, dissipative component (essential for system operation), contributing to itself approximately 50% of the environmental cost. Lastly, the turbine has a moderate impact in terms of self-contribution, and the pump and all recompression system components contribute marginally to the environmental cost buildup.

**Table 6.** Exergo environmental results, main parameters.

k	Component	Single score [kPts]	$\dot{Y}_k$ [Pts/s]	$\dot{B}_{D,k}$ [Pts/s]	$\dot{B}_{TOT,k}$ [Pts/s]	$f_{d,k}$ [%]	$r_{d,k}$ [-]
1	Pump	11.93	5.20E-04	3.00E-03	3.52E-03	14.78	0.21
2	RH	25.63	1.12E-03	4.93E-03	6.05E-03	18.46	0.35
3	HEGeo	210.0	9.15E-03	6.00E-02	6.91E-02	13.24	0.28
4	Turbine	609.29	2.65E-02	6.04E-02	8.69E-02	30.52	0.50
5	Condenser	70.23	3.06E-03	1.01E-01	1.04E-01	2.93	-
6	Pre-cooler	3.40	1.48E-04	1.39E-04	2.87E-04	51.54	-
7	Compressor - I	2.10	9.17E-05	5.50E-04	6.42E-04	14.28	0.19
8	Intercooler	5.44	2.37E-04	7.00E-04	9.37E-04	25.28	-
9	Compressor - II	1.94	8.43E-05	5.05E-04	5.89E-04	14.32	0.19
10	Post Cooler	7.00	3.05E-04	9.31E-04	1.24E-03	24.68	-
11	Well	5142.	2.25E-01	0.00E+00	2.25E-01	100.0	0.00

## Stream Cost Composition

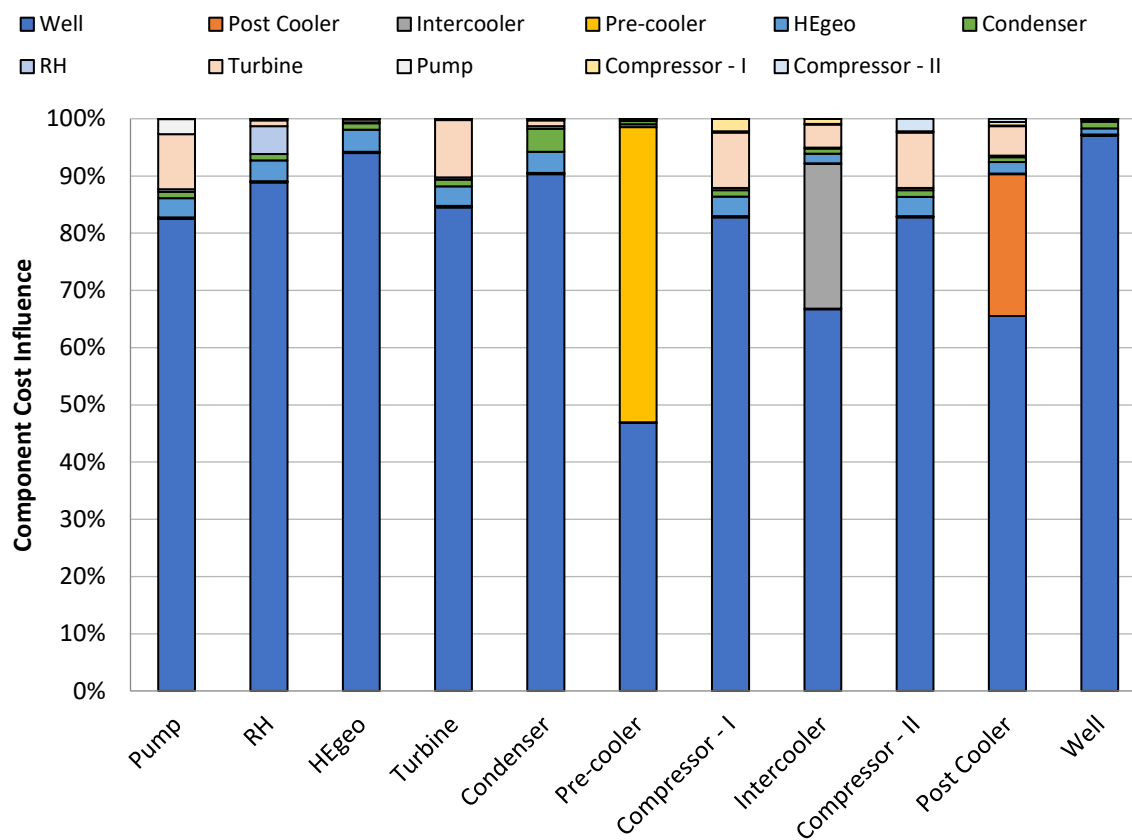


Figure 12. Environmental stream cost contribution to each component. (self and from all others)

## 5. Conclusions

A complete performance evaluation of the innovative Qualtra geothermal power plant was performed. Qualtra represents a new-generation fully closed-cycle Geothermal Power Plant, deploying the full potential of binary cycle technology and coupling it to complete reinjection of greenhouse gases, thereby determining a very low environmental impact in this specific category (6.56 g CO<sub>2</sub>/kWh). The complete LCA shows substantially low impacts in all relevant categories, with the largest contribution due to the activity of drilling of the wells.

The thermodynamic performance was assessed through the application of exergy analysis, including the additional equipment needed for GHG reinjection. The exergy efficiency is an appreciable 28%, with most of the exergy destruction contributed by the wells, by the turbine and Main Heat Exchanger.

The Exergo-Economic analysis determined a final expected cost of electricity of about 9,4 €/kWh. The cost of the wells emerges as the most relevant contribution as is common in geothermal projects, followed by the power machinery (turbines) and by the heat rejection equipment (condensers/cooling towers).

The Exergo-Environmental Analysis confirmed that the drilling and construction of the wells represent the largest share of the resource/impact. Within the powerhouse equipment, the Turbine emerges as both resource-intensive and contributing by the destruction of exergy (inefficiency). The Main Heat Exchanger is the third contributor in terms of exergy destruction (irreversibility in heat transfer), while it is marginally resource-intensive. The Condenser/Air-Cooled Towers system determines an appreciable loss of exergy (considerable release of heat to the environment, even if

of low quality), which is a system effect (heat rejection is needed; passive component). The exergo-environmental analysis allows to calculate a Single Score for the production of electricity (0,083 Pts/kWh); this competitive value - both referred to existing geothermal power plants (flash technology) or to other renewables like solar PV [23,24] – is a valuable result of the fully closed power plant layout.

### List of Symbols

$b$	specific environmental cost per unit exergy, EcoPoints/kJ
$\dot{B}$	environmental cost per unit time, Ecopoints/s
$c$	specific cost per unit exergy, €/kJ
$\dot{C}$	cost rate, €/s
$e$	specific exergy, kJ/kg
$\dot{E}_x$	total exergy of a stream, kW
$f$	capital intensity exergo-economic factor
$f_a$	resource intensity exergo-environmental factor
$h$	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
$r$	cost increase exergo-economic factor
$r_a$	impact increase exergo-environmental factor
$s$	specific enthalpy, kJ/(kgK)
$T$	temperature, K
$y$	exergy destruction ratio
$\dot{Y}$	LCA impact rate of a component, Ecopoints/s
$\dot{Z}$	Component Capital + Operation and Maintenance levelized cost rate, €/s
$\varepsilon$	component or system exergy efficiency

#### Subscripts:

$o$	reference environment
$d$	direct
$D$	Destruction
$e$	outlet (exit)
$F$	Fuel
$in$	inlet
$ind$	indirect
$k$	k-th component
$L$	Loss
$P$	Product
$Res$	Resource
$Rock$	Hot Rock reference

#### Acronyms:

GHG	GreenHouse Gases
GPP	Geothermal Power Plant

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