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Exergo-economic and exergo-environmental assessment of two large CHP geothermal power plants

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ABSTRACT

An Exergo-Economic and Exergo-Environmental Analysis is presented for two large geothermal power plants located in Iceland – Hellisheidi and Nesjavellir. The latest configuration of the power plants - including for Hellisheidi acid gas removal and Carbon capture - is analyzed. Cost and LCA data available within the EU H2020 GECO project were processed with an exergy approach, with the purpose to identify the major points of cost build-up or environmental impact along the energy conversion process. A considerable relevance of the cost and impact due to the activity of wells drilling was confirmed for geothermal energy systems; within the operation of the plant, the major effects of exergy destruction are found at the turbines and condensers. The inefficiencies and the buildup of cost and environmental impact along the energy conversion chain are highlighted and the outcomes are discussed with a comparison between the two plants. These are confirmed as performing very well both from the economics and sustainability points of view: recent and foreseen improvements for emissions and carbon capture will not change substantially the economics and will be very effective from the point of view of environmental performance.

1. Introduction

Geothermal Energy is a Renewable Resource that can provide low-cost and environmentally friendly power and heat in several locations around the world (IRENA, 2017). Some countries like Iceland have an abundance of RES (notably, Hydro and Geothermal), and Geothermal Energy has a fundamental role as it provides heat as well as electricity. This led to the building of some of the largest power plants in the world: specifically, Hellisheidi (303 MW_e and 133 MW_t) and Nesjavellir (120 MW_e and 300 MW_t).

Geothermal energy has the potential to play a frontline role in the present challenge of Energy Transition: in fact, it typically produces baseload energy, thereby substituting fossil fuels in support of Variable Renewable Energies (such as wind and solar PV). Demonstration of integration with Carbon Capture and Storage (CCS) is on the way (specifically, in the site of Hellisheidi); this is very promising for the future of Geothermal Energy and will pave the way to a business and sustainable development model extending beyond the present boundaries (production of electricity and heat).

Opposition to Geothermal is largely based on prejudices about its sustainability and environmental impact (Manzella et al., 2018). These are largely based on memory from past projects, which have not always guaranteed the high standards which are today possible with modern technology. Prevention of risks during the drilling and field development is a measure that can reduce undesirable issues to the level accepted in most human industrial activities. Modern technologies of drilling and solutions for the treatment of emissions occurring during the operation of the plant (Baldacci et al., 2005) have reduced significantly the environmental impact and extensive epidemiology studies (Bustaffa et al., 2020) have demonstrated that the effects on public health are marginal. The near-future technologies will allow cancelling also the global effect of greenhouse gas emissions, which are in any case of natural origin and for many sites correspond to the level of global diffusive flux from the surface (Sbrana et al., 2021).

Regarding the relevant global issue of CO_2 emissions, the demonstration projects active in the Hellisheidi site (Clark et al., 2020), involving reinjection of the greenhouse gasses in the underground and

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Nomenclature

$\dot{B}_{D,k}$	Environmental impact of exergy destruction, component k, Pts/s
$\dot{B}_{TOT,k}$	Total environmental impact, component k, Pts/s
$\dot{B}_j$	Environmental cost, stream j, Pts/s
b_j	Specific environmental cost, stream j, Pts/kJ or Pts/kWh (final product)
$\dot{C}$	Cost rate, €/s
$\dot{C}_{D,k}$	Cost rate of exergy destruction or losses, component k, €/s
c	cost per unit exergy, €/kJ or €/kWh (final product)
e	specific exergy, kJ/kg
$\dot{E}x$	Exergy, kW
$\dot{E}x_D$	Exergy destruction, kW
f_k	Exergo-economic factor, component k
$f_{d,k}$	Exergo-environmental factor, component k
h	Enthalpy, kJ/kg
ir	interest rate
$\dot{m}$	Mass flow rate, kg/s
n	Number of lifetime years
N	Number of streams
r_k	product/fuel relative difference of economic cost, component k
$r_{d,k}$	product/fuel relative difference of environmental impact, component k
s	Entropy, kJ/(kgK)
T	Temperature, K
y_k	Exergy destruction ratio, component k
$\dot{Y}_k$	specific environmental cost of component k, Pts/s
Z_k	cost of component k, €
$\dot{Z}_k$	capital cost rate of component k, €/s
ε	Exergy efficiency

Subscripts

0	Reference environment
an	Annual
d	direct
D	Destruction
DH	District Heating
e	exit
el	electricity
F	Fuel
in	inlet
ind	indirect
k	k-th component
j	j-th stream
L	Loss
P	Product
PP	Power Plant
S	System
Res	Resource

Acronyms

CHP	Combined Heat and Power
DH	District Heating
EEA	Exergo-Economic Analysis
EEvA	Exergo-Environmental Analysis
GPP	Geothermal Power Plant
HPC	High-pressure Condenser
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
NCG	Non-Condensable gasses
PEC	Purchased Equipment Cost
TCI	Total Capital Investment

subsequent mineralization, represent a pilot application with considerable potential for technology transfer (with necessary adaptation to the specific mineral context of the underground). When practiced at a large scale (if possible – depending on the local features of the underground rocks), capture and reinjection of CO_2 and other non-condensable gasses in geothermal fields, with long-term mineral fixation, will indeed be a remediation technology providing greenhouse effect credits rather than representing an emissions stream as it is considered today.

From the point of view of environmental impact, significant steps towards an objective evaluation have been drawn by the application of sustainability assessment protocols (ON, 2018; Aradòttir and Hjálmarsson, 2018) and by the use of Life Cycle Analysis (Frick et al., 2010; Bayer et al., 2013; Marchand et al., 2015; Asdrubali et al., 2015). It is possible today to apply guidelines (GEOENVI project website, 2023; Douziech et al., 2021) and provide a quantitative and comparative analysis of a variety of GPP technologies applied in different locations and resource conditions. The shortcomings of the methodology have been identified and a path to its improvement (largely depending on its generalized application) has been established: the available results already indicate what should be the direction of technology improvement (e.g.: electrical drive for drilling; capture of emissions, such as H_2S and Hg; reinjection and mineralization of CO_2; development of closed-loop technology).

The application of LCA to geothermal energy conversion and utilization has been demonstrated to be capable to produce quantitative results and to draw a comparison among different types of plants and resource conditions (Zuffi et al., 2022). Moreover, it allows a correct allocation of environmental costs to different products (electricity and heat). However, LCA is typically a global approach applied to the whole plant/geothermal project. It is of primary importance to be able to document the process of the build-up of the economic cost and environmental impacts of energy products (electricity and heat). For this purpose, specific analysis tools can be applied, such as the Exergo-Economic Analysis (EEA), and the Exergo-Environmental Analysis (EEvA).

In the present study, exergy analysis, LCA, exergoeconomic, and exergoenvironmental evaluation methodologies were applied for two reference cases within an EU H2020 project, using wherever possible direct and updated information from project partners for plant parameters, equipment, and infrastructural costs; recent evaluation approaches and secondary data sources were applied for the LCA. The two plants are compared under these uniform conditions, which is a further novelty in the scientific literature on geothermal energy.

2. Methodology

2.1. Exergy analysis

Exergy is an indicator of the capacity of a system, of a matter stream flow, or an Energy interaction (heat, work, potential or kinetic energy) to produce work when interacting with the reference environment (Kotas, 1985; Szargut et al., 1988). Exergy analysis is applied in several fields of thermodynamic energy conversion and utilization, including geothermal energy systems producing electricity and heat (Di Pippo, 2004); in the present study, the exergy analysis is performed at the component rather than at the global level, thereby allowing precise identification of the most dissipative steps in the energy conversion process. Referring to steady operating conditions and considering the inlet or output streams of a component, the physical exergy of each stream is defined as:

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

where $\dot{m}_i$ is the mass flow rate of the substance under consideration; h_i, s_i are, respectively, its enthalpy and entropy; h_0, s_0 are the enthalpy and entropy of this substance at an equilibrium state with the environment at the reference temperature T_0 and pressure p_o.

A component-level approach is necessary for the EEA and EEvA (Bejan et al., 1996; Meyer et al., 2009): the exergy destructions and losses, the exergy efficiency, and the exergy destruction ratio are calculated for each component. Fuel and Product are defined at the level of the k-th component (Lazzaretto and Tsatsaronis, 2006) so that an exergy balance can be expressed as follows:

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

Eq. (2) considers the different meanings of Exergy Destruction $\dot{E}x_{D,k}$ and Exergy Loss $\dot{E}x_{L,k}$: $\dot{E}x_{D,k}$ is due to inefficiencies of the component, while $\dot{E}x_{L,k}$ represents a direct dissipation of exergy to the environment, which can either be a feature of the component or – often – a system effect (heat rejection and the associated exergy loss is encountered at stacks, condensers, and cooling towers which are typical non-productive components, which are however functional to the system).

The exergy efficiency of each component is defined as:

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

while the exergy destruction ratio is calculated as:

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

The overall exergy efficiency of the system can be calculated with a direct approach:

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

Or indirectly:

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

Eq. (6) is particularly important as it allows us to compare consistently very different sources of irreversibility/inefficiency. Friction and mixing losses, heat transfer with finite temperature difference – as well as direct dissipation of heat or streams of matter to the environment in non-equilibrium conditions.

The main exergy input in the system is the heat extracted by the fluid from the reservoir rock that has been evaluated considering the Carnot factor using the rock temperature:

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

The definition of the exergy input as proposed in Eq. (7) implies that the exergy destruction in the well accounts for both the pressure losses (in the pipes and the porous reservoir) and the irreversibility of heat transfer between the rocks and the brine. $\dot{Q}_{Res}$ is evaluated considering the enthalpy balance between the re-injection and production brine, T_{rock} was evaluated as the temperature of the fluid at the bottom of the production well.

2.2. Economic analysis

Cost correlations are applied to obtain the investment, operation, and maintenance (O&M) costs of each component (Turton et al., 2017); specific information related to the field of geothermal energy systems (Shamoushaki et al., 2021) was also applied. The annual investment cost of the k-th component is calculated considering a 10% interest rate and a lifetime of 20 years.

The obtained equipment costs were updated to the reference year through the CEPCI (Chemical Engineering Plant Cost Index) inflation index (Turton et al., 2017). As proposed by Schuster et al. (2009) and Fiaschi et al. (2019), the O&M cost for each component was defined as a fraction (1.5%) of the Purchased Equipment Costs (PEC).

The Total Capital investment cost was calculated following the methodology used by Talluri et al. (2019). 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).

Cost correlations, tuned where possible with direct information from the plant ownership, were applied for the evaluation of the base Purchase Equipment Costs (PECs). Details about the PECs are documented in Appendix A. Appendix B documents the procedure for calculating the Total Capital Investment from the PEC (and, consequently, the $\dot{Z}_k$ in [€/s] to be used in the Exergo-Economic Analysis).

2.3. Exergo-Economic analysis

The Exergo-Economic Analysis (EEA) is a methodology originally formulated to evaluate systems producing different types of energy (electricity, heat, cold, and material flows) by combining the exergy and the economic analyses, 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).

Referring to Fig. 1, the c cost balance applied to the k-th component can be set as (8):

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

That is, introducing the cost per unit exergy:

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

$\dot{C}_{P,k}$ 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.

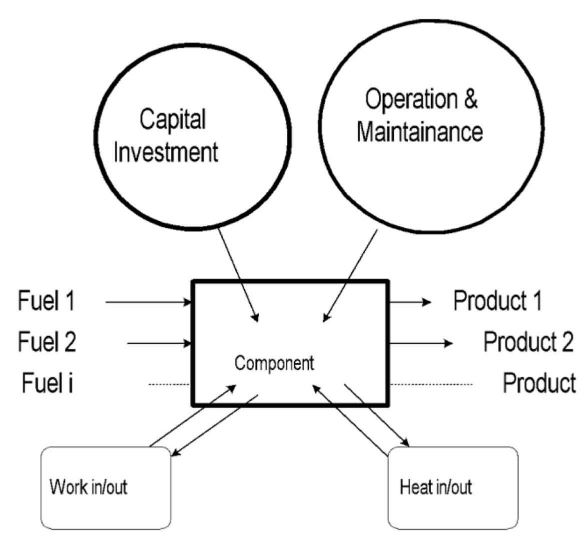

Fig. 1. Schematic of k-th component.

Auxiliary equations for each component can be introduced considering the SPECO methodology defined by Lazzaretto and Tsatsaronis (2006). Exergy losses are considered to be priceless while solving the system of equations defined by (9). Nevertheless, after the solution of the system, for each component, the cost of the destruction or the losses can be estimated by pricing it as the cost of the fuel:

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

In this approach $\dot{C}_{D,k}$ is thus an estimate of the maximum economic savings that can be realized by eliminating the specific exergy destruction.

Non-productive (also called dissipative) components do not have an exergy product and their cost is redistributed among all the other components according to their exergy destructions as prescribed by the SPECO methodology (Lazzaretto and Tsatsaronis, 2006).

The results of an EEA are usually interpreted through a set of key performance indicators: y_k (Eq. (4)) indicates the relevance of the component in the overall exergy balance. An exergo-economic factor f_k, which compares the investment cost of the component to the sum of the investment cost and the cost of exergy destruction, can be calculated as follows:

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

The f_k factor identifies the relevance of the impact coming from the exergy destruction (performance) of the k-th component in comparison with its investment cost.

The product/fuel relative difference of the economic costs for the k-th component r_k is given in the following equation:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{12}$$

A high value of r_k indicates that there is a relevant relative cost increase across the component.

When referring to products like heat, a final step is calculating the cost per unit mass instead of that per unit exergy (for electricity, electricity = exergy). This can be done by multiplying the cost per kJ by the specific exergy of the product stream [kJ/kg] (Bejan et al., 1996):

$$c^*_{P,k} = c_{p,k}\ e_j \tag{13}$$

As a logical consequence, a low value is thus attributed to the cost of a product when the specific exergy of the stream is limited (as – for example – in the case of district heating networks, in comparison to high-value products like electricity).

2.4. *Exergo-environmental analysis*

The general framework of the Exergo-Environmental Analysis (EEvA) is similar to that of an EEA. EEvA has been applied to geothermal power plants in recent studies (Basogul, 2019; Huang et al., 2020; Cao and Ehyaei, 2021), but a comprehensive description of the methodology including its link to LCA, as well as a comparative analysis of different plants, is substantially missing and will be presented in the following.

To correctly perform an EEvA, it is first necessary to perform an LCA with some specific requirements. Economic costs are substituted conceptually by a single environmental performance indicator, which must be calculated for each k-th component. This requires particular attention in performing the LCA, which is different from the traditional one which builds the inventory (LCI) for the whole system. Rather, it is necessary to build separate LCIs for each component, so that the materials/resource investment and the lifetime environmental effects can be accounted for separately for each component. Of course, the sum of all components - plus general environmental effects which must be referred to the whole system – is equivalent to the traditional (global level) LCI. Moreover, the EEva requires a normalized and weighted Single Score for each component (usually expressed in Ecopoints – which take the place of the Capital Cost in EEA to account for the resource intensity of each component).

In addition, the single score of the mechanical components considers the environmental cost of the component itself plus an extra contribution. This extra cost represents the environmental cost of all the processes analyzed in the life cycle that does not consist of a specific mechanical component but are necessary for the correct operation of the system (piping, building, operation phase, maintenance, and so on). This contribution is allocated among the evaluated single scores using the percentage of total environmental impact scores as the distribution weight.

The Single Score requires procedures that lay outside of the mandatory part of an LCA, namely: Normalization and Weighting. These last are different depending on the LCA method selected: however, it is possible – and indeed recommended – to identify what are the main impact categories typical of the system and compare different methods (possibly using the same category indicators – or applying a suitable conversion of equivalent measurement units for the category indicator).

As stated in the introduction, there is a wide literature on LCA, and recent advances have been reported with specific reference to geothermal energy: however, it is important to state that the approach here presented represents a step forward (disaggregation of the LCI into components; application of Normalization and Weighting; benchmarking among different LCA methods), which is recommended before applying the EEvA. The LCA results are expressed considering 1 MWh of exergy as a functional unit (Pts/MWh).

Specifically, the 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): this represents a step forward to LCA because it shows at the component level what is the margin for improvement of the environmental performance. In terms of methodology, the EEvA can be carried out similarly to the EEA replacing the economic with the environmental costs (Ecopoints) still referring to the exergy unit. The environmental cost rates related to each jth stream $\dot{B}_j$ (Pts/s) are allocated to their exergy content $\dot{E}x_j$ (kW) to evaluate the specific environmental impacts b_j (Pts/kJ; the final environmental cost of electricity is usually converted into Pts/kWh) through:

$$b_j = \frac{\dot{B}_j}{\dot{E}x_j} \tag{14}$$

This methodology is based on the solution of impact balances performed for each k – th component, using (14):

$$\sum \dot{B}_{j,k,in} + \dot{Y}_k = \sum \dot{B}_{j,k,e} \tag{15}$$

Where $\dot{Y}_k$ (Pts/s) is the environmental impact rate associated with the construction, O&M, and End Of Life (EOL) phases (the EEvA, as is the case for LCA – considers the full Life Cycle, and consequently, also the EOL). The environmental costs per unit of exergy (Pts/MWh) of product $b_{P,k}$ and fuel $b_{F,k}$ are defined as in the case of the EEA. This allows the evaluation of the environmental cost rate $\dot{B}_{D,k}$ (Pts/s) associated with the exergy destruction occurring inside each component through:

$$\dot{B}_{D,k} = b_{F,k} \cdot \dot{E}x_{D,k} \tag{16}$$

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 (16):

$$f_{d,k} = \frac{\dot{Y}_k}{\dot{B}_{D,k} + \dot{Y}_k} \tag{17}$$

The relative difference of the specific environmental impacts for the k-th component is given in the following Eq. (17):

$$r_{d,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} \quad (18)$$

The parameter $r_{d,k}$ has a significant meaning: the higher its value, the greater the potential for improvement.

3. Description of the geothermal power plants

Both plants here considered are connected to the Reykjavík District Heating network and represent fundamental assets within the power and heat system of Iceland. For both plants, the system boundaries include the production and reinjection wells; electricity is delivered at high voltage, and heat is provided to the district heating pumping station located close to the geothermal power plant (the primary and secondary district heating networks are excluded from this study). Emissions are only to the atmospheric environment and are the object of recent system improvements. In 2014 an industrial-scale pilot capture plant began operations in Hellisheidi where H_2S and CO_2 were captured in a water scrubbing process. After the gas is dissolved in water, the water is injected into the bedrock where the gas forms stable minerals. As of December 2022, the relative gas capture has demonstrated to capture 30% of CO2 and 80% of H2S emissions. Upscaling of gas capture is planned for Hellisheidi in 2025 and Nesjavellir in 2030, with an estimated 95% capture of both gas streams . NesjavellirBoth plants were the object of several Research and Innovation Transfer Projects, among them notably the EU CARBFIX (CARBFIX project website, 2023), GEOENVI (GEOENVI project website, 2023), and GECO (GECO project website, 2023). In the case of Hellisheidi, the GPP includes a burn and scrub treatment using additional equipment for NCGs purification; H_2S is thus removed from the stream, about 7530 tons per year, while about 13,900 tons per year of CO_2 are reinjected into the underground dissolved in the water reinjection stream. Recent reports indicate effective sequestration with substantial mineralization of the carbon-rich stream (Galezka et al., 2022).

The power plants in Hellisheidi and Nesjavellir have progressively evolved towards a final configuration, which is today stabilized and will undergo in the future possible adjustments for emissions treatment. This is quite common in geothermal projects for several reasons: first of all, the uncertainty about the real availability and properties of the resource is considerable, and the potential of a location is often reliably assessed only after a period of operation; moreover, there is a progressive adaptation of the resource conditions (in general, a decay), with changes in pressure, temperature, optimal flow rate, and composition. In both locations, the production of electricity and heat started around 2006, and a continuous renovation of wells is active since then.

For both plants, a life cycle assessment methodology (LCA) was applied, following the LCA guidelines for geothermal plants developed within the GEOENVI H2020 project (Parisi et al., 2020).

For the Hellisheidi CHP plant, the Life Cycle Assessment (LCA) studies reported in the literature are based on the original inventory (LCI) provided by Karlsdòttir et al. (2015). Paulillo et al. (2019) and Colucci et al. (2021) have reprocessed these data using different LCA tools and considering updated LCIs based on more recent primary and secondary data (the LCI was reloaded using EcoInvent 3.8).

Within the GECO project, the LCI was reassessed using updated primary data (including emissions treatment equipment) and reprocessed using the Recipe 2016 V1.1 method of assessment and EcoInvent 3.8 for secondary data (Ramìrez et al., 2023).

Concerning Nesjavellir, there are no LCI data or LCA results published in the literature. Therefore, within the collaboration of the GECO project partners, LCI data from the power plant was made available to perform the analysis. For a complete view of all assumptions that were used, the LCI inputs and outputs, and the results obtained from LCA are provided as supplementary material.

As both plants are of the combined heat and power (CHP) type, exergy allocation was applied so that the two types of products can be considered: the Functional Unit is 1 MJ of exergy. Within the plant, components dedicated to electricity or heat production were identified wherever possible; when components were serving a dual purpose, their environmental single score was allocated according to the exergy fractions retraceable to power or heat respectively (Fiaschi et al., 2021). After the Life Cycle Assessment, the LCI was reprocessed to disaggregate the contribution of the most relevant components (Fig. 2 and Table 1 for Hellisheidi; Fig. 3 and Table 2 for Nesjavellir); normalization and weighting were applied according to the recommended Recipe 2016 approach, to build the Single Score, a set of data which is necessary for the following EEvA step.

3.1. Hellisheidi power plant

The Hellisheidi power plant is located in South-West Iceland, around 30 km east of the capital town Reykjavik. The power plant was commissioned in 2006 with an initial electricity production capacity of 90 MW_e and no heating but has since then been developed further. Currently, the electric production capacity of the plant is 303 MWe which delivers electricity to Iceland's national grid and 133 MW_t to the district heating of Iceland's capital region.

The Hellisheidi power plant (Fig. 2) follows a double-flash scheme (Di Pippo, 2015) applying the integration of a cold-water resource, which is used for a dual purpose: 1) to reduce the size of the High-Pressure steam condenser (HPC) 2) to recover heat for the DH network (from the HPC, and heat recovery with a dedicated Heat Exchanger HE from the low-pressure flash drain stream). This solution allows to limit the size of the cooling towers and represents a good example of CHP integration for a power plant having a large power output. The fundamental components of the GPP are listed in Table 1.

The power plant uses 54 production wells, of which 16 narrow and 38 wide, and 17 reinjection wells. Since 2018, all wells are drilled using an electrical drive – replacing the use of diesel oil, thereby with notably reduced environmental impact.

Since 2014, abatement of CO_2 and H_2S has been applied at the Hellisheidi plant at a large scale. With the abatement methods, called Carbfix and Sulfix, the CO_2 and H_2S coming from the plant NCG extraction system are dissolved in water and reinjected back into the basaltic rock formation. The Carbfix method has proven highly efficient with 95% of the CO_2 being mineralized within two years after reinjection (Clark et al., 2020). The abatement solutions require additional piping to transport gas and water from the power plant. The fluids are transported to a water scrubbing system where the gas dissolves in water and thereafter is transported via pipelines to reinjection wells. In 2017, the reinjection of CO_2 and H_2S amounted to 10,000 and 5000 tons respectively. This corresponds to 34% and 68% of the plant's annual emissions.

3.2. Nesjavellir power plant

The Nesjavellir geothermal plant is located near the Hengill volcano in southwest Iceland, 27 km away from the capital Reykjavik. Construction of the plant began in 1987, and in 1990 the production of thermal energy (100 MWt), began. In 1998, the first two 30 MW turbines were installed for electricity production, in 2001 the third turbine was installed, and in 2005 the fourth and final one. The power plant operates with a classical single-flash arrangement: however, it is largely dedicated to heat as well as electricity production; in normal conditions, the cooling towers are not operational (they are present only to allow operation when heating is not required), and all the exhaust heat is effectively recovered and directed to the district heating.The nominal output of the plant is 120 MW of electricity and 300 MW of heat.

There are currently 26 active wells, of which 21 are production and 5 are reinjection, with depths ranging from 1000 to 2200 m and temperatures from 150 °C to over 380 °C.

For the district heating network, cold water is drawn from a well near

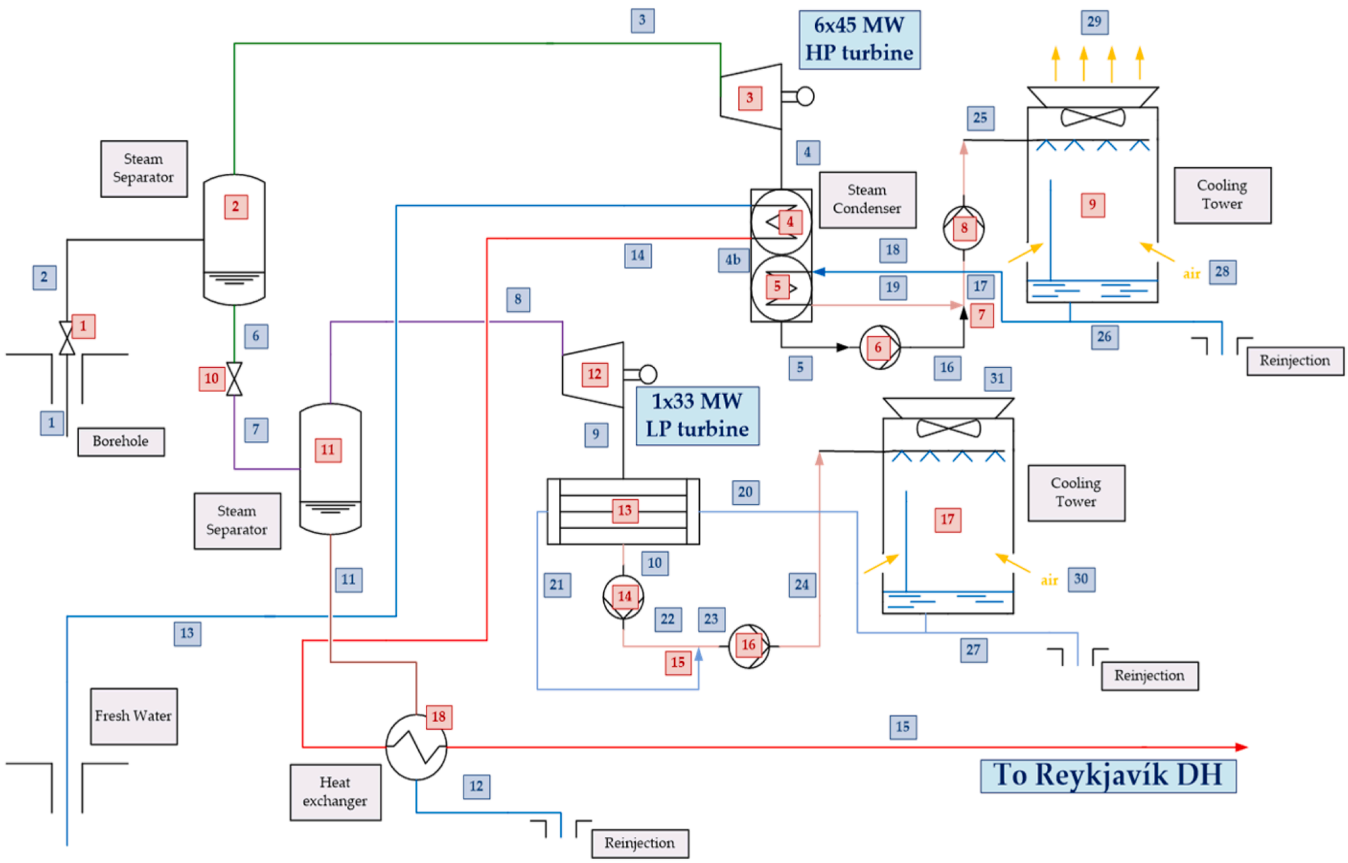

Fig. 2. Simplified schematic of the Hellisheidi power plant, with identification of components and streams (Blue numbers represent the streams. Red numbers represent the plant components - Table 1).

Table 1
Components of the Hellisheidi Power Plant (red numbers in Fig. 2).

Component #	Component name	Component #	Component name
1	Wellhead Valve	10	HP Throttling valve
2	HP Steam Separator	11	LP Steam Separator
3	HP Turbines	12	LP Turbine
4	DH condenser HP	13	Condenser LP
5	Condenser HP	14	Pump 3
6	Pump 1	15	Mixing point 2 (LPCT)
7	Mixing Point 1 (HPCT)	16	Pump 4
8	Pump 2	17	LP Cooling Tower LPCT
9	HP Cooling tower HPCT	18	Heat Exchanger for DH

Lake Thingvallavatn. The water is heated and then transferred to Reykjavik via a 27 km aqueduct with a capacity of 1,6 m^3 per second at a maximum temperature of 100 °C and a pressure level of 3.6 MPa. The hot water is stored in a reservoir 410 m above sea level by pumps, from where the water flows to Reykjavik by gravity and takes about two hours to reach the capital. Thanks to the efficient insulation of the pipes, the temperature loss is less than one degree Celsius. The geothermal plant in Nesjavellir covers 40% of Reykjavik's hot water demand for heating and domestic use. The power plant configuration is shown in Fig. 3; the list of components is summarized in Table 2.

4. Results

The results are first presented for Hellisheidi in terms of exergy, exergo-economic, and exergo-environmental analyses. The Nesjavellir case is then presented similarly.

4.1. Hellisheidi power plant

4.1.1. Hellisheidi exergy analysis

Fig. 4 shows the relative exergy destruction for each component of the Hellishedi Power plant. The component with the highest exergy destruction is the geothermal well (due to friction losses and heat dispersed from the wellbore as the fluid is coming to the surface). After the well, the other components responsible for considerable exergy destruction are the turbines and the condenser in the high-pressure section of the plant. These 3 elements cover about 94.5% of the total exergy destruction, which is distributed as follows: 72.6% by the wells, 11.5% by HP turbines, and 10.5% by the HP condenser.

The total exergy input of the plant is 955.9 MW, while the exergy output is 315.67 MW, divided into 303 MW of electricity and 12.54 MW of thermal exergy. Thus, the exergy efficiency of the plant results $\varepsilon_S = 33\%$; this performance is highly affected by the wells system. If the wells are not considered, the surface plant's exergy efficiency reaches a value $\varepsilon_{PP} = 48.3\%$.

The Sankey diagram in Fig. 5 shows how the exergy extracted from the reservoir is converted into mechanical power and heat for the DH network. The rectangles represent the components of the plant while the thickness of the connection between them represent an exergy flux (the thickness is proportional to the absolute exergy flow in kW). The exergy destruction are represented in red while the exergy losses in blue.

From Fig. 5 is clear that after the extraction, most of the exergy is directed toward the HP Turbine. The remaining exergy (coming out from the *HP Steam Separator* as brine) is almost equally divided between the LP turbine and the heat exchanger that provides heat to the DH network. What remains after the *HE for DH* is re-injected while the discharge of the turbines has to be condensed using the two independent *cooling systems* (i.e. the group of components that contains the condenser

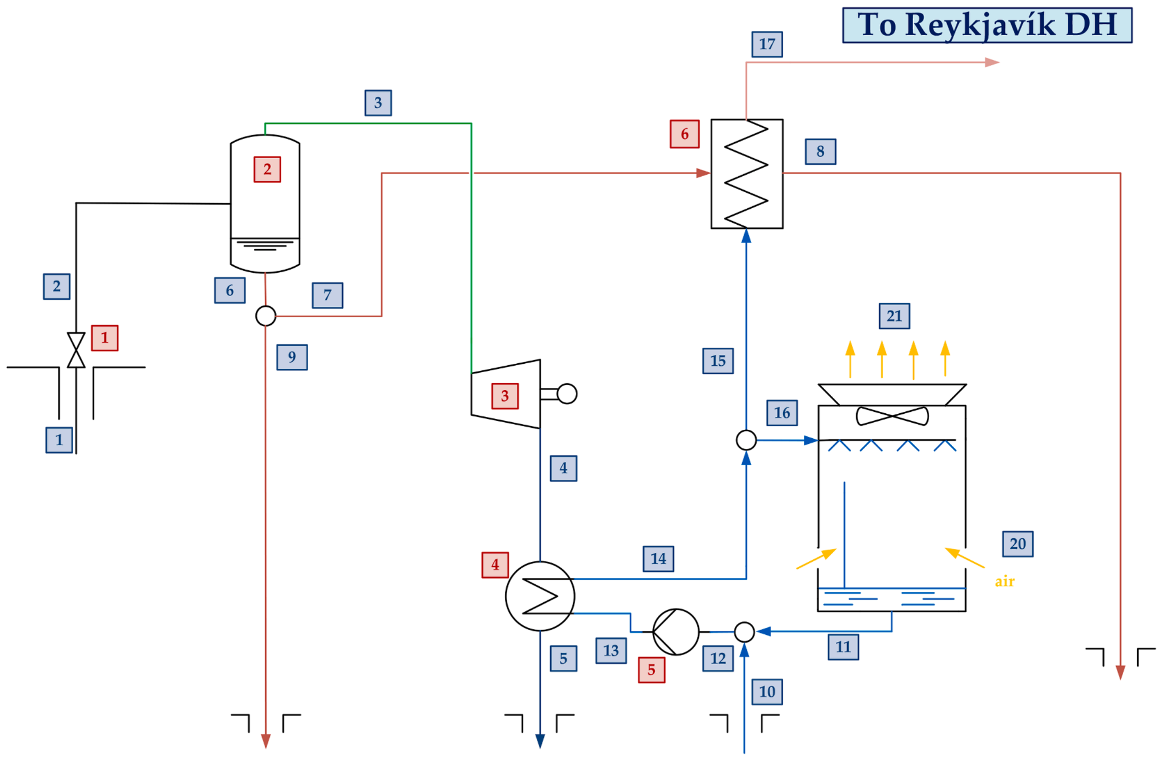

Fig. 3. Simplified schematic of the Nesjavellir power plant, with identification of components and streams (Blue numbers represent the streams. Red number represent the plant components - Table 2).

Table 2
Components of Nesjavellir Power Plant (red numbers in Fig. 3).

Component #	Component name	Component #	Component name
1	Wellhead Valve	4	Condenser
2	Steam Separator	5	Pump
3	Turbines	6	HE for DH

and the cooling tower). As can be seen, the cumulative exergy destruction of the power plant determines a large share of the plant inefficiencies, while the effect of exergy losses is kept low thanks to the CHP nature of the power plant which allows extensive recovery of waste heat.

4.1.2. Hellisheidi exergo-economic analysis

The first step of the EEA is to retrieve the Purchase Equipment Cost of the components (Table 3, column 3). The PEC was calculated through correlations, as explained in paragraph 2 (exergo-economic analysis). From this, the Direct and Indirect costs were evaluated using the recommended standard approach in Chemical Engineering (Turton et al., 2017). The overall calculated specific investment cost of the power plant is 3769 €/kW, which is close to expectations for modern GPPs (IRENA, 2021). A direct result of the EEA is the cost of electricity and heat production. The obtained LCOE is 5.5 c€/kWh, which is in line with the national electricity production cost in Iceland from geothermal power plants which is about 5.8 c€/kWh (Sigfùsson, 2015); the cost of the DH hot water referred to exergy is 9.3 c€/kWh$_t$ or - referred to the volume of water - 0.834 €/m^3.

In this study, the cost of the emission treatment equipment was neglected as it was 2 orders of magnitude lower than the cost of the wells system.

Table 3 provides the main exergo-economic calculated parameters. From this table, it can be noticed that there are components where the economic impact is mainly due to the exergy destruction $\dot{C}_{D,k}$, such as the HP turbines or the DH condenser, whereas the capital cost $\dot{Z}_k$ contributes much less; for components such as the wells or the pumps, the capital cost is instead in practice the only contributor to the cost build-up.

Concerning the whole economic impact ($\dot{Z}_k + \dot{C}_{D,k}$), the HP cooling towers result to be the most impacting components after the wells, accounting for about 25% of the total economic impact; of this 70% is due to the exergy destruction ($\dot{C}_{D,k}$), while 30% is due to the capital cost ($\dot{Z}_k$), which is indeed the highest one (excluding the wells) as can be seen in Table 3.

Another significant contribution to the economic cost comes from the HP turbines (14% of the total economic impact ($\dot{Z}_k + \dot{C}_{D,k}$)), which scores a high capital cost (contributing to about 40% of the total HP turbine economic impact). Therefore, it can be highlighted that the most impacting components for the power plant are the Wells, the HP cooling tower, the HP turbines, and the HP Condenser, contributing to the total economic impact of 42%, 25%, 14%, and 9%, respectively. If only the purchase equipment cost is considered, on the other hand, the wells contribute 70% of the total cost of the plant.

As indicated in Table 3, the DH condenser HP, the HP Condenser, the LP Condenser, Pump 3, and the HE for DH display relatively high values of r_k, which indicates the possibility of an economic cost reduction with relatively low effort. The high exergy destruction in the condenser is mainly due to the very low value of exergy at the outlet compared to the inlet, therefore the relative cost of the component drastically rises. The cooling tower and the valves are dissipative components, therefore they do not have an output product ($c_{p,k} = 0$).

The EEA procedure also allows the calculation of the contributions of all components to the cost build-up for each component k (Fig. 6). Indeed, it is possible to identify the self-contribution (the share of the cost determined by the component itself), and the external contribution (the share of the cost determined by non-ideal performance and cost accumulation of all the other plant components). As was expected, the cost of the wells is impacting heavily all other items, with external

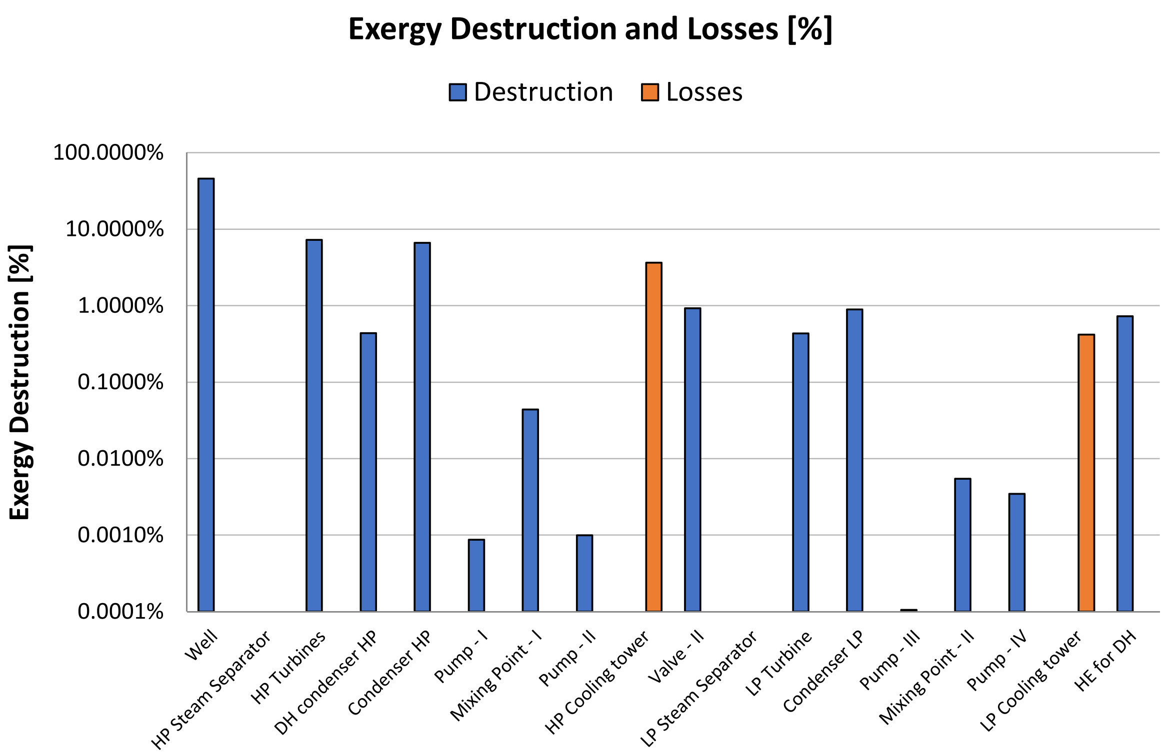

Fig. 4. Bar graph of exergy destruction for each component (Hellisheidi).

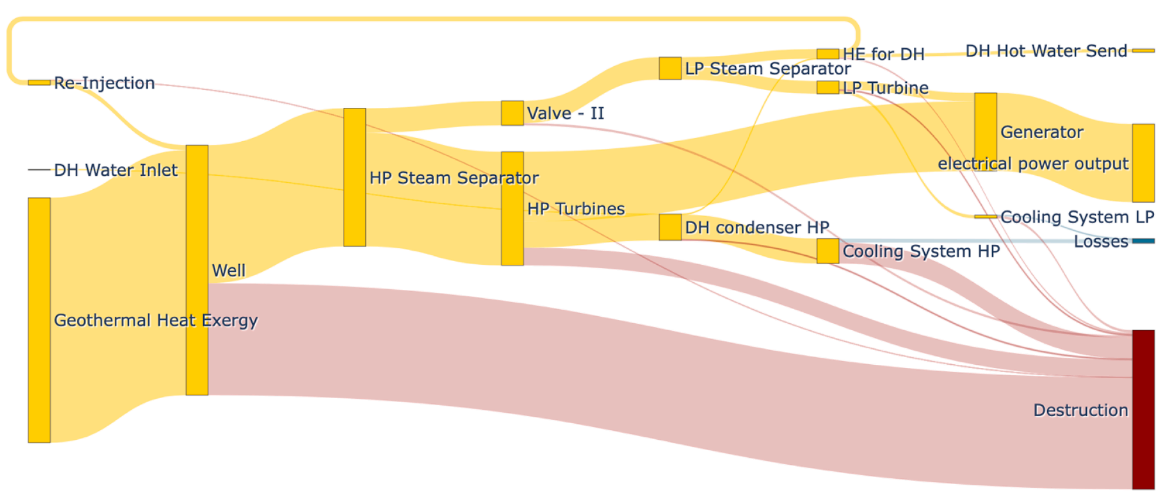

Fig. 5. Sankey exergy conversion diagram of Hellisheidi power plant,Color code: Yellow = standard exergy fluxes, Blue = exergy losses, Red = exergy destruction. The thickness of the connection lines is proportional to the exergy flux (in kW). To enhance the readability of the plot, the component called *Cooling System* groups together all the components related to the heat rejection from the *Turbine (HP and LP respectively),* i.e. *the condenser, the cooling tower, and the pumps.*

contributions higher than 80% for all components. Other components with relevant cost impacts are the HP cooling towers, the HP turbines, and the HP condenser.

4.1.3. Hellisheidi exergoenvironmental analysis

The results of the EEvA are resumed in Table 4, in which the following data are reported for each component: single score LCA value (first column), the specific environmental cost of the component $\dot{Y}_k$ (second column), environmental impact of exergy destruction $\dot{B}_{D,k}$ (third column), total environmental impact $\dot{B}_{TOT,k}$ (fourth column) that is the sum of $\dot{Y}_k$ and $\dot{B}_{D,k}$, exergo-environmental factor $f_{d,k}$ (fifth column), and relative differences in the specific environmental impacts $r_{d,k}$ (sixth column).

The environmental cost of the emission treatment equipment exclusively considers the steel used in its construction, consisting of the compressor and absorption column. The environmental cost of the operation phase is neglected because it is minimal for the results obtained. In addition, the useful effect of CO_2 capture and H_2S abatement is considered.

The parameter $\dot{B}_{TOT,k}$ (column 4) considers both the component's life cycle and the destruction of the exergy. Also, from the environmental point of view (similar to economics), the element with the highest total impact is the system of wells, causing about 42.7% of the total impact.

The other components that are causing significant environmental impact are the HP cooling tower (19% of the total), the HP turbine (15% of the total), and the HP condenser (10% of the total).

Table 3
Values of relevant exergo-economic variables.

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	Wells + WH Valve	4.70E+08	3.4968858	0	3.497	0.0000	0.0371	100	0
2	HP Steam Separator	2.38E+06	0.01765	0	0.01765	0.0371	0.0373	100	0.0032
3	HP Turbines	5.67E+07	0.4212	0.71325	1.13445	0.0373	0.0562	37.13	0.5076
4	DH condenser HP	1.39E+06	0.01033	0.0434	0.05373	0.0373	0.2086	19.23	4.6003
5	Condenser HP	1.82E+07	0.1351	0.6524	0.7875	0.0373	0.1614	17.16	3.3326
6	Pump1	55,017	0.0004089	0.00013	0.0005389	0.0555	0.0994	76.09	0.7902
7	Mixing Point 1	0	0	0.01746	0.01746	0.1496	0.1517	0	0.0139
8	Pump2	770,381	0.005726	0.00015	0.005876	0.0555	0.0724	97.51	0.3036
9	HP Cooling tower	9.32E+07	0.6927	1.4337	2.1264	0.1488	0	32.58	–
10	Throttling valve	0	0	0.0914	0.0914	0.0373	0	0	–
11	LP Steam Separator	677,297	0.005034	0	0.005034	0.0373	0.0375	100	0.0056
12	LP Turbine	7.57E+06	0.05625	0.043	0.09925	0.0375	0.0502	56.61	0.3406
13	Condenser LP	2.50E+06	0.01861	0.0886	0.10721	0.0375	0.1858	17.37	3.9596
14	Pump 3	23,520	0.0001748	1.5E-05	0.000189	0.0555	0.1515	91.83	1.7289
15	Mixing point 2	0	0	0.0025	0.0025	0.1747	0.1774	0	0.0153
16	Pump 4	203,171	0.00151	0.0005	0.00201	0.0555	0.0816	74.74	0.4703
17	LP Cooling Tower	1.53E+07	0.1137	0.1897	0.3034	0.1703	0	37.47	–
18	HE for DH	3.04E+06	0.02261	0.0722	0.09481	0.0375	0.0791	23.86	1.1106
–	**Total Plant**	**6.72E+08**	–	–	–	–	–	–	–

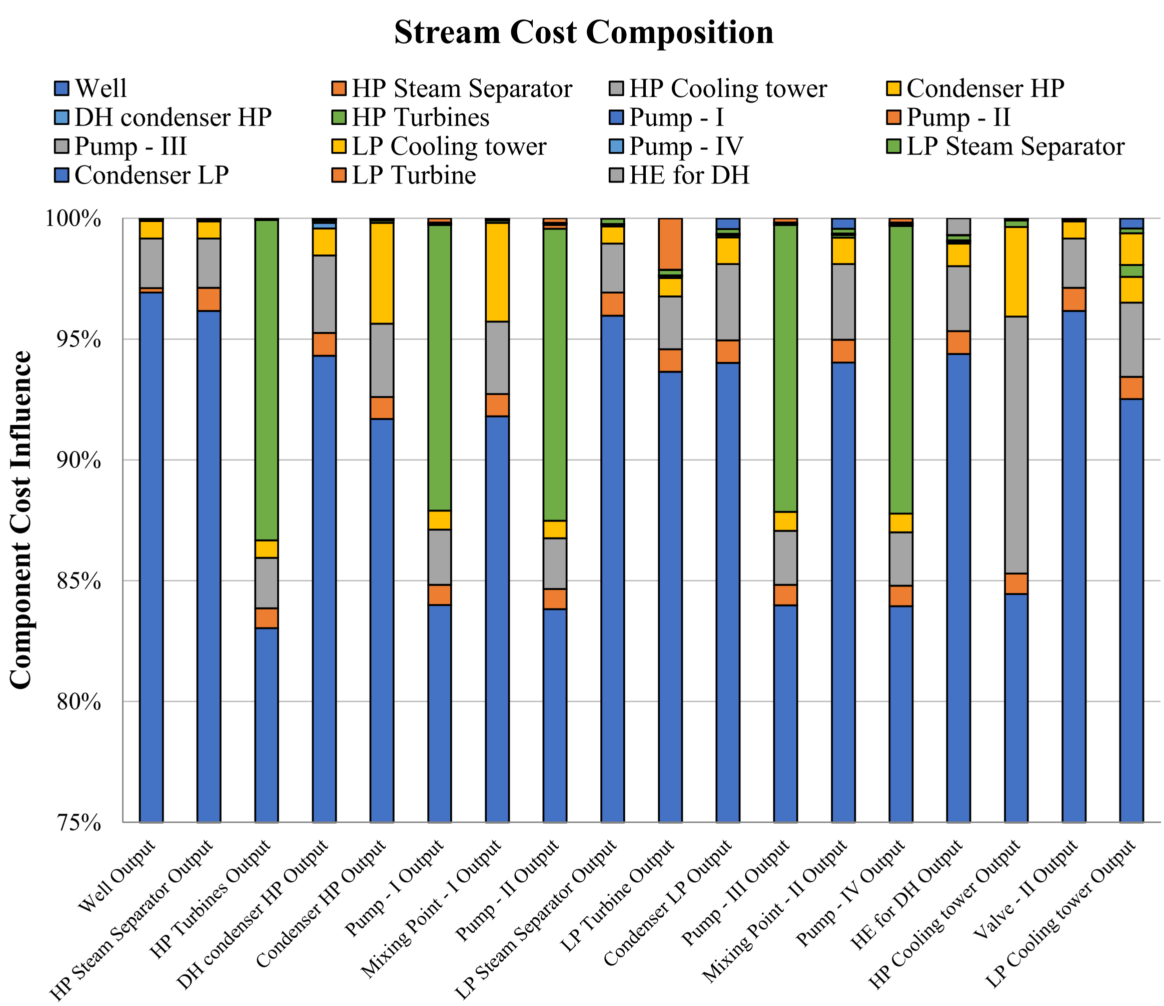

Fig. 6. Cost decomposition for each component (self and share from all others; Hellisheidi).

From the analysis, it can be seen that the components which deserve attention for improvement in terms of sustainability are the ones with high $r_{d,k}$: the DH Condenser HP, the HP Condenser, the LP Condenser, and the DH Heat Exchanger. On the other hand, all elements that have a low $r_{d,k}$, have a limited potential for improvement, with the result that possible improvement interventions are complex and onerous from the point of view of the use of natural resources.

Finally, the environmental costs of the electricity and heat produced by the power plant is $b_{el} = 2.4$ cPts/kWh$_e$, while the environmental cost of heat is b_{DH} 7.7 cPts/KWh$_t$, which can be converted (multiplying the cost per unit exergy by the specific exergy of the stream) in *69.5* cPts/m^3 of hot water distributed to the DH network.

Table 4
Values of relevant exergo-environmental variables.

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	Wells + WH Valve	4.35E+04	1.62E+00	0.000E+00	1.62E+00	1.00	0.00
2	HP Steam Separator	8.88E+02	3.31E-02	0.000E+00	3.31E-02	1.00	0.02
3	HP Turbines	6.85E+03	2.56E-01	3.069E-01	5.63E-01	0.45	0.55
4	DH condenser HP	2.00E+03	7.46E-02	1.867E-02	9.33E-02	0.80	18.33
5	Condenser HP	3.32E+03	1.24E-01	2.807E-01	4.05E-01	0.31	3.33
6	Pump1	5.69E-01	2.12E-05	5.712E-05	7.84E-05	0.27	0.27
7	Mixing Point 1	0.00E+00	0.00E+00	7.501E-03	7.50E-03	0.00	0.01
8	Pump2	1.54E+01	5.74E-04	6.515E-05	6.39E-04	0.90	0.10
9	HP Cooling tower	3.00E+03	1.12E-01	6.139E-01	7.26E-01	0.15	–
10	Throttling valve	0.00E+00	0.00E+00	3.932E-02	3.93E-02	0.00	–
11	LP Steam Separator	3.60E+02	1.34E-02	0.000E+00	1.34E-02	1.00	0.05
12	LP Turbine	8.38E+02	3.13E-02	1.934E-02	5.06E-02	0.62	0.41
13	Condenser LP	5.58E+02	2.08E-02	3.973E-02	6.06E-02	0.34	4.23
14	Pump 3	8.81E-02	3.29E-06	6.915E-06	1.02E-05	0.32	0.23
15	Mixing point 2	0.00E+00	0.00E+00	1.200E-03	1.20E-03	0.00	0.01
16	Pump 4	3.64E+00	1.36E-04	2.270E-04	3.63E-04	0.37	0.20
17	LP Cooling Tower	5.01E+02	1.87E-02	8.882E-02	1.07E-01	0.17	–
18	HE for DH	1.10E+03	4.12E-02	3.237E-02	7.36E-02	0.56	1.79

Fig. 7 shows the contributions of each component to the cumulative environmental cost for each component k. Similar to the economic analysis, the component environmental cost is heavily impacted by the external contribution from the wells, with values higher than 75% for all the components. Similarly to the exergoeconomic case, the other components with relevant environmental impact are the HP cooling towers, the HP turbines, and the HP condenser (the performance of these components is also reflected in significant external contributions to those connected).

4.2. *Nesjavellir power plant*

4.2.1. *Nesjavellir exergy analysis*

The results of the exergy analysis for the Nesjavellir power plant are here reported. Fig. 8 shows that the component with the highest exergy destruction is again the geothermal wells system. The other components responsible for considerable exergy destructions are the condenser, the turbines, and the HE for DH. These 4 elements cover about 99.99% of the total exergy destruction, which is distributed: 53.09% by the wells, 23.33% in the HP condenser, 14.09 HE for DH, and 9.48% by HP turbines.

The total exergy input of the plant is 403.22 MW, while the exergy output is 151.68 MW, divided into 119.94 MW of electricity and 31.73 MW of thermal exergy. Thus, the exergy efficiency of the plant is 37.6%, with significant dissipations traceable to the wells. If the wells are not considered the surface plant exergy efficiency reaches a value of 51.1%.

From the Sankey diagram in Fig. 9, if compared with the Hellisheidi case, in Neisjavellir the thermal output represents in terms of exergy a

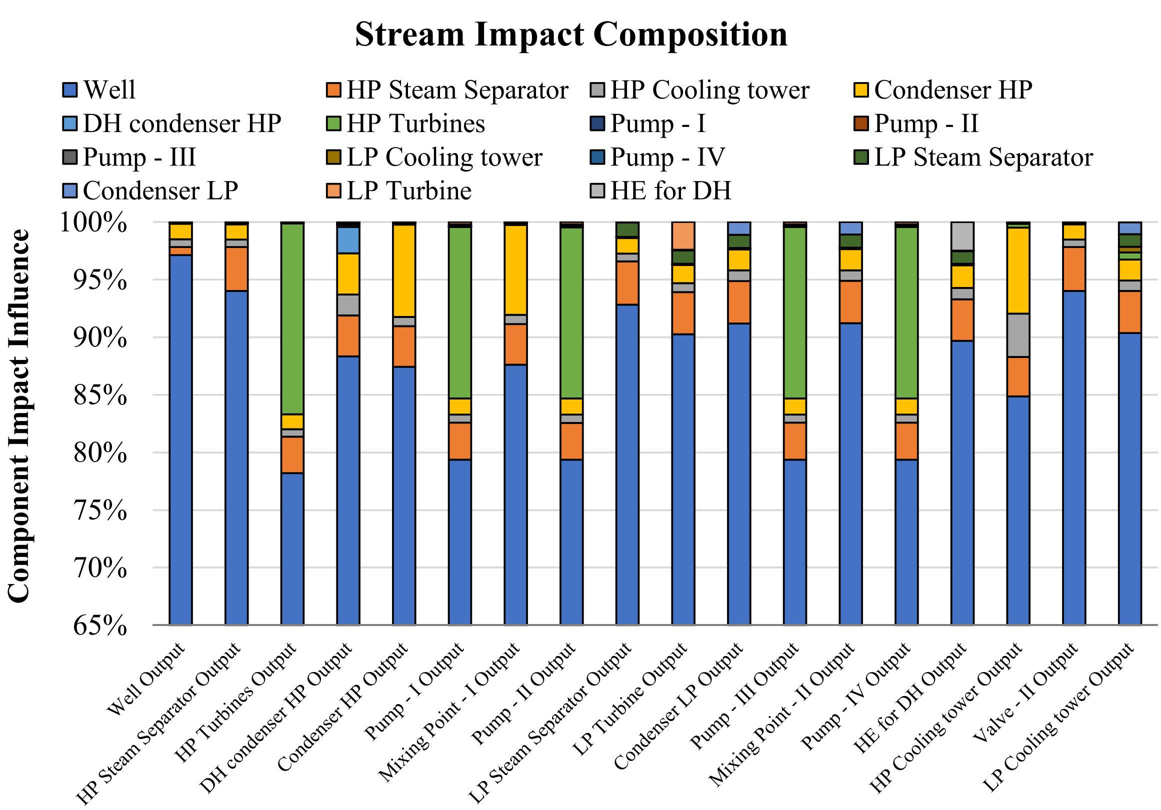

Fig. 7. Environmental impact contribution to each component from the others (Hellisheidi).

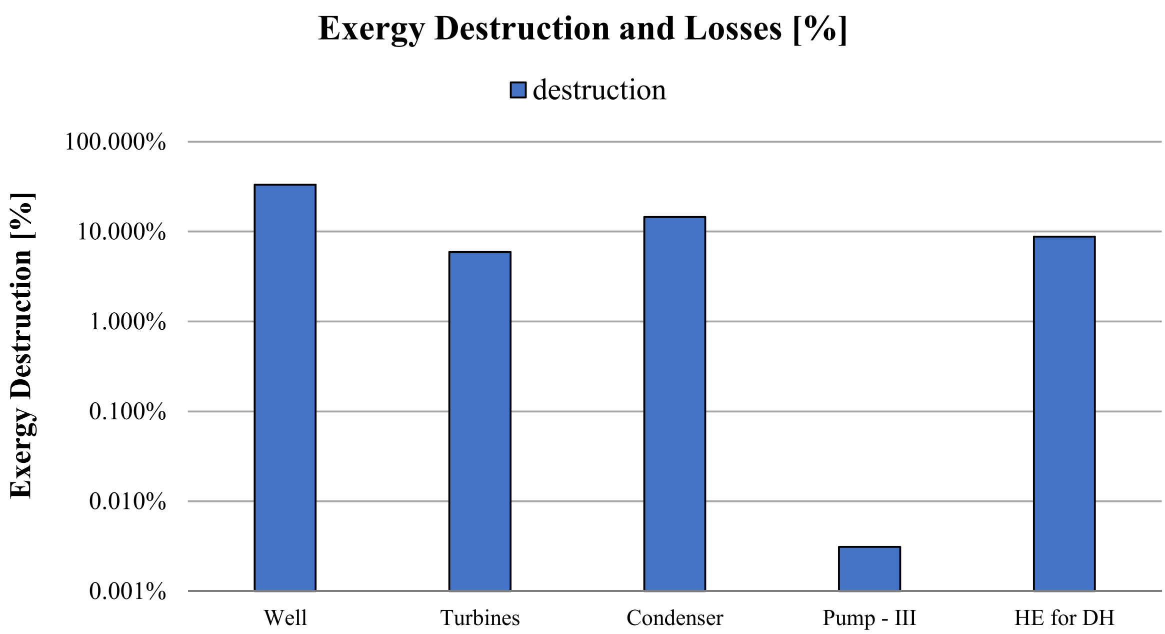

Fig. 8. Bar graph of the exergy destruction for each component (Nesjavellir).

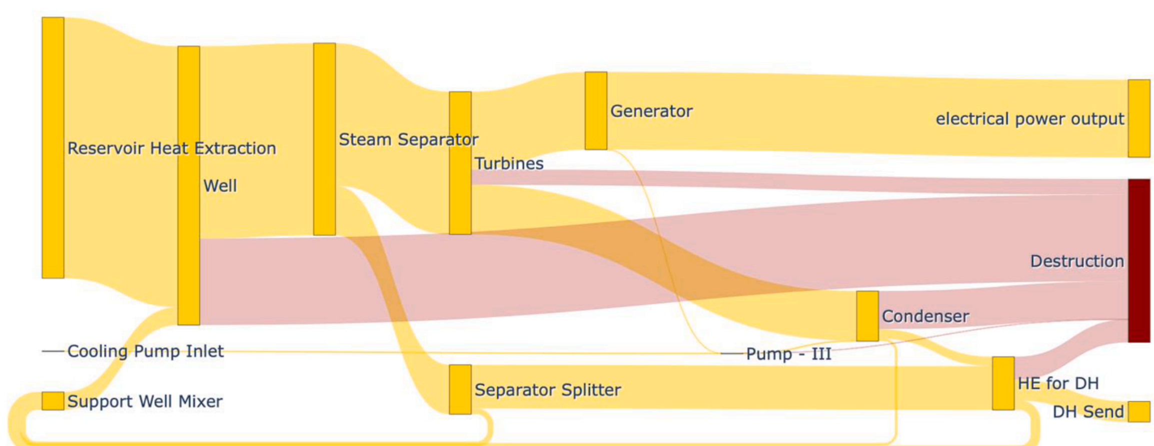

Fig. 9. Sankey exergy conversion diagram of Nesjavellir power plant. color Code: Yellow = standard exergy fluxes, Red = exergy destruction. The thickness of the connecting lines is proportional to the exergy flux (in kW).

more important contribution. This happens because Neisjavellir is a single flash plant, meaning that all the exergy not immediately directed toward the turbine will be used for providing heat to the DH network. Again, the cumulative exergy destruction of the power plant determines a large share of the plant inefficiencies, while in this case there are no exergy losses, thanks to the complete CHP nature of the power plant which allows complete recovery of the waste heat from the GPP (the cooling towers are used only in case of absence of the DH supply).

4.2.2. *Nesjavellir exergo-economic analysis*

The overall calculated specific investment cost of the power plant is 3551 €/kW, a close value to that of Hellisheidi. The calculated cost of electricity was 2.31 c€/kWh, while the cost of heat production referring to exergy was 6.3 c€/kWh$_t$ or 0.509 €/m^3 referred to the unit volume of hot water.

Table 5 resumes the main exergoeconomic calculated parameters for the Nesjavellir power plant. The components that have a high economic

Table 5
Values of relevant exergo-economic variables.

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	Well	2.20E+08	1.1089	0	1.1089	0	0.0148	100	0
2	Steam Separator	1.40E+06	0.0073	0	0.0073	0.0139	0.0139	100	0.0064
3	Turbines	4.20E+07	0.2151	0.0927	0.3078	0.0139	0.0232	69.9	0.6616
4	Condenser	9.00E+06	0.0453	0.2281	0.2734	0.0139	0.086	16.6	5.1631
5	Pump – III	140.,691	0.0007	0.0001	0.0008	0.0232	0.0497	89.8	1.1441
6	HE for DH	4.20E+06	0.0212	0.1378	0.1590	0.0139	0.0473	13.3	2.3932
7	Separator Splitter	0	0	0	0	0	0	0	0
		2.77E+08			1.86E+00				

impact due to exergy destruction $\dot{C}_{D,k}$ are the condenser and the HE for DH, whereas for the wells and the turbines, the capital cost $\dot{Z}_k$ contributes is essentially the only contributor to the cost build-up.

Concerning the whole economic impact ($\dot{Z}_k + \dot{C}_{D,k}$), the turbines are found to be the most impacting component after the wells, accounting for about 17% of the total economic impact; of this 70% is due to the capital cost ($\dot{Z}_k$), while 30% is attributable to the exergy destruction ($\dot{C}_{D,k}$)).

Another significant contribution to the economic cost comes from the condenser (15% of the total economic impact ($\dot{Z}_k + \dot{C}_{D,k}$)), which scores a high exergy destruction cost (83% of the total component impact cost). Therefore, it can be highlighted that the most impacting components for the power plant are the Wells, the turbines, and the condenser, contributing to the total economic impact of 60%, 17%, and 15%, respectively. If only the purchase equipment cost is considered, on the other hand, the wells contribute 79% of the total cost of the plant.

As can be seen in Table 5, the values of r_k for all components are not so high, meaning that it would be difficult to obtain an economic cost reduction with relatively low effort.

Fig. 10 shows that the cost of the Wells is impacting heavily on almost all components, with an external contribution higher than 70% for all components except for the pump, which on the other hand is mostly influenced by its endogenous contribution. Following the contribution of the well, also the turbine shares a significant part of the pump cost build-up, while the other components' contributions result in negligible.

4.2.3. Nesjavellir exergo-environmental analysis

The results of the EevA for the Nesjavellir power plant are resumed in Table 6. From the environmental point of view (similar to economics), the element with the highest total impact ($\dot{B}_{TOT,k}$) is the system of wells, causing about 41.91% of the total impact. The other components that hold a consistent environmental impact are the condenser (27.39% of the total), the turbines (14.80% of the total), and the HE for DH (13.32% of the total).

The condenser and the HE for DH have a high value of $r_{d,k}$. This means that these components should be carefully assessed to improve with a potentially marginal effort the sustainability of the plant. The environmental costs of the electricity and heat produced by the power plant resulted to be 2.2 cPts/kWh$_e$, and 10.1 cPts/kWh$_t$ of exergy, or 81.8 cPts/m^3 of hot water, respectively.

Finally, Fig. 11 displays how, as for the economic analysis and similarly to the Hellisheidi power plant, there is a significant external contribution from the wells, with values over 70% for all components except the pump. Finally, the turbine has a high self-contribution (28%) and contributes significantly to the cost buildup of the pump (about 12%).

4.3. Comparison of results

In terms of exergy, both plants have a high performance (Hellisheidi: $\varepsilon_S = 33\%$; ε_{PP} =48,3%; Nesjavellir: $\varepsilon_S = 37{,}6\%$; ε_{PP} =51,1%). The superior performance of the Nesjavellir GPP is motivated both by the good resource conditions and by the fact that heat is completely recovered as a by-product of electricity (there is thereby no exergy loss at the cooling towers).

These results are also reflected in the exergoeconomic analysis (Hellisheidi: $c_{el} = 5.5$ c€/kWh: $c_{DH} = 9.3$ c€/kWh$_t$; Nesjavellir: $c_{el} = 2.3$ c€/kWh: $c_{DH} = 6.3$ c€/kWh$_t$). The difference in power and heat costs between the two power plants is due to the following main effects:

- Production of heat in Nesjavellir takes place with complete recovery of sensible heat from power plant cooling: in normal operation, the plant does not need external cooling (the cooling towers are present only for emergencies or in case of an outage of the district heating). On the other hand, even if the production of heat in Hellisheidi also determines a notable cooling load reduction for the HP condenser/ cooling towers assembly, external cooling is necessary for Hellisheidi. This means that non-productive components (HP and LP condensers/cooling towers) are present, whose cost must be redistributed across the productive components.
- Considering both heat and power, the overall exergy production of Nesjavellir is almost half of the production of Hellisheidi (152 MW in Nesjavellir, 315 MW in Hellisheidi). To achieve this production, Nesjavellir requires one-third of the wells required by Hellisheidi (20 wells in Nesjavellir, 63 wells in Hellisheidi). This results in a significant economic advantage.
- According to the exergoeconomic analysis, the ratio between the relative cost of heat and power per kWh of exergy is higher for Nesjavellir (2,74 in Nesjavellir, 1,67 in Hellisheidi). This means that in Nesjavellir heat production is more valuable than power production in comparison with Hellisheidi. This will lower the LCOE in Nesjavellir because if the heat is sold at a higher price the energy

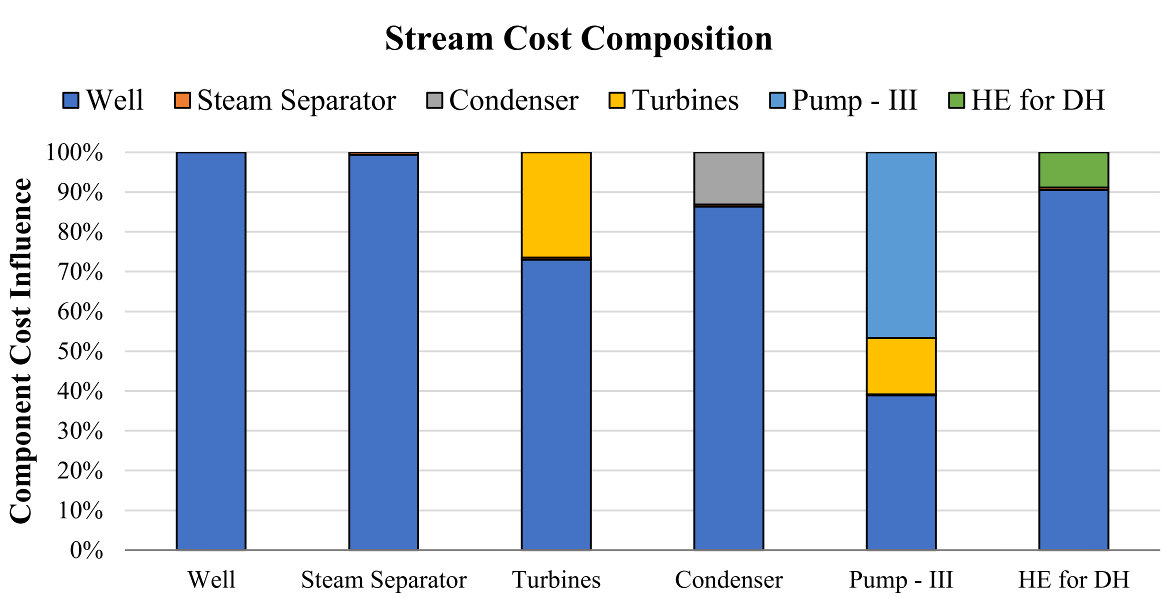

Fig. 10. Cost contribution to each component (self and from all others, Nesjavellir).

Table 6
Values of relevant exergo-environmental variables.

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	Well	2.81E+04	1.05E+00	0.000E+00	1.05E+00	1.00	0.00
2	Steam Separator	1.73E+03	6.44E-02	0.000E+00	6.44E-02	1.00	0.06
3	Turbines	5.76E+03	2.15E-01	1.550E-01	3.70E-01	0.70	0.66
4	Condenser	8.12E+03	3.03E-01	3.816E-01	6.85E-01	0.57	10.05
5	Pump – III	0.00E+00	0.00E+00	1.347E-04	1.35E-04	0.00	0.12
6	HE for DH	2.74E+03	1.02E-01	2.306E-01	3.33E-01	0.43	3.62

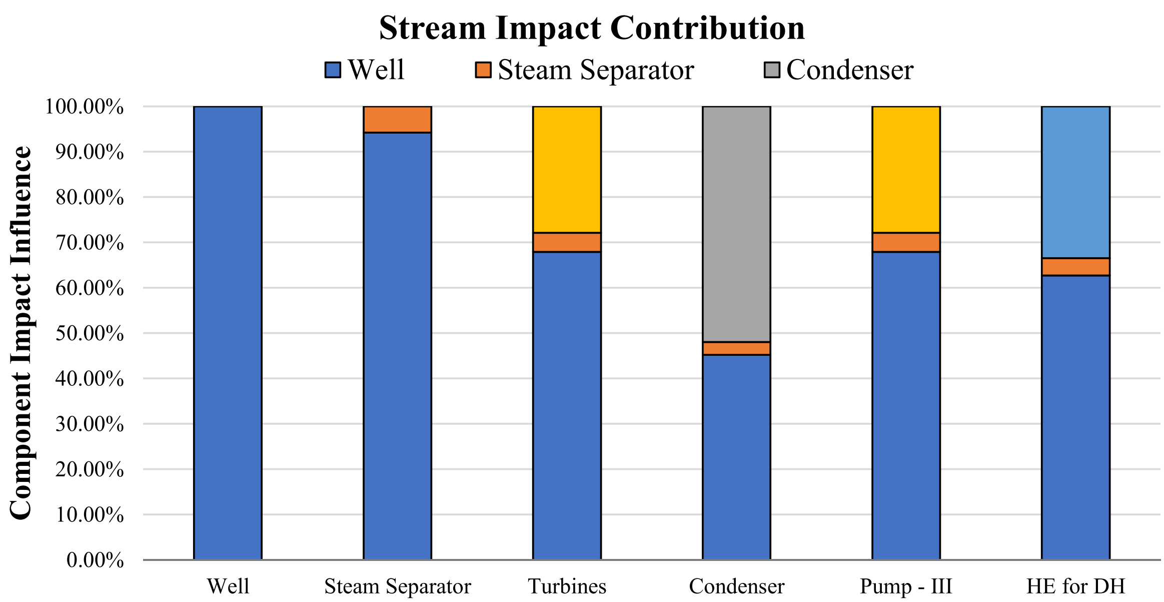

Fig. 11. Environmental cost contribution to each component.
(self and from all others; Nesjavellir).

price can be lowered. The difference between the heat costs is explained by looking at the cash flow between the components in the two different power plants resulting from eq. (8) (Figs. 12-13). In Nesjavellir the cost for heat production is higher than in Hellisheidi because of the larger amount of exergy used for heat generation, which is related to the fact that most of the exergy destruction of the plant happens in the heat exchangers used for heat generation.

From the point of view of the EEvA, the plants produce electricity and heat with very low overall weighted impact (Recipe 2016): Hellisheidi: b_{el} = 2.4 cPts/kWh: b_{DH} = 7.7 cPts/kWh$_t$; Nesjavellir: b_{el} = 2.2 cPts/kWh: b_{DH} = 10.1 cPts/kWh$_t$). The larger environmental cost of heat at Nesjavellir reflects the fact that the plant is largely dedicated to heat rather than electricity production, and this is reflected in the material/resource balance of the LCA.

5. Conclusions

Two large Geothermal Power Plants producing electricity and heat for district heating have been analyzed using exergy, exergoeconomic, LCA, and exergoenvironmental analyses. Concerning environmental impacts, the present study gathered updated primary raw data referred

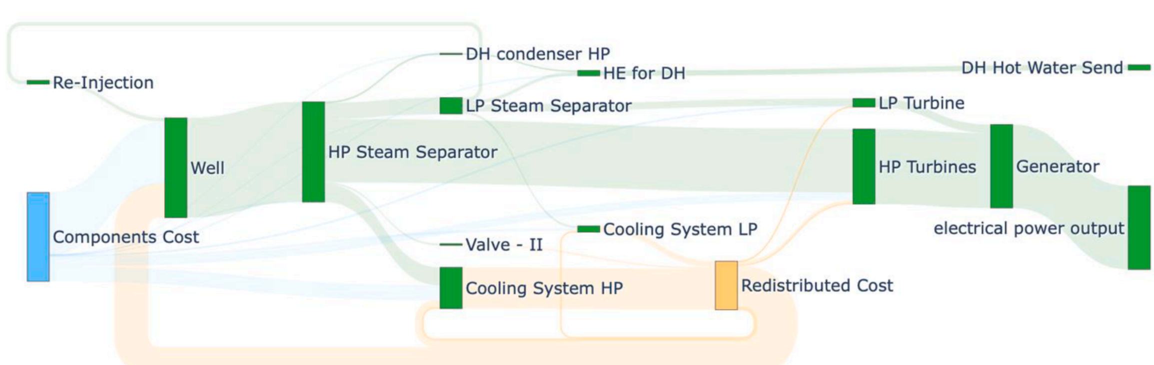

Fig. 12. Cash flow across components in Hellisheidi.
color Code: Green = cost associated with an exergy transfer between components, Orange = overall cost of the losses in dissipative components (to be redistributed), Blue = component cost.
The thickness of the connecting lines represents the cash flow (in €/s). For green streams the color intensity is proportional to the relative exergy cost (in €/kJ).

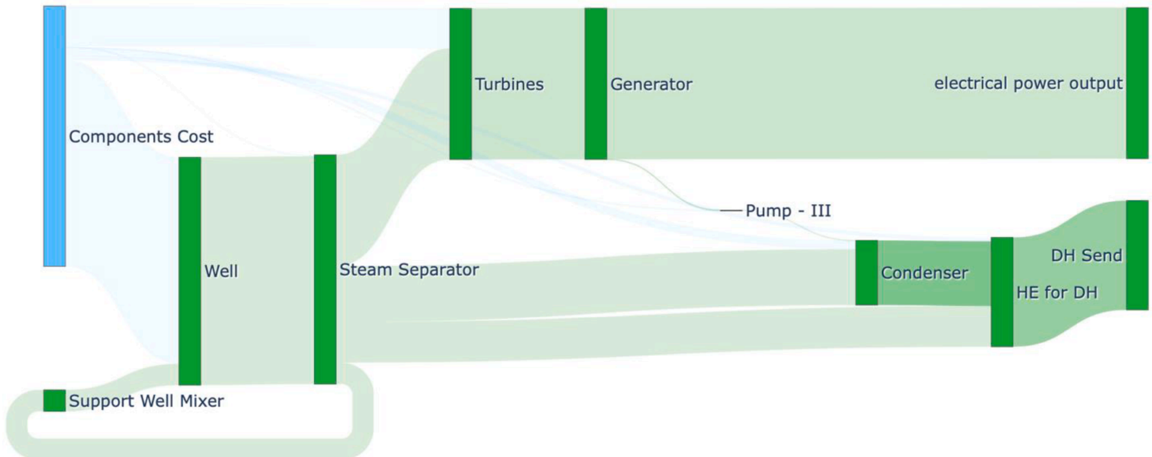

Fig. 13. Cash flow across components in Nesjavellir.

to i) construction, ii) operation (including abatement operations and maintenance), and iii) wells closure of the geothermal plant. The LCA inventory was normalized to 1 kWh of electricity and 1 kWh of heat production in the plant. Results were modeled with the most updated LCA database and assessed by the ReCiPe method. Finally, specific efforts were given to identify hot spots in the life cycle and, where possible, suggest improvements.

The results allow us to correctly allocate the production costs/impacts of the two different products (electricity and heat); moreover, the build-up of the economic and environmental costs along the energy conversion process was reconstructed in detail, identifying the critical components and providing suggestions for improvement.

The overall results obtained by the two GPPs are very good:

Hellisheidi:

- Economics: 5.5 c€/kWh for electricity and 9.3 c€/kWh$_t$ of exergy (0.834 €/m^3 of hot water) for DH hot water supply
- Sustainability: 2.4 cPts/kWh$_e$ for electricity and 7.7 cPt/kWh$_t$ of exergy (32.1 cPts/m^3 of hot water) for DH hot water (exergo-environmental impact using ReCiPe normalized/weighted LCA evaluation)

Nesjavellir:

- Economics: 2.3 c€/kWh$_e$ for electricity and 6.27 c€/kWh$_t$ of exergy (0.509 €/m^3) for DH hot water supply;
- Sustainability: 2.31 cPts/kWh$_e$, and 10.09 cPt/kWh$_t$ (81.8 cPts/m^3) for hot water.

The Nesjavellir plant has a much higher thermal exergy output compared to Hellishedi. The electricity cost is lower for Nesjavellir compared to Hellisheidi – electricity is a kind of by-product. This also motivates the higher relative environmental cost for DH water of the Nesjavellir plant, as a considerable share of the equipment's environmental impact is charged to the heat supply.

The economic cost of the wells represents a high share of the capital investment of a geothermal project, compared to their environmental impact. Indeed, the operation phases for Nesjavellir and Hellisheidi power plants are relevant from an environmental point of view, while they have less impact from the economic point of view, which is dominated by the capital cost of the wells.

The recent improvements in emissions treatment realized in Hellisheidi (NCG reinjection with a substantial reduction of emissions to the atmosphere) do not have a relevant effect in terms of increase of the economic and environmental costs; this is largely due to the large contribution of the wells to the cost-build-up. Therefore, the introduction and improvement of emissions treatment solutions is a very recommendable practice.

CRediT authorship contribution statement

Giampaolo Manfrida: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Lorenzo Talluri:** Data curation, Investigation, Methodology, Software, Validation, Writing – original draft. **Pietro Ungar:** Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. **Claudio Zuffi:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Maryori Díaz-Ramírez:** Data curation, Investigation, Project administration, Software. **Héctor Leiva:** Data curation, Investigation, Software, Validation, Visualization. **María Dolores Mainar-Toledo:** Funding acquisition, Investigation, Project administration, Supervision, Validation, Visualization. **Snorri Jokull:** Data curation, Project administration, Resources, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We provided all the necesary data in the resubmitted paper as Additional Material (Excel file) or Appendixes.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geothermics.2023.102758.

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Further reading

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