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Environmental Impact Assessment of Nesjavellir Geothermal Power Plant for Heat and Electricity Production

María Dolores Mainar-Toledo [1,*], Maryori Díaz-Ramírez [1,2], Snorri J. Egilsson [3], Claudio Zuffi [4], Giampaolo Manfrida [4] and Héctor Leiva [1]

[1] Research Centre for Energy Resources and Consumption (CIRCE), Avenida Ranillas Edificio Dinamiza, 3D, 50018 Zaragoza, Spain; circe@fcirce.es (M.D.-R.); hdleiva@fcirce.es (H.L.)
[2] CIRCE Institute, Fundación CIRCE, Universidad de Zaragoza, 50009 Zaragoza, Spain
[3] Reykjavik Energy, Bæjarháls 1, 110 Reykjavik, Iceland; snorri.jokull.egilsson@or.is
[4] Department of Industrial Engineering, University of Florence, 50139 Florence, Italy; claudio.zuffi@unifi.it (C.Z.); giampaolo.manfrida@unifi.it (G.M.)
* Correspondence: mdmainar@fcirce.es

Abstract: This work is focused on presenting the main results and discussions concerning the environmental benefits of reducing the non-condensable gases emitted from the Nesjavellir geothermal power plant. The primary objective of this study is to conduct a life cycle evaluation to analyse the overall environmental benefit effects of producing 1 kWh of electricity and 1 kWh of thermal energy in the geothermal power plant at Nesjavellir, which is located in Iceland. The assessment is performed both before and after implementing an abatement system designed to reduce CO_2 and H_2S gases. The production of geothermal energy is increasing every year and, therefore, it is crucial to identify and quantify the key environmental factors of producing this type of energy and improvements for the future energy transition of the energy generation sector. Firstly, the results show that the environmental impact of electricity production is higher compared to heat production. More in detail, the emissions due to the nature of the geothermal fluid and the construction phase represent the most relevant environmental load for both electricity and heat production for nearly all the 18 environmental impact indicators studied. Furthermore, considering the abatement system for the non-condensable gas emissions, reductions of 78% and 60% in global warming potential is achieved for a production of 1 kWh of electricity and 1 kWh of thermal energy. In terms of external environmental costs, the implementation of an abatement system results in a reduction exceeding 95% for both electricity and thermal energy production per kilowatt-hour. The outcomes obtained from both the baseline scenario and the application of the abatement system undeniably prove that the latter results in a substantial decrease in the overall environmental impacts linked to the generation of 1 kWh of electricity and 1 kWh of heat, encompassing a notable reduction in external environmental costs (externalities).

Keywords: life cycle assessment; environmental indicators; geothermal energy; exergy; district heating system; non-condensable gases reinjection

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1. Introduction

Energy is the primary necessity for development, innovation and modernisation in nearly all key sectors including health, education, agriculture and industry [1]. Thus, the demand for energy faces a constant increase [2]. Currently, the majority of energy production methods rely on the consumption of fossil fuels [3]. This originates a wide-spread of issues of serious concern, such as ozone depletion or greenhouse gas emissions accounting to global warming and climate change [4]. In an effort to deal with this escalating demand, the scientific community is continuously aiming to find and improve new approaches to develop sustainable energy technologies. Renewable energy sources (RESs) are, therefore, essential instruments to break the dependency of humankind on fossil fuel expenditure [5].

Among the RESs, the utilisation of geothermal energy for heat and/or electricity production has earned increased appeal [6] due to current and upcoming political objectives aimed at decreasing greenhouse gas emissions [7], consequently diminishing the depletion of limited energy sources while ensuring sufficient energy supply. Geothermal energy delivers heat and/or electrical power from a renewable energy source that is detached from atmospheric limitations, such as solar radiation intensity or wind flow speed [8]. Although only a reduced portion of this great potential is currently being exploited [9], the geothermal energy capacity worldwide reached over 15 GW in 2021 [10]. High-temperature and high-enthalpy geothermal reservoirs, situated at remarkably favourable geological countries (e.g., Iceland, Italy, the United States, Indonesia, Philippines, etc.), provide the largest share of this capacity [11].

Geothermal energy, however, entails a critical concern in regard to the environmental impact, among others, associated with the construction, operation and end-of-life (EOL) [12,13] of a power plant. There are critical concerns with the high amount of non-condensable gases included in the geothermal fluid composition, which will later represent an environmental impact due to the emissions released to the atmosphere during GPP operation, apart from the problems that are created in the operation (corrosion, calcite deposition, etc.) and the health and safety risks. In this sense, recent efforts are based on the application of solutions [14] aiming to minimise the emissions of pollutants, such as carbon dioxide and hydrogen sulphide [15].

This study analyses the Nesjavellir geothermal power plant (GPP) as it replicates the solution that is already implemented in the Hellishedi geothermal power plant [16,17]. The innovations applied to this power plant are Carbfix [18] and Sulfix [19], which aim to minimise the emissions of CO_2 and H_2S, respectively. The GECO project has proven to be technically feasible in the Nesjavellir GPP by reducing a portion of the gaseous emissions. Further research is needed to evaluate the environmental impact and cost implications of including these innovations at the Nesjavellir GPP plant.

The application of the life cycle assessment (LCA) methodology has proven to be a valuable and promising tool for conducting a comprehensive analysis of the environmental impacts of geothermal energy conversion [16,17,20]. Its utilisation has demonstrated its capability to generate quantitative results and facilitate comparisons among different types of plants and resource conditions. The application to the Nesjavellir GPP is expected to be useful to identify actions [21] to improve the environmental impacts associated with innovations applied to the geothermal energy production processes with the aim of reducing CO_2 and H_2S emissions.

Specific efforts were particularly focused on identifying hot spots in the life cycle of the Nesjavellir power plant in terms of exergoenvironmental analyses based on the life cycle assessment (LCA) evaluations [17]. In addition, they were useful to suggest improvements where possible.

The present work provides a deeper assessment of the environmental impacts associated with innovations applied to the Nesjavellir GPP with the aim of reducing CO_2 and H_2S emissions. Moreover, an additional analysis was conducted, considering the monetarisation of the environmental impacts or so-called externalities; they appear when there are relevant and undesirable consequences for third parties. In this sense, this study also evaluates the reduction in environmental external costs by comparing the Nesjavellir GPP before and after implementing the NCG reduction technology.

2. Materials and Methods

2.1. Nesjavellir GPP

The Nesjavellir GPP, located in the high-enthalpy Nesjavellir Geothermal Field, is one of the largest geothermal power stations in Iceland [22]. Originally commissioned in 1990, the plant has been continuously remodelled up to this day to facilitate a capacity of 120 MW of electricity generation and 290 MW of district heating. It operates as a combined cycle plant, in which a blend of geothermal brine and steam is transported to a central separation station at 14 bars and 200 °C. According to Reykjavik Energy, the current owner of the plant, the power that is generated is sufficient to provide heat for homes and electricity for approximately 7500 people [23]. In Figure 1, a descriptive flow chart of the plant showing the different geothermal fluid outputs can be observed.

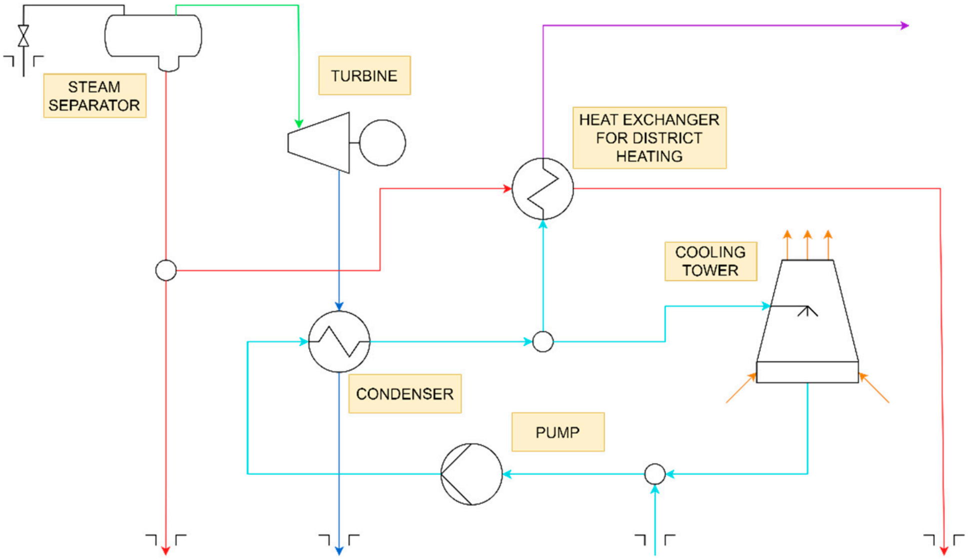


Figure 1. Simplified diagram of the Nesjavellir power plant (source: Reykjavik Energy).

Gaseous emissions from geothermal fluids are an unavoidable aspect of high-enthalpy geothermal applications. Annual emissions of geothermal gases can reach up to 15,000 tonnes of CO_2 and 7500 tonnes of H_2S, according to data collected by Reykjavík Energy [24]. In this regard, the Icelandic government introduced a new regulation in 2010 concerning the H_2S concentration in the air, imposing stringent requirements on the geothermal industry to decrease emissions of this chemical compound from their power plants. Since the commissioning of the Nesjavellir power plant in 1990, Reykjavík Energy has been actively dedicated to finding solutions focused on H_2S abatement.

Relevant examples include the two experimental projects involving gas re-injection, CarbFix and SulFix. Both technologies allow for the sequestering of CO_2 and H_2S into minerals. CarbFix and SulFix technology are based on dissolving gases in formation fluids and well water during subsurface injection. This solubility capture approach facilitates the carbonation of the host rock, ensuring the long-term secure sequestration of CO_2 and H_2S in the subsurface. SulFix technology aims to assess the feasibility of in situ sequestration of H_2S minerals in basaltic rocks by employing methods and a technology similar to CarbFix. Figure 2 represents a simplified model of the pilot plant modified from the Hellisheidi power plant, which is utilised as the abatement system for non-condensable gases emitted by the Nesjavellir power plant. This technology encompasses the dissolution in the water of geothermal gases (mainly CO_2 and H_2S), followed by their injection into the bedrock. In CarbFix, the re-injection target zone is situated between 30 and 80 °C and depths ranging from 400 to 800 m. In contrast, SulFix targets the >200 °C high-temperature geothermal system below 800 m [25].

Figure 1 illustrates the process of two-phase flow from geothermal wells, where steam and geothermal brine are separated at a central station operating at an absolute pressure of 12 bars. The separated steam is then transported to the power plant, where it undergoes moisture separation., facilitating the generation of electric energy by redirecting the steam through condensing turbines.

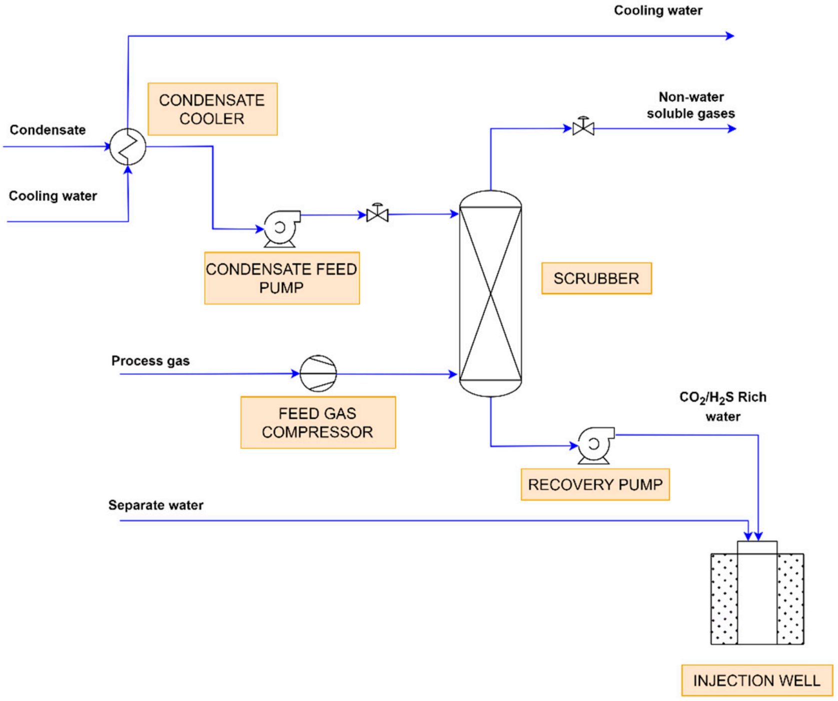


Figure 2. Schematic representation of the geothermal gas injection process at the CarbFix pilot plant of the Nesjavellir power plant (source: GECO project).

Subsequently, the exhaust steam from the turbines is used to preheat fresh water, while the geothermal brine from the steam separators heats the preheated water from the condensers to the temperature required for the district heating system.

To prevent the corrosive effects caused by the saturation of cold ground water with dissolved oxygen when heated, the heated water undergoes a deaeration process before leaving the plant. Deaeration is achieved by boiling the water under vacuum conditions and injecting small amounts of geothermal steam, which contains H_2S.

2.2. Environmental Evaluation Methodology

The LCA methodology' framework is standardised by ISO 14040, ensuring that evaluation methods are developed with significant consistency and quality assurance, enabling meaningful comparisons. Life cycle assessment (LCA) methodology is a valuable approach utilised to optimise various industrial processes and energy systems [26–31]. With this methodology, it becomes possible to identify hot spots in the production process life cycle and suggest improvements, such as minimising material consumption, reducing the impact of harmful emissions and enhancing equipment performance.

In accordance with established standards, the LCA studies involve four interconnected stages: (1) definition of goal and scope, (2) inventory analysis, (3) impact assessment and (4) interpretation. For this study, the LCA modelling was conducted using the Simapro v9.1 software, while the ReCiPe 2016 Midpoint (H) v 1.04 method (2010 Global) was employed for the assessment. Inventory data for the development of the life cycle inventory (LCI) were obtained from the Ecoinvent database version 3.8, as provided by Karlsdottir et al. [32], and primary data from the company in charge of the management of Nesjavellir GPP, Reykjavik Energy. In addition, all assessments presented in this study were performed following updated guidelines for geothermal plants obtained from the GEOENVI H2020 project [32].

Despite the Nesjavellir GPP being a combined heat and power (CHP) plant, this study does not describe the three more common allocation methods used in LCA evaluations (i.e., energy, exergy and economic allocations) for this type of energy plant [33]. Instead, this paper focuses exclusively on exergy allocation to assess the environmental burden of electricity and heat from the geothermal CHP plant, as it is the one that is more recently in use and not extensively reported in the literature [16,17,34].

2.2.1. Goal and Scope Definition

The initiation of any LCA study involves defining the study's goal and scope, which includes establishing the study's scope, system boundary and the definition of the functional unit. The main objective of this analysis is to evaluate the environmental performance associated with the overall environmental effect of producing 1 kWh of electrical and 1 kWh of thermal energy in the geothermal plant at Nesjavellir, Iceland. This approach aims to identify crucial aspects related to specific production phases and opportunities for the technological improvements from a life cycle perspective. The system boundaries of this LCA study adopt a cradle-to-grave approach, encompassing the three phases of construction, operation and dismantling (Figure 3).

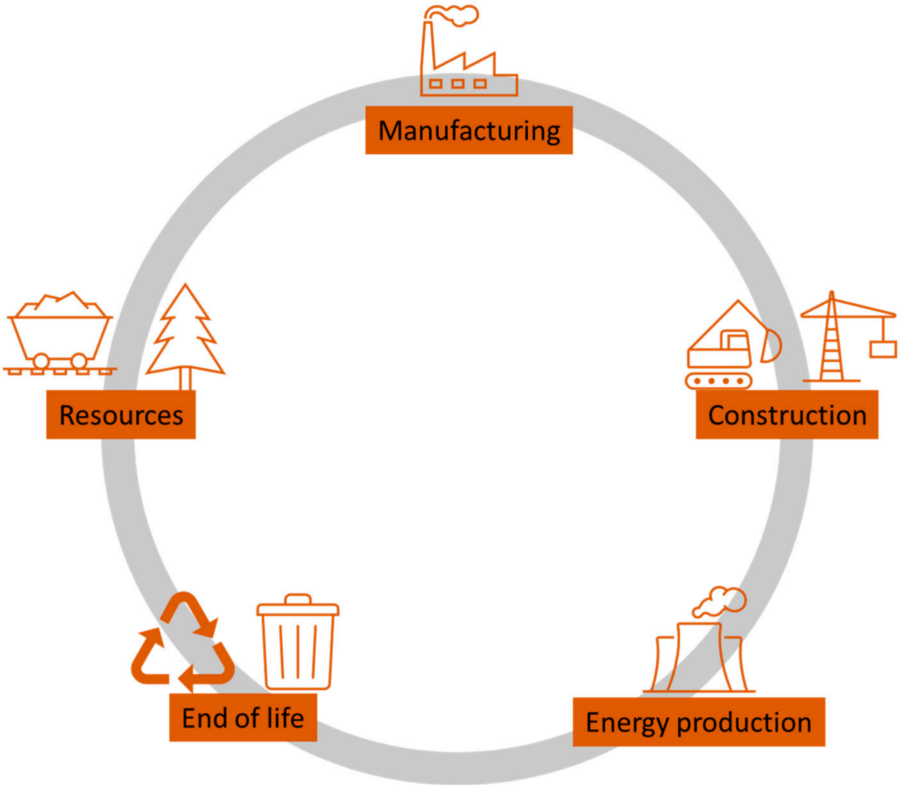


Figure 3. Supply chain of producing 1 kWh of thermal and electricity energy.

Functional Unit: The functional unit serves as the reference to which the inputs and outputs of the process are related and is determined based on the principal function of the processes under assessment. In this work, 1 kWh of provided or delivered electricity and 1 kWh of provided or delivered heat were selected as functional units, considering a temporal scale of 30 years.

System Description and Boundaries: The system is based on a cradle-to-grave approach and follows the energy production of both energy sources (electricity and heat) for the construction, operation and use, and dismantling phases of the GPP from a life cycle perspective. As the Nesjavellir power plant produces both electricity and hot water simultaneously, certain processes are solely dedicated to either electricity or heat production, respectively. Expectedly, some of these processes can be defined as multifunctional and are involved in the production of both energy types. Figure 4 displays the different unit processes and how they are distributed regarding the source of energy production.

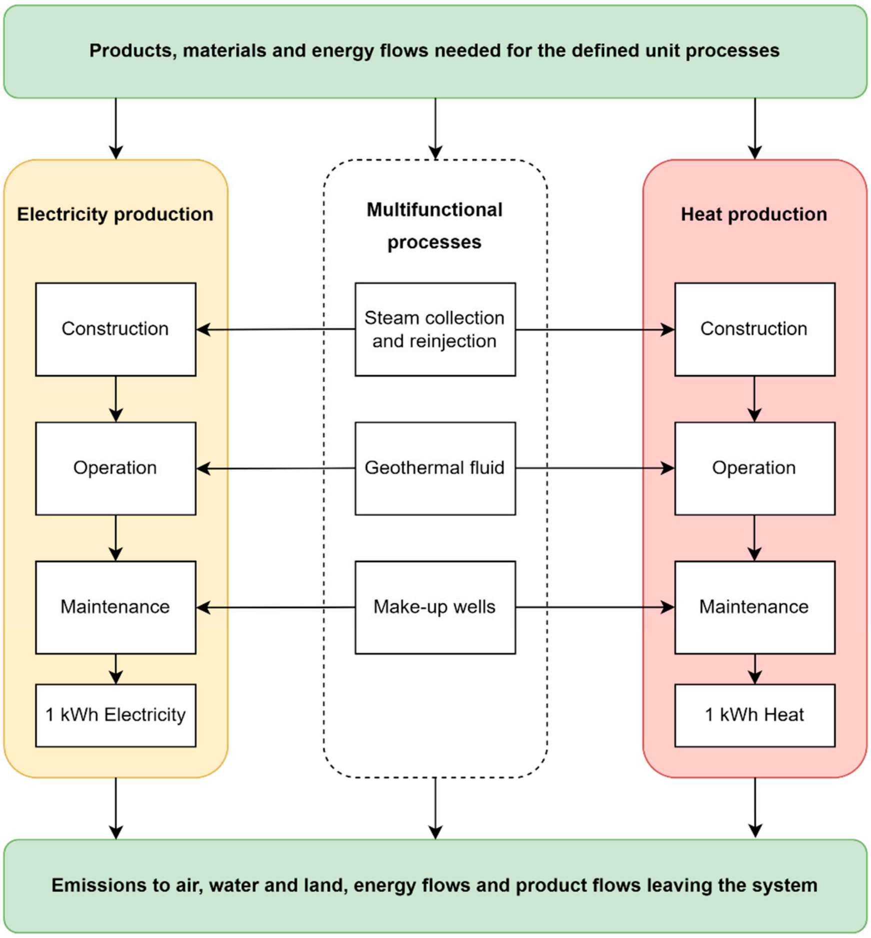


Figure 4. Principal unit processes outlining the generation of electricity and heat at the Nesjavellir CHP plant.

The life cycle assessment (LCA) methodology comprehensively evaluates the entire life cycle of the geothermal power plant, taking into account not only the operational phase, but also the upstream processes involved in the extraction and production of raw materials essential for its construction. As a result, the environmental impact assessment for generating 1 kWh of product encompasses the entire supply chain, including activities like mining, processing and transporting raw materials (Figure 3) such as steel, concrete and other construction materials.

2.2.2. Exergy Allocation Factors

The exergy allocation approach takes into account the quality of energy and assigns a higher share of the environmental impacts to electricity. The main reason for allocating the contribution of the impact based on exergy is because there is a mechanical component, the heat exchanger, that is shared by the two types of energy production. Due to the aforementioned reason, the system exergy converted from electricity and heat was chosen as the allocation factor to exclusively allocate all the multifunctional processes (M), as shown in the work by Maryori et al. [16].

Going into more detail, the exergy allocation factor is a ratio comprising, in the numerator, the contribution of electrical exergy or heat exergy, and in the denominator, the total exergy generated. Additional information concerning the calculation of the exergy allocation factor was included in a previous study [35]. Consequently, the allocation factor applied for multifunctional processes resulted in 78.8% for electricity production and 21.2% for heat production.

$$Exergy = \frac{P_{n,e} \times (1 - A_p)}{\left[P_{n,e} \times (1 - A_p)\right] + \left[P_{n,h} \times \left(\frac{T_{env}}{T_f}\right)\right]}, \quad (1)$$

where:

$P_{n,e}$—the installed electricity capacity (MW);
$P_{n,h}$—the installed hot water capacity (MW);
A_p—the auxiliary power demand (4%);
T_{env}—the average temperature of the surrounding environment (K);
T_f—the log-mean temperature of the district heating network (K).

2.2.3. Life Cycle Inventory

The inventory analysis involves a meticulous data collection process encompassing all inputs and outputs (e.g., energy, materials and emissions) that are identifiable within the system boundaries of the GPP. This process also entails data homogenisation based on the chosen functional unit. The subsequent sections include a general description of the key considerations regarding the life cycle inventory (LCI) of the system. Firstly, an exhaustive revision of the literature on previous inventories from other CHP plants was performed, and primary data were compiled from the following life cycle stages: construction, operation and use, and maintenance, as well as closure of the plant.

Secondly, secondary data were gathered for different phases of the GPP's life cycle such as wells (production, reinjection and make-up), installed capacity for power and heat production, capacity factor and abatement equipment in recent years.

It is crucial to emphasise that the LCI referred to the manufacturing process was based on foreground information provided by the GECO project partners and background data for the remaining stages.

Construction

In this stage, there are common processes needed for both the production of power and the production of heat; in this case, they are named as multifunctional processes. The rest of the processes are dedicated to either power production or heat production; in this case, geothermal wells, wellhead equipment, collection pipelines, extraction site-land use, power plant buildings and mechanical equipment are included. In this phase, the NCG reinjection system or abatement system is included.

Operation and Maintenance

This stage comprises inputs and outputs related to plant operation for power and heat production, including abatement processes that correspond to CarbFix and SulFix technology. In this stage, impacts are related to geothermal fluid, the consumption of chemicals during maintenance and the machinery component replacement. Emissions of H_2S from the geothermal fluid are modelled in this work as sulphur dioxide. Results will be referred to the terrestrial acidification. Furthermore, a 1% machinery component replacement per year was assumed for power and heat production.

Dismantling

This stage was considered in a simplified way due to the limited raw data available. Accordingly, the input and output information (materials and waste) considered at the Nesjavellir GPP was related to the closure of the wells after 30 years of operation. The standard cementing process for well closure was considered, which was derived from the data generated from ENEL GP in the GEOENVI project [32].

2.2.4. Impact Assessment

During this stage, an evaluation of the potential environmental impacts associated with the inventory data is performed. The environmental analysis was executed using SimaPro software version Analyst 9.3.0.3, in conjunction with in-house databases complemented by Ecoinvent 3.8. For this particular study, the ReCiPe 2016 v1.1 midpoint environmental method was applied, and hierarchical evaluation was undertaken. Due to ReCiPe, eighteen midpoint impact categories were involved, specific indicators were chosen for detailed analysis because of their relevance to the study's objectives. The selected impact categories are presented in Table 1 [34].

Table 1. Environmental impact indicators and respective units for the study.

Impact Category	Unit	Abbr.
Global Warming Potential	kg CO_2 eq	GWP
Stratospheric Ozone Depletion	kg CF-11 eq	ODP
Ionising Radiation	kg Co-60 eq	IRP
Ozone Formation, Human Health	kg NOx eq	HOFP
Ozone Formation, Terrestrial Ecosystem	kg NOx eq	EOFP
Fine Particulate Matter Formation	kg PM2.5 eq	PMFP
Terrestrial Acidification	kg SO_2 eq	TAP
Freshwater Eutrophication	kg P eq	FEP
Marine Eutrophication	kg N eq	MEP
Terrestrial Ecotoxicity	kg 1,4-DCB	TETP
Freshwater Ecotoxicity	kg 1,4-DCB	FETP
Marine Ecotoxicity	kg 1,4-DCB	METP
Human Carcinogenic Toxicity	kg 1,4-DCB	HTPc
Human Non-Carcinogenic Toxicity	kg 1,4-DCB	HTPnc
Land Use	m^2a crop eq	LOP
Mineral Resource Scarcity	kg Cu eq	SOP
Fossil Resource Scarcity	kg oil eq	FFP
Water Consumption	m^3	WCP

2.2.5. Interpretation

This LCA stage provides an understanding and analysis of the inventory phase results, the consequential impacts in light of possible uncertainties of the data used and the assumptions that were considered, as well as the eventual drawing of conclusions and recommendations for the improvement of the design.

2.3. Environmental Evaluation Methodology

For determining external environmental costs, different weighting methodologies exist. All of them share a common framework based on the analysis of the cause–effect chain to derive environmental impacts from the life cycle inventories. Then, a monetary weight is assigned to each environmental impact according to the equation below:

$$EC = EI \times ECF \tag{2}$$

where:

EI—the environmental indicator referred to the unit of the reference substance under consideration (for example, kg CO_2 eq as the unit for the global warming indicator per kWh);
ECF—the external environmental cost factor related to the environmental impact (EI) under consideration in EUR/(unit of the *EI*).

Thereby, the external cost (*EC*) is obtained in euros.

Appendix B, Table A12 summarises the cost factors of 2015 for different environmental impacts, and the same factors are updated to 2021 prices [36], considering the 18 environmental impact categories in the ReCipe midpoint (H). The integrated economic value conversion system was established through the regulation of pollutant discharge fees, environmental tax and the WTP theory [37]. Externalities arise when significant and undesirable consequences affect third parties. For this study, the externalities compared the cost associated with the emissions caused by an activity, and in this case, there was a focus on GPP gases emitted. Therefore, the negative externalities of the baseline were evaluated to compare the values with the same power plant implementing GECO technology. Incorporating externalities' costs into the GECO project and the economic system is of paramount importance. These external costs can exert a profound influence on the selection of competitive strategies within the energy production market.

3. Results

3.1. Life Cycle Assessment of Nesjavellir GPP Baseline

The impacts associated with both productions, electricity and heat, for 1 kWh_e and 1 kWh_t, can be seen in Figure 5 for all the phases of the GPP explained in Section 2.2.3. The results are expressed in percentage, considering 100% as the sum of the environmental impact for both energy productions, and for each impact category. The highest impact for all the categories is due to the electricity production of 1 kWh_e (blue bars). For heat production, 1 kWh_t, the highest impact is seen in the water depletion category, which is due to the use of large quantities of fresh water for district heating in Reykjavik. All the previous results are in line with the results obtained in the work by Diaz et al., 2023, in relation to the Hellisheidi GPP [16].

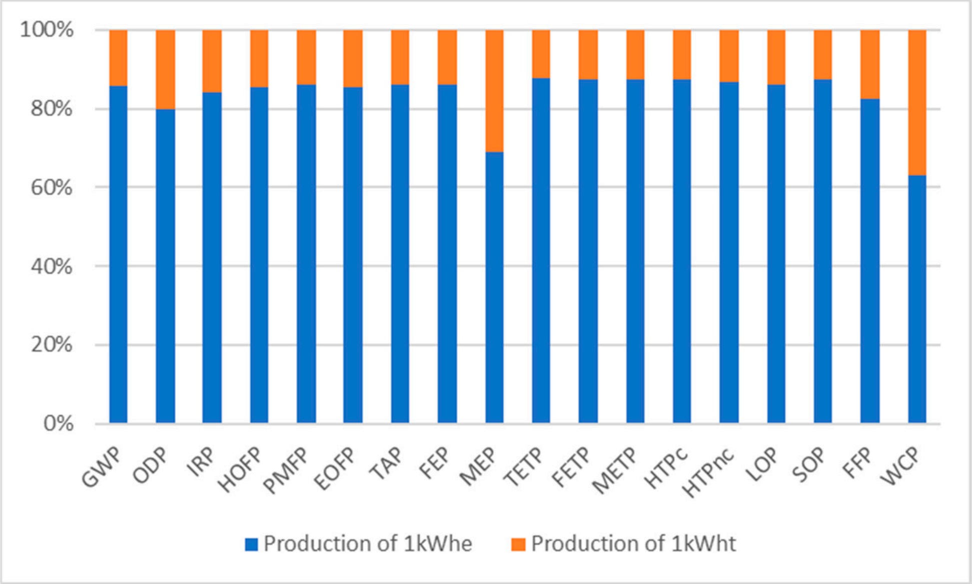
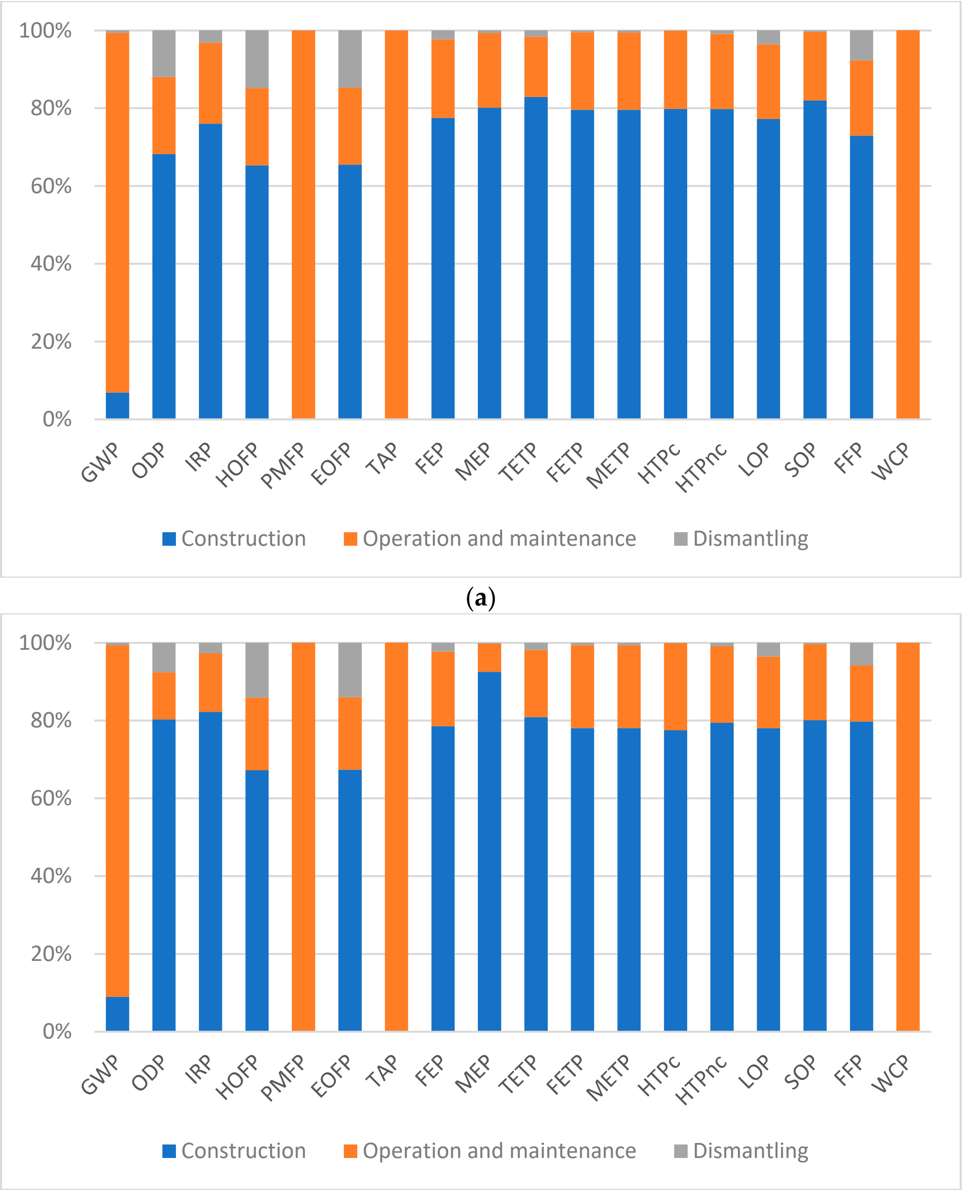


Figure 5. Environmental impacts related to production of 1 kWh_e and 1 kWh_t.

Regarding the global warming potential indicator, 1 kWh of produced electricity represents a total of 15.47 g CO_2 eq, while 1 kWh of produced heat has an associated impact of 2.55 g CO_2 eq, i.e., the impact of producing 1 kWh_e is six times greater than producing 1 kWh_t. These obtained values are within the order of magnitude represented by Karlsdottir et al. [36] where the allocation exergy method is applied to assess the case study of Hellisheidi.

3.2. Life Cycle Assessment of the Three Main Stages of the Baseline Scenario

A detailed analysis of the three main stages of the life cycle was carried out. The results of construction, operation and maintenance, and dismantling are shown in Figure 6.



(**a**)

(**b**)

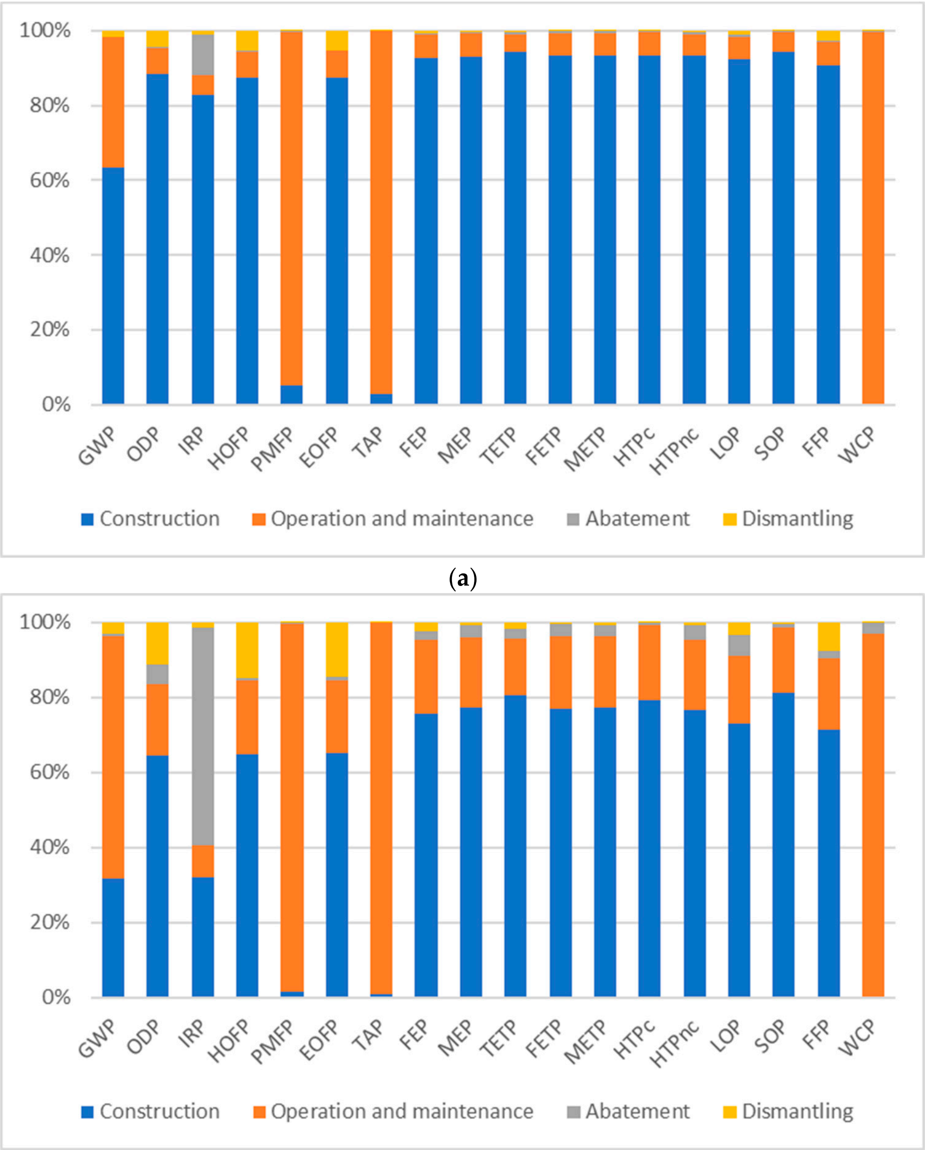
Figure 6. Environmental impacts related to the three main stages. (**a**) Production of 1 kWh_e and (**b**) production of 1 kWh_t.

The construction phase has the most relevant environmental load for both electricity and heat production in nearly all 18 indicators studied. Exceptions are observed for the global warming potential, terrestrial acidification, fine particulate matter formation and water consumption, in which the highest environmental impacting process is the operation and maintenance stage (O&M).

Furthermore, the dismantling stage had the lowest impact on all the evaluated indicators. The trends observed for the three stages studied are observed in the work of A. Paulillo et al. [38], dedicated to evaluating the case study of Hellisheidi.

3.3. Results Comparison by Applying Abatement Stage

Figure 7 is included to compare the environmental load achieved by the implementation of a fourth stage, which corresponds to the abatement system. This technology, developed within the GECO project, allows for a 95% reduction in CO_2 and H_2S emissions form the Nesjavellir GPP. As in the baseline scenario, the 18 indicators studied are shown to produce 1 kWh_e and 1 kWh_t.



(**a**)

(**b**)

Figure 7. Environmental impacts of all stages related to production of (**a**) 1 kWh$_e$ and (**b**) 1 kWh$_t$ when implementing abatement system on Nesjavellir.

Concerning the global warming potential indicator, the implementation of the abatement system results in the production of 3.4 g CO_2 eq and 1.01 g CO_2 eq for 1 kWh$_e$ and 1 kWh$_t$, respectively. Compared to the plant model without the NCG system capture, it reveals reductions of 78% and 60% in the global warming potential terms for the production of 1 kWh$_e$ and 1 kWh$_t$, respectively. The introduction of the CarbFix abatement system to remove CO_2 and H_2S from the NCGs emitted by the Nesjavellir GPP brings about changes in the evaluated environmental impacts for the baseline scenario. The abatement stage considers the construction of the facilities (equipment and piping) as well as its operation and maintenance (equipment replacement and water consumption). The energy consumption is embedded in the plant's net electricity. The NCGs are linked to the geothermal fluid extracted from the subsurface which, for simplicity of calculations, is analysed in the operation and maintenance of the baseline scenario (orange bars).

In more detail to the category impacts, Figure 8 illustrates the relevant impact changes between the baseline scenario and the abatement system studied. The main results reveal that the technology of the NCG reduction system is environmentally plausible from the baseline scenario, increasing the amount of CO_2 and H_2S captured. Figure 8 shows the most significant changes in terms of the global warming potential, terrestrial acidification and water consumption, and the latter is increased due to the amount of water used in the scrubber.

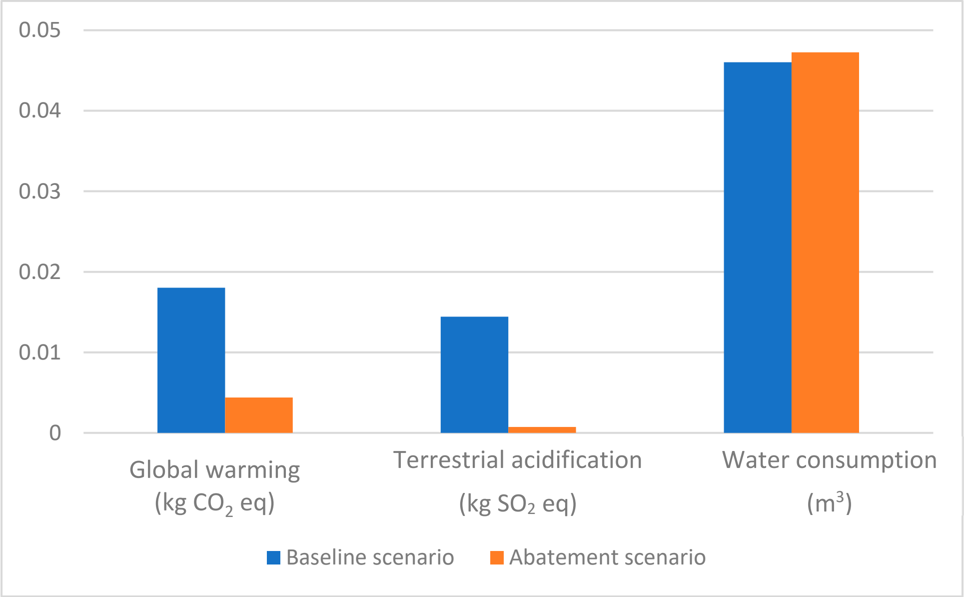


Figure 8. Comparison of baseline scenario and abatement system implementation.

3.4. Environmental Evaluation Methodology

Tables 2 and 3 represent the cost associated with the externalities for the initial scenario without the abatement system. The parameters of global warming potential and terrestrial acidification are considered for 1 kWh of electricity and thermal energy. These values are relevant since they are compared with the case in which the GECO project innovations are implemented (CarbFix technology modified).

Table 2. Life cycle inventory assessment midpoint results of Nesjavellir GPP baseline (externalities for 1 kWh_e).

Impact Category	**Unit**	**Economic Value Conversion Factor (EUR/EI) [39]**	**Total Environmental Impact per Functional Unit (EI/kWh_e)**	**External Cost (EUR/kWh_e)**
Climate change	kg CO_2 eq	0.03	0.0155	4.65×10^{-4}
Terrestrial acidification	kg SO_2 eq	1.01	0.0124	0.0125
Total	-	-	-	0.01297

Table 3. Life cycle inventory assessment midpoint results of Nesjavellir GPP baseline (externalities for 1 kWh_t).

Impact Category	**Unit**	**Economic Value Conversion Factor (EUR/EI) [39]**	**Total Environmental Impact per Functional Unit (EI/kWh_t)**	**External Cost (EUR/kWh_t)**
Climate change	kg CO_2 eq	0.03	0.00255	7.65×10^{-5}
Terrestrial acidification	kg SO_2 eq	1.01	0.002	0.00202
Total	-	-	-	0.0021

Tables 4 and 5 summarise the information related to the externalities for each of the productions.

Table 4. Life cycle inventory assessment midpoint results of Nesjavellir GPP including the abatement system (externalities for 1 kWh_e).

Impact Category	Unit	Economic Value Conversion Factor (EUR/EI) [39]	Total Environmental Impact per Functional Unit (EI/kWh_e)	External Cost (EUR/kWh_e)
Climate change	kg CO_2 eq	0.03	0.00339	1.017×10^{-4}
Terrestrial acidification	kg SO_2 eq	1.01	6.63×10^{-4}	6.696×10^{-4}
Total	-	-	-	0.00078

Table 5. Life cycle inventory assessment midpoint results of Nesjavellir GPP including the abatement system (externalities for 1 kWh_t).

Impact Category	Unit	Economic Value Conversion Factor (EUR/EI) [39]	Total Environmental Impact per Functional Unit (EI/kWh_t)	External Cost (EUR/kWh_t)
Climate change	kg CO_2 eq	0.03	0.00101	3×10^{-5}
Terrestrial acidification	kg SO_2 eq	1.01	1.03×10^{-4}	1.04×10^{-4}
Total	-	-	-	0.000134

Figure 9 is a clear representation of the added value of implementing the abatement system developed in the GECO project. There is a significant change associated with the externalities. The change in the cost associated with the emissions in the baseline and after applying the GECO project technology has reduced the external costs to result in a 97% impact for the production of 1 kWh_e and a 98% impact for the production of 1 kWh_t.

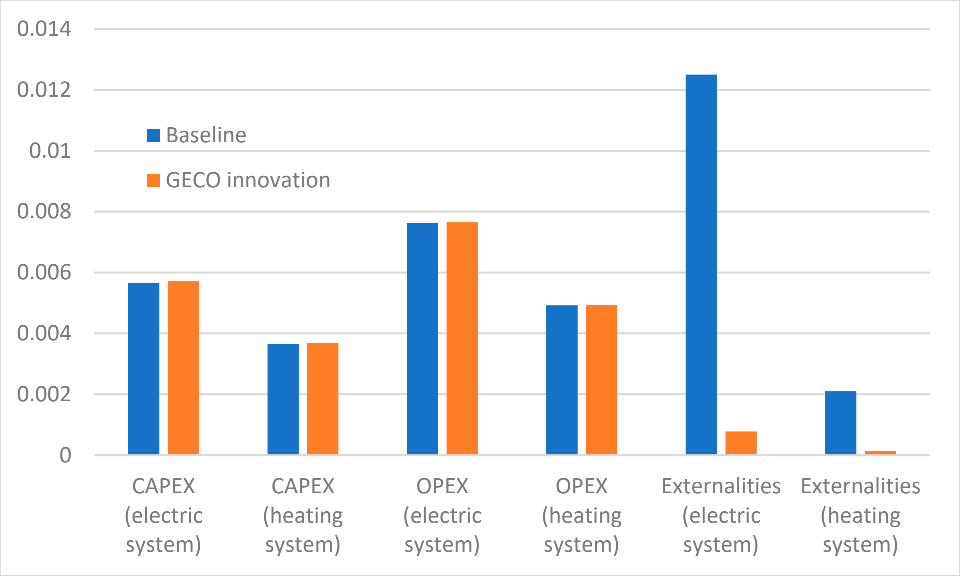


Figure 9. Comparison in terms of EUR/kWh between the baseline and the geothermal plant implementing the capture and reinjection system in Nesjavellir.

4. Conclusions

This study was dedicated to the environmental assessment of the Nesjavellir GPP as well as the implementation of the abatement system developed in the GECO project. In this vein, primary raw data concerning geothermal wells and different technical parameters as well as secondary data from the database used for the LCA modelling were obtained. The LCI data was allocated using the exergy approach, with material and energy burdens normalised per functional unit of 1 kWh for net electricity and 1 kWh of net heat produced. The results show that when reducing the NCG in the pilot plant, there are already environmental, cost, and environmental cost benefits for the global warming and terrestrial acidification impact categories for the case of the environmental impacts and costs.

Though the comprehensive baseline (initial situation) LCA was carried out in this work, it becomes evident that the construction stage plays a pivotal role in shaping the overall global environmental burden of the system. The findings underscore the crucial significance of addressing environmental considerations during the construction phase of the Nesjavellir GPP for effective environmental impact mitigation and sustainability. Related impacts were found to be dominated by the geothermal wells, mechanical equipment and power plant building. This environmental behaviour of the Nesjavellir GPP has reflected similar trends that were determined for the environmental performance of the Hellisheidi GPP defined by previous works in the literature.

When installing the abatement system, there were some categories that were improved in the global environmental performance of the Nesjavellir GPP, mainly the global warming potential, terrestrial acidification and fine particulate matter formation. Therefore, the benefits of incorporating this type of technology have been supported by the LCA and externality studies.

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Nomenclature

EI	Environmental indicator
GPP	Geothermal power plant
LCA	Life cycle assessment
LCI	Life cycle inventory
NCG	Non-condensable gases
WTP	Willingness to pay

Appendix A. LCI of Nesjavellir Power Plant

LCI for the construction stage of Nesjavellir power plant.

Table A1. Inventory related to geothermal narrow wells (construction) per plant lifetime.

Construction—Geothermal Narrow Wells	Amount	Unit
Steel (for well casing)	2,373,155.4	kg
Portland cement (drilling)	136,500	kg
Portland cement (well casing)	1,314,366.9	kg
Silica flour (well casing)	525,747.9	kg
Wyoming bentonite (well casing)	26,287.8	kg
Perlite (well casing)	26,287.8	kg
Retardant (drilling)	2436	kg
Water binder	4200	kg
Drill soap (drilling)	12,425.7	kg
Bentonite clay (drilling)	823,200	kg
Caustic soda (drilling)	58,612.47	kg
Water (from ground, for concrete)	12,534,459	kg
Water (from ground, for drilling)	12,534,459	kg
Diesel (operating of drill rig)	2,004,307.2	L

Table A2. Inventory related to geothermal reinjection wells (construction) per plant lifetime.

Construction—Geothermal Reinjection Wells	Amount	Unit
Steel (for well casing)	162,657	kg
Portland cement (drilling)	9222.15	kg
Portland cement (well casing)	88,800.75	kg
Silica flour (well casing)	35,520.35	kg
Wyoming bentonite (well casing)	1776.05	kg
Perlite (well casing)	1776.05	kg
Retardant (drilling)	164.6	kg
Water binder	283.75	kg
Drill soap (drilling)	839.5	kg
Bentonite clay (drilling)	55,616.75	kg
Caustic soda (drilling)	3959.95	kg
Water (from ground, for concrete)	76,986.2	kg
Water (from ground, for drilling)	846,848.4	kg
Diesel (operating of drill rig)	137,376	L

Table A3. Inventory related to wellhead equipment (construction) per plant lifetime.

Construction—Wellhead Equipment	Amount	Unit
Excavation	78,000	m^3
Fill	2600	m^3
Concrete	468	kg
Steel	378,924	kg
Stainless steel	416	kg
Aluminium	31,668	kg

Table A4. Inventory related to collection pipeline (construction).

Construction—Collection Pipeline	**Amount**	**Unit**
Excavation	93,600	m^3
Fill	43,160	m^3
Concrete	3,744,000	kg
Steel	1,024,400	Kg
Aluminium	32,240	Kg
Rockwool	223,600	Kg

Table A5. Inventory related to extraction site land use (construction).

Construction—Extraction Site Land Use	**Amount**	**Unit**
Land use for drilling operations	135	m^2
Land use for drilling operations	810	m^2
Land use for drilling operations	810	m^2

Table A6. Inventory related to heating station buildings (construction).

Construction—Power Plant Buildings	**Amount**	**Unit**
Excavation	230,100	m^3
Filling	168,900	m^3
Concrete	21,600,000	m^3
Steel	6,617,400	kg material
Stainless steel	75,600	kg material
Aluminium	88,200	kg material
Cooper	19,800	kg material
Mineral wool	74,700	kg material
Asphalt	531,000	kg material

Table A7. Inventory related to power plant buildings (construction).

Construction—Electrical Distribution Buildings	**Amount**	**Unit**
Excavation	38,750	m^3
Fill	40,770	m^3
Concrete	17,551,200	m^3
Steel	742,983.8	kg material
Cast iron	41,423.70	kg material
Black steel	267,113	kg material
PVC	1660.20	kg material
Rock wool	35,155	kg material
Iron	69,600	kg material
Aluminium	69,600	kg material
Plastic	196	kg material
Seals	225	kg material
Wood	11,385	kg material
Aluminium cladding	7656	kg material
Stainless steel	42,140	kg material
Antifreeze	2072	kg material
Asphalt	154,767	kg material
Fibreglass	3750	kg material
Stone	10,267	kg material

Table A8. Inventory related to mechanical equipment for electricity and heat.

Equipment	Material	Amount	Unit
HP Steam Separator	Steel	179,961	kg material
	Aluminium	3355	kg material
	Mineral wool	18,007	kg material
	PE plastic	701	kg material
HP Pre-separator	Steel	31,945	kg material
	Aluminium	599	kg material
	Mineral wool	3216	kg material
	PE plastic	125	kg material
HP Moisture Separator	Steel	104,134	kg material
	Aluminium	1654	kg material
	Mineral wool	8875	kg material
	PE plastic	345	kg material
Steam Hood	Steel	59,831	kg material
	Stainless steel	22,160	kg material
	Aluminium	1428	kg material
	Mineral wool	5552	kg material
	PE plastic	304	kg material
HP Turbine	Steel	816,000	kg material
	Transformer oil + lubricant oil	28,160	kg material
Cold and Engines	Steel	25,688	kg material
	Aluminium	32,128	kg material
	GRP fibreglass reinforced plastic	380,932	kg material
HP Condenser	Stainless steel	425,600	kg material
	Aluminium	3240	kg material
	Titanium	106,400	kg material
	Mineral wool	1440	kg material
Electrical Transformers	Steel	203,175	kg material
	Copper	74,770	kg material
	Transformer oil	107,394	kg material
	Wood	10,691	kg material
Cooling Tower	Steel	6422	kg material
	Aluminium	8032	kg material
	GRP fibreglass reinforced plastic	95,233	kg material

The "six-tenths rule" was used for the scaling of the abatement equipment [40] at the Nesjavellir plant. Through this method, it was possible to make an estimate for the calculation of the amount of material needed in the scale-up from the pilot plant. This required values for the materials used in the pilot plant equipment and the gas removal capacities (%) of both the pilot plant and the future facility. The re-injection values are 8% and 95%, respectively. These parameters are related according to Equation (A1):

$$\frac{Material_2}{Material_1} = \left(\frac{Removalcapacity_2(\%)}{Removal\ capacity_1\ (\%)}\right)^n \tag{A1}$$

where:

Material$_1$—the amount of material corresponding to the pilot facilities (kg);
Material$_2$—the amount of material corresponding to the facilities expected for 2030 (kg);
Removal capacity$_1$—the percentage of gases not emitted to the atmosphere (8%);
Removal capacity$_2$—the percentage of gases not emitted to the atmosphere expected for 2030 (95%);
n—William exponent, which may vary from 0.48 to 0.87 for equipment.

Table A9. Inventory related to the abatement process (equipment).

Equipment	Material	Amount	Unit
Housing	Steel	16,771.19	kg material
Heat exchanger	Stainless steel	3310	kg material
Compressor	Steel	4650.91	kg material
	Copper	618.64	kg material
Absorption tower	Stainless steel	4767.36	kg material
Pump 1	Stainless steel	75.42	kg material
	Copper	10.03	kg material
Pump 2	Stainless steel	68.41	kg material
	Copper	9.10	kg material

Table A10. Inventory related to the abatement piping (construction).

Material	Amount	Unit
High-density polyethylene	48,182.38	kg material
Polyurethane (insulation)	698.42	kg material
Cross-linked polyethylene	103.69	kg material
Polyethylene	736.62	kg material
Stainless steel	3658.25	kg material

Table A11. Inventory related the operation and maintenance of abatement stage.

	Operation Phase (Utilities)		
	Material	**Amount**	**Unit**
Utility consumption	Water	41,754,956,217	l
	Electricity	220,373,380	kWh
	Maintenance Phase (Replacement)		
Equipment	**Material**	**Amount**	**Unit**
Heat exchanger	Stainless steel	9930.307	kg material
Compressor	Stainless steel	11,162.17	kg material
	Copper	1484.75	kg material
Pump 1	Stainless steel	133.10	kg material
	Copper	17.70	kg material
Pump 2	Stainless steel	120.73	kg material
	Copper	16.05	kg material

Appendix B. Economic Value Conversion Factors

Table A12. Economic value conversion factors (EUR/midpoint impact unit).

Impact Category	Unit	Economic Value Conversion Factor (EUR)
Climate change	kg CO_2 eq	0.0273
Terrestrial acidification	kg SO_2 eq	0.9191
Freshwater eutrophication	kg P eq	4.0768
Marine eutrophication	kg N eq	1.274
Terrestrial ecotoxicity	kg 1.4-DB eq	10.2284
Freshwater ecotoxicity	kg 1.4-DB eq	10.2284
Marine ecotoxicity	kg 1.4-DB eq	10.2284
Agricultural land occupation	m^2a	0.14833
Urban land occupation	m^2a	0.10374
Natural land transformation	m^2a	2.9666
Water depletion	m^3	0.0546
Metal depletion	kg Fe eq	0.004368
Fossil depletion	kg oilg eq	0.02457
Ozone depletion	DALY	8471.827
Photochemical oxidant formation	DALY	8471.827
Particulate matter formation	DALY	8471.827
Human toxicity	DALY	8471.827
Ionising radiation	DALY	8471.827

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