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Research article

Environmental benefits for a geothermal power plant with CO_2 reinjection: case study of the Kizildere 3 U1 geothermal power plant

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ABSTRACT

Geothermal power plants (GPP) with high non condensable gases (NCG) content geothermal fluid have shown to be environmental impacting relating to their energy production, which could be critical if no corrective actions are achieved. The GPP of Kizildere 3 U1, located in Türkiye (Denizli), in where the geothermal fluid contains high percentage of CO_2, 99% of the NCG fraction, which represents the 3% of the geothermal fluid mass, is taken as a relevant case study to implement a new innovation consisting of NCG reinjection to reduce the amount of NCGs released to the atmosphere. In order to calculate the present environmental impacts which the plant is causing (baseline); and the potential reduction of environmental impacts which can be achieved with the innovation (reinjection), a life cycle assessment (LCA) calculation were developed. Primary data were collected for all the relevant stages of the energy conversion cycle and complemented where necessary with secondary data from other geothermal power plants studies. The main results of the baseline environmental assessment show that the construction phase is the most impacting phase due to the materials used in the power plant building construction, electrical generation equipment and distributed machinery and infrastructures; the effects in the operation phase are dominated by the geothermal fluid composition. In this sense, the application of CO_2 reinjection at the Turkish site into the reservoir will prevent the emission of 1,700 tons·year^{-1} in the pilot site and 10% of the total emissions released along the life span of the GPP.

1. Introduction

1.1. Literature review

Geothermal energy is a renewable energy source, which can play an important role in the light of the energy transition in Europe [1], due to the later the interest of installing this type of energy is increasing in the last years in countries with high enthalpy geothermal potential, as the case of the country of Croacia, analysed in the study of Kurevija and Vulin [2] and Tuschl et al. [3] Guzovićet al. [4] or Slovakia [5]. Geothermal power plants (GPPs) will indeed be more and more valuable in assisting other renewables, which are highly variable (wind, solar, wave energy) [6], as it is capable of baseload production currently provided by fossil fuels [7]. With suitable sizing of the plants and management of the fields, and thanks to the practice of liquid reinjection in the reservoirs, geothermal hydrothermal resources have proven to be capable of extended lifetime (over 100 years for the case of Larderello, Italy [8]). However, when compared to other renewables GPP have encountered difficulties in social acceptance because of potential risks [9], emissions during operation, from the point of view of environmental impact [10], and or social [11], regulatory [12] and economic challenges [13]. The matter of risk is inherent in the deep underground mining activities and should be treated with suitable measures during the exploration/drilling activities and through careful monitoring of the geological response of the system. On the other hand, emissions to the atmosphere are of major concern as the geothermal resources - depending on the specific location – may contain contaminants, such as arsenic, antimony, heavy metals (mainly Hg), H_2S, and NH_3 [14]. A specific case is that of greenhouse gas emissions: depending on the

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Nomenclature

GPP	Geothermal power plant
IP	Intermediate pressure
LCA	Life cycle assessment
LCI	Life cycle inventory
LP	Low pressure
NCG	Non condensable gases
HP	High pressure

specific site, it is common to find relatively large concentrations of CO_2 in the resource, as well as smaller quantities of CH_4 (which however has very high GHG potential). In this sense, GHG emissions can be much larger and can represent a global challenge [15], there is evidence from measurements taken in geothermal regions that a close number of overall emissions from the geothermal fluid would anyway reach the environment as diffuse ground emissions [16,17].

Where large reservoirs are documented, with a good confinement of the resource guaranteed by an impermeable cap rock layer, it is possible to consider confinement of the gas within the liquid phase in the reservoir at high pressure and depth. The two-phase reinjection technology being demonstrated in the GECO project [18] can be attractive under these conditions, as it allows to inject potentially large gas flow rates with a limited stream of liquid. In fact, GECO project has demonstrated technical feasibility of NCG reinjection in Kizildere 3 U1, but environmental benefits have not been demonstrated enough, so far. Recently, the idea of demonstrating a quantitative approach to the environmental evaluation of geothermal energy utilization has led to the application of life cycle analysis (LCA) to this field [19], such as the work of Karlsdóttir et al., analysing the Life Cycle Inventory of an Icelandic GPP from the perspective of the LCA[20] or the LCA approach for environmental performance optimization of the Geothermal energy production in Italy [21], but also to compare environmental impacts of the GPPs compared with other renewable energies [22]. The LCA approach is indeed very attractive; however, it is not yet fully consolidated as several methods of assessment – derived from different fields of science – can be applied to GPP, leading possibly to a widespread in the results. For example, matters as the use of land are strongly discussed, as well as the use of water resources (which does not account for the difference between deep and surface water, which is a key issue in geothermal energy as the two streams must be kept separate as far as possible). Moreover, the direct contribution of species such as H_2S to acidification is currently being questioned [23] and the ecotoxicity of substances like heavy metals [24] or hazardous materials [25] is subject to high uncertainty. The recent publication of LCA guidelines in the GEOENVI H2020 project [26] has allowed to identify what are the major environmental impact categories and has confirmed the high attention to GHG global emissions. Indeed, the emissions of CO_2 are so concentrated (nearly pure and released at one single point – typically the cooling tower) that solutions for carbon capture, utilization and storage (CCUS) are much more attractive in the field of geothermal power production than in many other applications which have to work on diluted emissions, or even capturing from the atmosphere [27].

1.2. *Contribution*

Today, the emission of pollutants (H_2S, Hg, NH_3) can be avoided by suitable treatment techniques [28] or by complete reinjection in the underground reservoir [29]. This last is indeed the new technology tested in the GECO project in Kizildere 3 U1, which is trying to tackle the problem of avoiding the GHG emissions.

In Türkiye, the NCG content can be over 10% of the steam flow rate extracted in flash power plant. Reinjection of this relevant gas stream becomes essential to slow down the pressure decay of the resource [30,

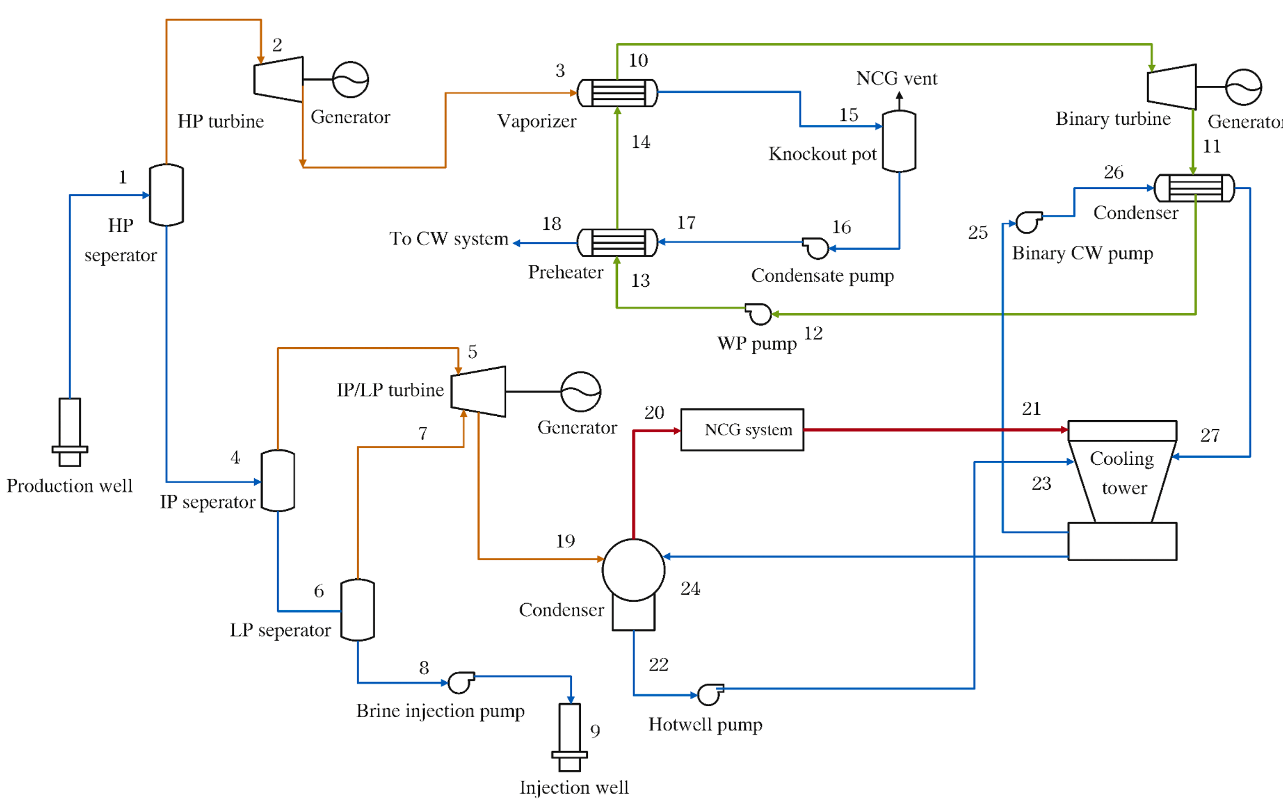

Fig. 1. Triple flash and binary combined cycle plant for Kizildere 3 U1 GPP.

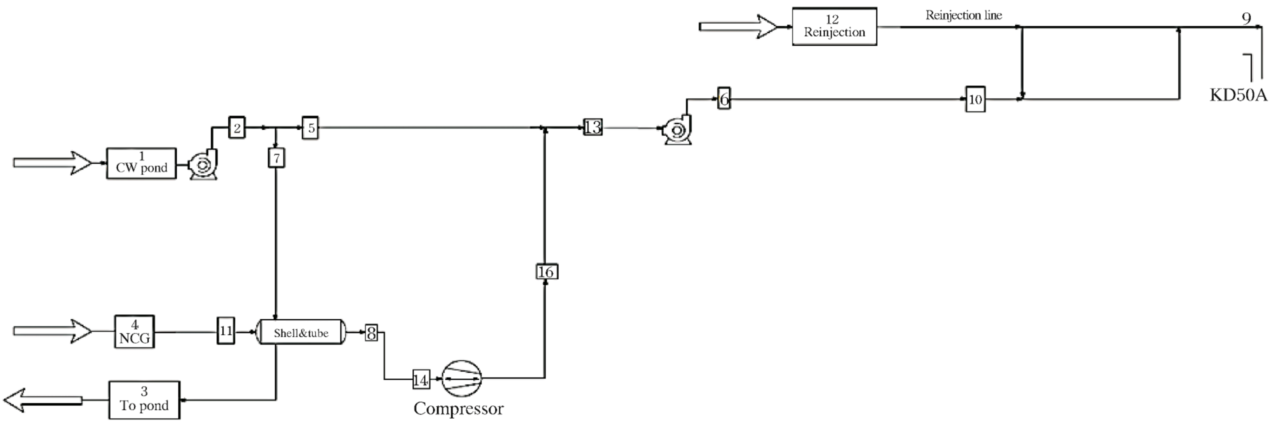

Fig. 2. NCG reinjection system.

31]. Currently, the geothermal fluid of the Kizildere 3 U1 geothermal power plant is composed by 3% of NCG, CO_2 being the main component with nearly the 100% of the total mass of NCG. Consequently, the application of CO_2 reinjection at the Turkish site into the reservoir will prevent the emission of 1,700 NCG tons·year^{-1} in the pilot site and 10% of the total emissions released along the life span of the GPP. In this sense, this study has demonstrated that the reinjection technology will reduce consistently the environmental impacts of the GPP plant in this pre-commissioning analysis by comparing the environmental impact of the current GPP and the GPP with the innovation implemented, at pilot and real scale. By demonstrating the correct performance of the innovation is an important milestone which could be the seed for improving the current Turkish GPP performance in terms of environmental impacts by reducing the NCG release to the atmosphere.

Following the latter, as summary, the aim of this paper is to evaluate for first time the current and after environmental assessment in order to find out the benefits or drawbacks of this new technology in the specific Kizildere 3 U1 GPP, as not previous studies have been made for the previous situation and, obviously, once the reinjection has been commissioned.

2. Method

2.1. General description of Kizildere 3 U1 power plant

2.1.1. Current situation

Kizildere 3 GPP, located in Denizli, has an installed capacity of 165 MWe which is the largest capacity of a power plant in Turkey. Kizildere 3 GPP consists of 2 units with capacities of 99.5 MWe and 65.5 MWe. Kizildere 3 U1 was commissioned in August 2017 and Kizildere 3 U2 was commissioned in March 2018. Kizildere 3 U1is the object of this study.

Fig. 1 shows a cycle schematic for the triple flash + binary combined cycle plant technology which has been utilized for Kizildere 3 U1 GPP. The amount of the geothermal fluid in Kizildere 3 U1 is 850 kg·s^{-1}. Thermodynamically, the geothermal fluid reaches the wellhead as a liquid, vapour and gas mixture because of the pressure loss due to friction and head loss. The geothermal fluid is transferred from the production wells to the system under high pressure via the pipelines to enter the flash system. In the flash system the geothermal fluid is diverted to the high-pressure separator and here the gas/vapour and liquid phases are separated. The gas/vapour phase is sent to the high-pressure turbine while the liquid phase enters the low-pressure separators. This process is repeated in intermediate and low-pressure separators. The high pressure (HP) flashed steam goes to a HP backpressure turbine, which exhausts to the binary bottoming unit. The HP turbine exhaust steam goes through a steam vaporizer that vaporizes the working fluid in the binary plant. Steam condenses during its passes through evaporizers and preheaters, which helps separating NCGs from the HP steam, where a considerable amount of the total NCG exists. The vaporized binary working fluid expands through the binary turbine and is then condensed using water cooled condensers. The binary circulating water pumps supply the binary plant with cooling water from the cooling tower. The working fluid is pumped through the closed binary plant loop by a working fluid feed pump. Geofluid condensate from the binary plant is pumped to a condensate storage tank for steam and turbine washing. The separated NCGs from the binary plant are sent to the cooling tower fan stacks.

The HP brine is flashed two more times consecutively (intermediate pressure-IP and low pressure-LP) and the steam is sent to the IP/LP turbine. The IP/LP turbine exhausts to a direct contact condenser, which is supplied with cold water from the counterflow cooling tower. The H_2O in the IP/LP exhaust condenses and is pumped out via the hotwell pumps back to the cooling tower. The NCGs left in the IP/LP turbine exhaust are cooled through the gas cooler portion of the condenser and discharged to the intercondenser in the NCG removal system. The NCG removal system consists of two 100% trains, the first consists of a set of first stage ejectors and liquid ring vacuum pump and the second train has an after ejector and after condenser. Once the NCGs have been brought from a vacuum to atmospheric pressure, they are sent to the cooling tower fan stacks. The component cooling water pumps distribute cooling water from the cooling tower to the NCG removal system equipment as well as to the generator and lube oil coolers.

2.1.2. NCG reinjection system

Currently, the geothermal fluid of the Kizildere 3 U1 geothermal power plant is composed by 3% of NCG, CO_2 being the main component with nearly the 100% of the total mass of NCG, with a total of around 70,000 tons·year^{-1} of NCGs released to the atmosphere.

In this sense, the application of CO_2 reinjection at the Turkish site into the reservoir will prevent the emission of 1,700 tons·year^{-1} in the pilot site and 10% of the total emissions released along the life span of the GPP. This will reduce consistently the environmental impacts of the GPP plant, as was demonstrated in this pre-commissioning analysis by comparing the environmental impact of the current GPP and of the GPP with the innovation implemented. Demonstrating the correct performance of the innovation will be an important milestone which could be the seed for improving the current Turkish GPP performance in terms of environmental impacts, by reducing the NCG release to the atmosphere.

Once the system is made real, a NCG reduction of 59.6% is expected, with almost 154,491.61 tons·year^{-1} NCG injection. A scaling up of the NCG system is also calculated in this work, from the point of view of LCA.

The reinjection system to reduce the NCG content (Fig. 2) will consist of the reinjection of the NCGs at lower temperature than the current exhaust value, by cooling the gas through water from the cooling tower system. This allows to reduce the size and power rating of the compressor. The cooled gas will be compressed to 14 bar_a and dissolved

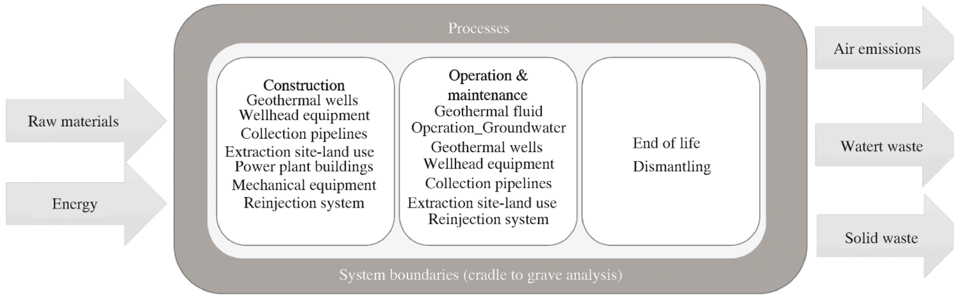

Fig. 3. Life cycle assessment (LCA) system boundaries for the present study.

Table 1
Impact categories selected for the present study.

Impact category	Abbreviation	Unit
Global warming potential	GWP	kg CO_2 eq
Fine particulate matter formation	PMFP	kg PM2.5 eq
Terrestrial acidification	TAP	kg SO2 eq
Freshwater eutrophication	MEP	kg P eq
Freshwater ecotoxicity	FETP	kg 1,4-DCB
Human carcinogenic toxicity	HTPc	kg 1,4-DCB
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DCB
Mineral resource scarcity	SOP	kg Cu eq
Fossil resource scarcity	FFP	kg oil eq

in part in the emergency dump pond water which is at about ambient temperature. After that, the mixture of gas and water will be directed into an existing active injection line and then injected into the injection well (Fig. 2).

New equipment needed is a 14 bar_a compressor. a 14–35 bar booster pump. a heat exchanger and piping and fittings. The cooling water pond pump already exists as well as the injection well.

2.2. Life cycle assessment (LCA)

In order to assess the impact of the current and after reinjection implementation performance of the GPP the LCA methodology is used. LCA is a compilation and evaluation of the inputs, outputs and potential environmental impacts of a product or service throughout its life cycle. LCA enables the identification of the most significant impacts and stages in the life cycle with higher potential for improvement.

Due to specific characteristics of different sectors, availability of the data and scope of the study, the LCA can be done in different manners. Furthermore, different methods can be applied for the evaluation of the environmental impact depending on the indicators of interest. In this framework, UNE-EN ISO 14,040[1] series defines the principles of life cycle assessment whose methodology must comprise four activities: goal & scope definition, inventory analysis, impact assessment and interpretation.

The UNE-EN ISO 14,044[2] gives more details about requirements and guidelines for the LCA but leaving space for choices that can have impact on the results and the conclusions of the assessment. Thus, methodology to be applied (following ISO14044 requirements and guidelines) must be defined prior to a LCA study.

The whole life cycle of the energy production analysis, with the overview of the UNE-EN ISO 14,040, was required prior to establish methodology for impact assessment. Subsequently, the goal & scope of the study as well as the system boundaries (processes to be considered and inputs/outputs to be accounted) were defined. In addition, the most appropriate characterization method and indicators for impact assessment were also established.

2.2.1. GECO LCA approach

2.2.1.1. Goal and scope. The main goal of this study is to assess the magnitude order of the environmental benefit of installing the NCG reinjection system in comparison with the current situation of Kizildere 3 U1 GPP. For the purpose, material and energy inputs were quantified per functional unit. The functional unit defined is 1 kWh of net electricity delivered to the gate of the GPP. In addition, 30 years were considered as timescale, according to the consensus found in other LCA studies [32] and GEOENVI project guidelines [33].

2.2.1.2. System description and boundaries. This study is based on the evaluation of the Kizildere 3 U1 GPP under a life cycle perspective from a cradle to grave approach. Accordingly, system boundaries defined in this study corresponded to the analysis of the power plant life cycle stages before and after the installation of the reinjection system. Kizildere 3 U1 GPP, the impact assessment includes the following processes: construction, operation (including maintenance) and wells closure of the geothermal plant (dismantling), and the raw materials and energy needed for them, as well as the air emissions, water waste and solid waste generated and released from them, according to Fig. 3.

2.2.2. Cut-off criteria

The cut-off criteria applied in this study is focused on considering the relative contribution of mass and energy to the functional unit, and the wastes generated (air emissions, water waste and solid waste). The following criteria are applied:

(i) Materials: flows of less than 1% of the cumulative mass were excluded because their environmental relevance is not a concern. However, it was ensured that the sum of the neglected material flows does not exceed 5% of the mass or environmental relevance.
(ii) Energy: flows of less than 1% of the cumulative energy are excluded from this analysis.

2.2.3. Life cycle inventory (LCI)

The LCI involved all the inputs and outputs (energy, materials and wastes) related to the system boundaries represented, mentioned before for the GPP. Firstly, the LCI for the current situation has been obtained, mainly, through primary data from Zorlu Energy[3] company, which is the company in charge of commissioning and operation management of Kizildere 3 U1 GPP. Secondly, the NCG reinjection system has been obtained through them accordingly to GECO project specifications. All inputs and outputs were referred to the functional unit and timescale defined in the goal and scope section. The modelling of the LCA has been

[1] “ISO - ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework”
[2] “ISO - ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines”
[3] https://www.zorlu.com.tr/en/default

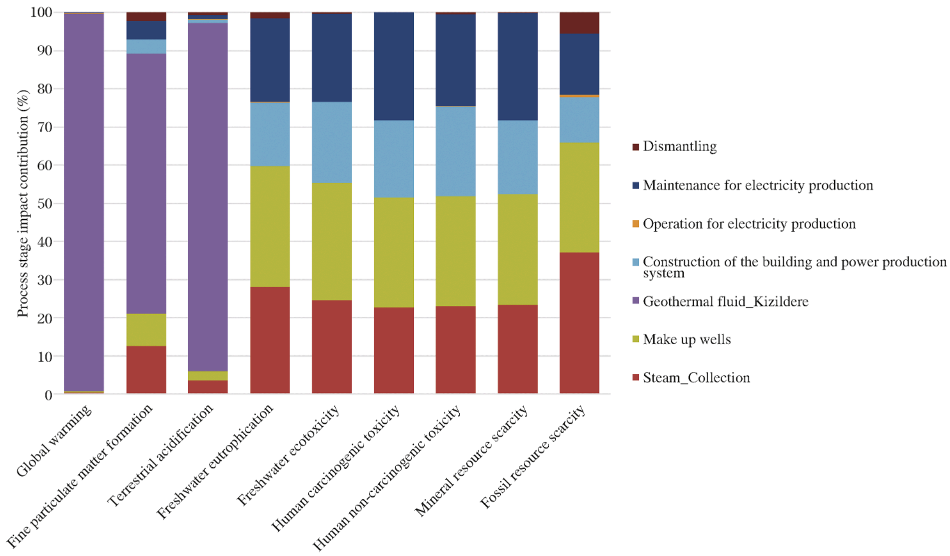

Fig. 4. Life cycle assessment of Kizildere 3 U1 GPP baseline scenario (*x*-coordinate: ReCiPe method impact categories; *y*-coordinate: percentage of process stage impact contribution).

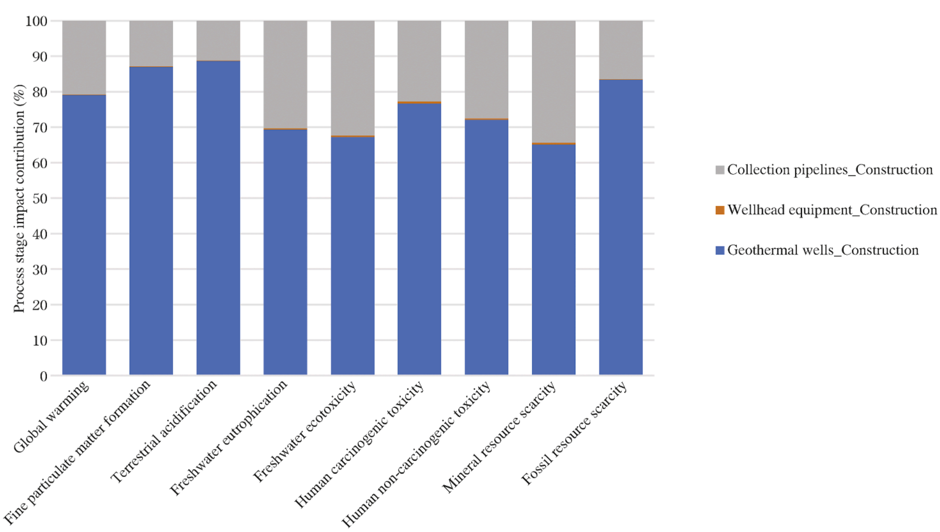

Fig. 5. Life cycle assessment of the steam collection phase for the baseline scenario (*x*-coordinate: ReCiPe method impact categories; *y*-coordinate: percentage of process stage impact contribution).

done considering the Ecoinvent v3.8 database. The most relevant information related to the life cycle stages is included in the Supplementary material.

2.2.3.1. Construction. This stage involves the construction phase of the GPP, wells and piping lines, more specifically: geothermal wells, wellhead equipment, collection pipelines, extraction site-land use, power plant buildings and mechanical equipment. This stage also involves the NCG reinjection system construction when considering the after situation.

2.2.3.2. Operation and maintenance. This stage comprises inputs and outputs related to the operation and maintenance of Kizildere 3 U1 GPP for electricity production, including reinjection processes for the after situation. In terms of operation, impacts were related to consumption of geothermal fluid. Concerning maintenance, inputs and outputs assessed were the ones related to make-up of wells (i.e., maintenance of geothermal wells, wellhead equipment, collection pipelines, extraction site-land use) and chemicals required to maintenance and machinery component replacement.

2.2.3.3. Dismantling. This stage was modelled in a simplified way due to primary raw data limitation. Accordingly, inputs and outputs considered in this work were related to wells closure of the geothermal plant (dismantling) after 30 years of operation. It was modelled by considering the wells closure following a standard process of cementing, which was derived from data generated in GEOENVI project.[4]

[4] GEOENVI Project. Tackling the environmenral concerns for deploying geothermal energy in Europe Available online: www.geoenvi.eu.

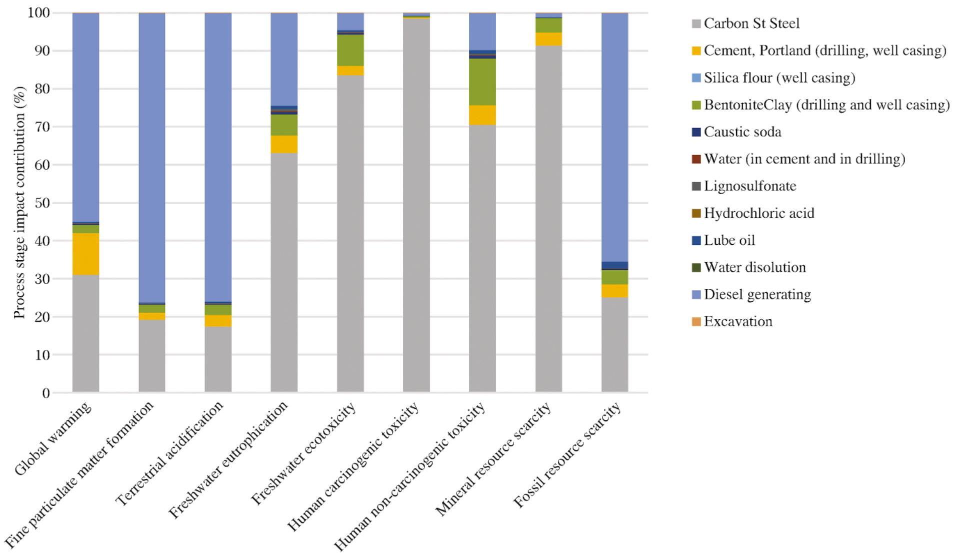

Fig. 6. Life cycle assessment for geothermal well drilling/construction for the baseline scenario (*x*-coordinate: ReCiPe method impact categories; *y*-coordinate: percentage of process stage impact contribution).

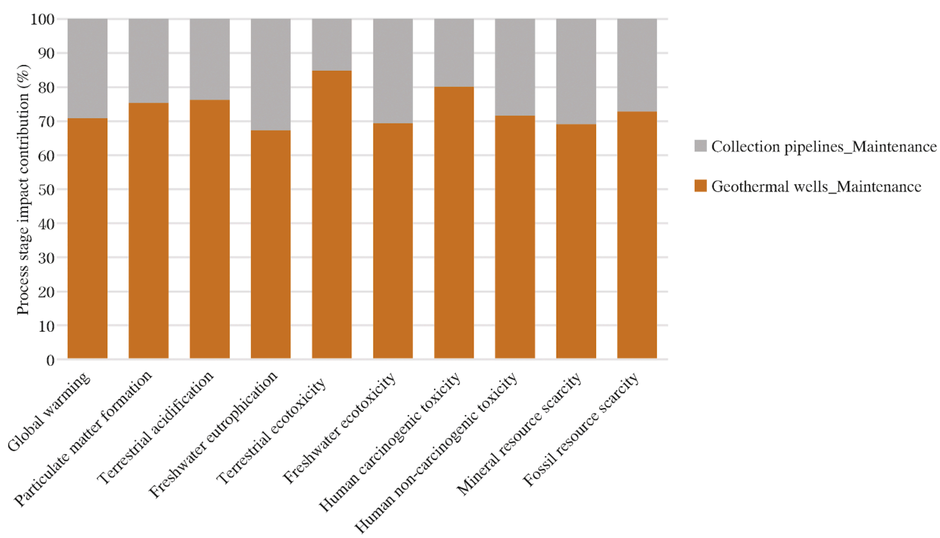

Fig. 7. Life cycle assessment of the make up well phase for the baseline scenario (*x*-coordinate: ReCiPe method impact categories; *y*-coordinate: percentage of process stage impact contribution).

2.2.4. Life cycle impact evaluation

2.2.4.1. Method and indicators. In this study, the environmental analysis was developed with the SimaPro software version Analyst 9.3.0.3, ReCiPe 2016 v1.1, midpoint method, hierarchist version, was the selected method of evaluation. The ReCiPe midpoint method was selected due to it is the one of the most recent and harmonised methods available in life cycle impact assessment. This approach allows calculating eighteen midpoint impact categories or environmental indicators. Among them, eight indicators have been selected to be studied in detail in this work, as a merged list from the studies of Colucci et al. [34] and Paulillo et al. [32], removing Marine ecotoxicity and Ionising radiation. According to this study, the more relevant categories for the environmental impact of Kizildere's geothermal power plant correspond to the list of impact categories of Table 1.

3. Results and discussion

Considering the whole life expectancy of Kizildere 3 U1 GPP of 30 years, when considering the current situation of the GPP the most impacting phases per kWh_e produced during the 30 years are (Fig. 4):

- When analysing the three main processes, the steam collection and the construction of the power production building and distribution infrastructure are the highest impacting processes for the construction phase; geothermal fluid and make up and maintenance of the well and the electricity production phases take the highest environmental impacts for the operation and maintenance phase (Fig. 4).
- Steam collection in fossil resource scarcity due to the diesel combusted in the drilling and construction of the geothermal wells (Fig. 5).
- Construction and make up wells impact in freshwater eutrophication, freshwater ecotoxicity, human carcinogenic and non-

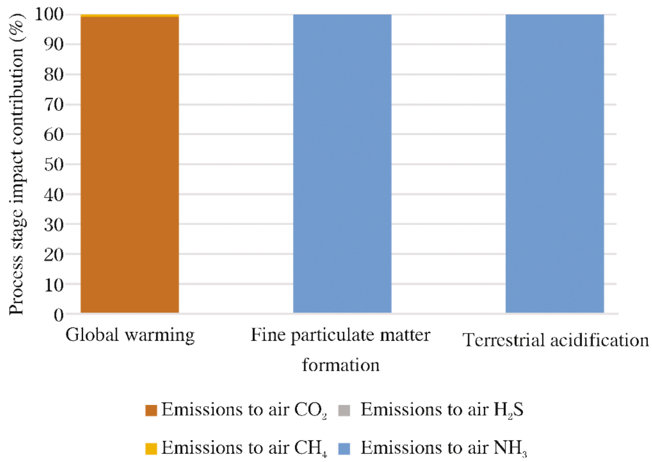

Fig. 8. Life cycle assessment of the geothermal fluid for the baseline scenario (*x*-coordinate: ReCiPe method impact categories; *y*-coordinate: percentage of process stage impact contribution).

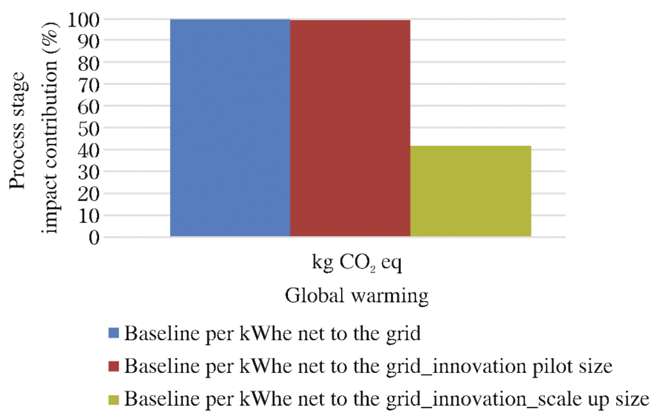

Fig. 9. Comparison of various scenarios impact assessment for global warming potential (*x*-coordinate: ReCiPe method impact categories; *y*-coordinate: percentage of process stage impact contribution).

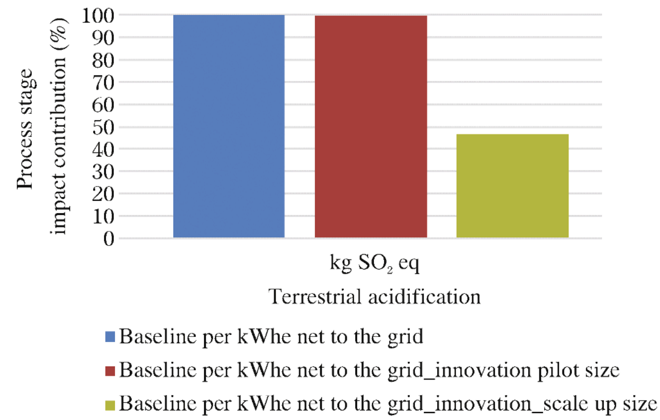

Fig. 10. Comparison of various scenarios impact assessment for terrestrial acidification (*x*-coordinate: ReCiPe method impact categories; *y*-coordinate: percentage of process stage impact contribution).

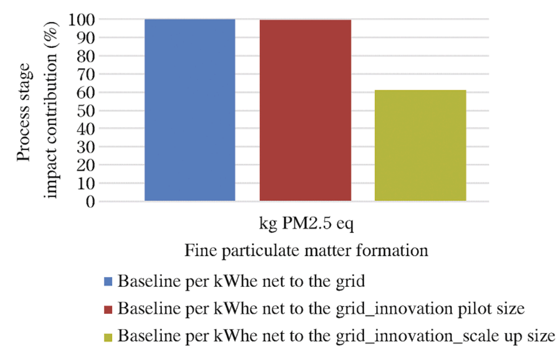

Fig. 11. Comparison of various scenarios impact assessment for fine particulate matter formation (*x*-coordinate: ReCiPe method impact categories; *y*-coordinate: percentage of process stage impact contribution).

carcinogenic toxicity and mineral resource scarcity due to the steel used in the construction and maintenance of the geothermal well (Figs. 6 and 7). For the geothermal fluid, the highest impactful processes relate to its very nature and the emissions released after passing through the electricity production cycle. The affected impact categories for releasing CO_2 and CH_4 emissions is the climate change, and the terrestrial acidification for the case of NH_3 emissions releasing (Fig. 8).

When including the NCG reinjection system (pilot case study) in the Kizildere 3 U1 GPP, new environmental impact results for the geothermal fluid are obtained. The most impacting phases for each impact categories were increased 0.4% in the worst case, mainly construction and maintenance of wells and energy production system; this is due to the addition of new materials for the new reinjection system. For the case of the scaling up of NCG reinjection system the impact categories have increased in a 6% for the worst case. Going in more detail to the impact categories where the geothermal fluid causes more impact and including the GECO solution implementation scenario together with the baseline scenario. Main results show that the inclusion of the NCG reinjection system is environmentally feasible from the current pilot situation for the global warming impact category with a reduction of 0.5% for the pilot size and 58% for the pilot scaling up of the environmental impact for global warming (Fig. 9). 0.5% for the pilot size and 53.4% for the pilot scaling up for the terrestrial acidification impact category (Fig. 10) and 0.3% for the pilot size and 38.9% for the pilot scaling up for the fine particulate matter formation impact category (Fig. 11).

4. Conclusion

The present work has been dedicated to analyse the environmental impact of Kizildere 3 U1 GPP.

Firstly, the current situation of the GPP has been analysed considering the main processes of the plant, from cradle to grave, considering 1 net kWh of electricity. The analysis ratifies results from other GPP where most impacting phases are the geothermal fluid, in this case because of the NCG emissions, more specifically the CO_2 and NH_3 emissions, and the construction and maintenance of the wells, mainly because of the steel and the fuel used for the well construction and drilling.

Within GECO project activities a reinjection system for the reduction of the NCG has been designed and was commissioned by the end of 2022. In this sense, the application of CO_2 reinjection at the Turkish site into the reservoir will prevent the emission of 1,700 tons·year^{-1} in the pilot site and 10% of the total emissions released along the life span of the GPP. Once the system is made real, a NCG reduction of 59.6% is expected, with almost 154,491.6058 tons·year^{-1} NCG injection.

This study pretends to find the environmental feasibility of the system depending on the decreasing of the amount of NCG released to the atmosphere by comparing the baseline scenario and 2 scenarios more varying the quantity of the NCG avoided, according to project theoretical results. Results show that both cases, pilot size and scale up size innovation improve the environmental performance of the GPP as it reduces the impact categories related to air pollution (global warming potential and Particulate matter formation) and terrestrial acidification.

Future steps will be when commissioning the system, a new analysis would be needed to take into account other components or processes of the plant being influenced by the installation of the reinjection system, and their environmental implications (positive or negative). Furthermore, a more in deep research will be needed by comparing different impact assessment methods considering the environmental impacts of the NCG components included in the geothermal fluid.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ural Halaçoğlu, Hakan Alp Sahiller, and Tuğrul Hazar are currently employed by Zorlu Enerji.

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CRediT author statement

María Dolores Mainar-Toledo: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Ural Halaçoğlu:** Resources, Validation, Writing – review & editing. **Hakan Alp Sahiller:** Resources, Validation, Writing – review & editing. **Tuğrul Hazar:** Resources, Validation, Writing – review & editing. **Claudio Zuffi:** Formal analysis, Investigation, Validation, Writing – review & editing. **Maryori Díaz-Ramírez:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Giampaolo Manfrida:** Formal analysis, Investigation, Validation, Writing – review & editing.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enss.2023.08.005.

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