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Scenarios for replacement of electric resistive space heating by a geothermal heat pump - Environmental amortization

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ABSTRACT

Geothermal energy has become of increasing scientific and industrial interest; hence, many works discuss and study its principles, uses, and technical/economic viability. However, much less research focuses on the environmental impact of geothermal energy projects.

In this research, we perform a life cycle assessment of five different geothermal heat pump systems (GHPS) installed across five different facilities: three single-family detached houses (heating capacity of GHPS: 10 kW, 15 kW, and 45 kWh, respectively), a multipurpose building (heating capacity of GHPS: 110 kW), and a residential area of semi-detached houses (heating capacity of GHPS: 210 kW).

The overall results demonstrate that the higher the heating capacity of a GHPS, the greater the environmental impact. Such results allow us to establish correlations between GHPS heating capacity and environmental impact across the 11 environmental impact categories.

Amortization periods were calculated with respect to the annual demand for heating and cooling of each facility. In the 10 kW and 15 kW GHPS, the amortization period is shorter than 11 years, followed by an eight-year period for the 45 kW GHPS. Similarly, the amortization period for the 210 kW GHPS decreases up to five years. Conversely, the 110 kW GHPS has an 18-year amortization period.

1. Introduction

All countries make individual and collective efforts to ease and accelerate the transition toward a global system of sustainable energy supply and less environmental pollution. In fact, renewable energies have been of ongoing scientific and academic interest since the beginning of the 21st century [1]. Nowadays, multiple works, such as those reported by Z. Z. Li et al. [2] and S. Li and Shao [3], address renewable energy issues across countries. Even though there is growing demand for energy among production systems, fossil fuels cannot remain the basis for energy supply. Hence, renewable alternatives have the potential to become the major energy supply pathway and replace other energies, such as those discussed by Haines et al. [4], Bahlawan et al. [5].

As de Vries et al. [6] and Dovì et al. [1] point out, energy transition is a reality particularly visible in developed countries, where energy policies and projects pave the way for a greener, more sustainable, and renewable future. The two major obstacles for the energy transition are the environmental and economic footprints of energy transition projects and policies. Renewable energy facilities can be environmentally profitable in the long term and thus have the potential to significantly reduce environmental pollution. However, countries usually must make high economic investments in the beginning of renewable policies and projects, since renewable energies are economically profitable in the medium to long term.

As discussed by Sullivan et al. [7], Hanbury and Vasquez [8] and Chang et al. [9], renewable energies such as solar power and wind power

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are consolidated worldwide. Nevertheless, the installed capacity of other renewable energies, such as geothermal energy, is much less than solar and wind systems. Geothermal has multiple applications, ranging from space heating and cooling to large-scale electricity generation for agriculture, livestock, and chemical plants. Utilization of geothermal resources largely depends on the resource temperature. Very-low-temperature resources (<30 °C) mainly serve heating and drying purposes. Low-temperature geothermal resources (<30 °C<90 °C) are primary used for space (home and buildings) heating and cooling, as well in agriculture, livestock, and industrial applications. Medium-temperature geothermal resources (<90 °C<150 °C) mainly have industrial applications. Finally, high-temperature geothermal resources (>150°) are chiefly used for electricity generation.

Since space cooling and heating are two of the most prominent applications of geothermal power [9,10], multiple research works discuss how to optimally use geothermal resources for such purposes [11,12]. According to Spain's Institute for the Diversification and Saving of Energy [13] – a public agency of Spain's Ministry of Industry, Energy, and Tourism – there are approximately 17.199.630 households in Spain (12, 039,741 apartments and 5,159,889 single family homes), which consume around 14,676 kilo tons of oil equivalent (ktoe) of energy each year. According to IDEA, 47 % of the energy demand from Spanish households is for space heating, 18 % for domestic hot water (DHW), and 0.8 % for space cooling. Together, these three activities account for 66.7 % of the total national energy demand from households.

This research work addresses the use of geothermal energy for urban space heating/cooling and DHW. To this end, we analyze very-low-temperature and low-temperature geothermal systems, known as geothermal heat pump systems (GHPS). Air conditioning systems for home and buildings rely on GHPS for both heating and cooling. GHPS can include vertical energy collectors, horizontal energy collectors, or shallow energy collectors. Both horizontal and vertical GHPS are the most prominent. They are composed of a series of vertically or horizontally wells, respectively, with a u-tube structure in the soil passing a working fluid through a heat exchanger, and transferring heat between the working fluid and the surrounding soil.

Multiple research works have studied the relationship between soil temperature and depth, which is a key factor to properly understand how geothermal energy works. At a certain depth below the frost line, the temperature of the earth remains constant throughout the year. Therefore, when ambient temperature is cold, GHPS collect heat energy from the soil to heat households and buildings. On the other hand, in a warm environment, GHPS perform the reverse process to transfer heat from the environment to the soil and thus cool houses or facilities.

Geothermal energy has become of increasing scientific and industrial interest; hence, many works discuss and study its principles, uses, and technical/economic viability. However, much less research focuses on the environmental impact of geothermal energy projects. Despite the importance of knowing these environmental impacts and being able to evaluate any geothermal energy project comprehensively. With this in mind, this article undertakes an analysis of the environmental impact of five GHPS to compare them and establish criteria that can serve to define good practices for such installations from an environmental impact perspective and not just in relation to their economic profitability. In this sense, life cycle analysis (LCA) is performed to know the environmental impact of a particular product or process throughout its lifetime, and it is as essential as any economic analysis. This article highlights the need to incorporate LCA results into the evaluation of energy systems projects that seek alternatives to conventional systems based on fossil fuels. As previously mentioned, industries must seek more reliable and less polluting systems which are also economically profitable [14–18].

Following the latest research trends on geothermal energy and LCA, this research performs an LCA of five GHPS, each with different heating capacities. Findings from this study have important implications for the geothermal energy industry, policymakers, and stakeholders. This research provides a framework for evaluating the environmental impact of GHPS and informs decision-making on system design, implementation, and policy development. The correlations established between GHPS heating capacity and environmental impact can guide the development of more sustainable geothermal energy projects, thereby optimizing the ecological footprint of this renewable energy source.

2. Materials and methods

2.1. Research goal and scope

In this research, we perform an LCA of five different GHPS installed across five different facilities: three single-family detached houses (heating capacity of GHPS: 10 kW, 15 kW, and 45 kWh, respectively), a multipurpose building (heating capacity of GHPS: 110 kW), and a residential area of semi-detached houses (heating capacity of GHPS: 210 kW). The first GHPS to be analyzed has a heating capacity of 10 kW. It is installed in a two-story single-family house that has a heatable area of 100 m2, low demand for DHW, and an annual energy demand of 14,238 kWh for heating and cooling.

The second GHPS has a heating capacity of 15 kW. It is installed in a detached single-family house with two floors. The house has an annual demand of 16,356 kWh for heating and cooling, low demand for DHW, and a heatable area of 150 m2. The third GHPS has a 45 kW heating capacity. It is installed in another detached single-family house, whose annual demand for heating and cooling is 35,219 kWh, the heatable surface is 190 m2 (a 160 m2 house and a 30 m2 garage), and demand for DHW is high. The fourth GHPS has a 110 kW heating capacity. It is installed in a multipurpose building having an annual demand of 68,500 kWh for heating and cooling, a heatable area of 1000 m2, and medium-to-high demand for DHW. The fifth and last GHPS has a 210 kW heating capacity. It is installed in a residential area gathering 42 semi-detached single-family houses (from 65 m2 to 150 m2 floor plans). For each of these systems, we estimated the annual demand using statistical data from IDEA and estimations from real GHPS with similar characteristics.

The analyzed GHPS have similar vertical energy collection systems which only differ in terms of the number and depth of the boreholes, the type of heat pump, and the type of water tank. The process of installing the GHPS has six phases: borehole drilling, pipe installation, borehole grouting, pipe filling, heat pump installation, and pipe-pump joining.

2.2. Functional unit

In this work, the functional unit refers to substituting a conventional cooling and heating system with a low-temperature GHPS without compromising energy demand or supply. To perform the LCA, we analyze five GHPS, differing in terms of heating capacity, demand for heating and cooling, and demand for DWH.

2.3. System boundaries

The boundaries of the five GHPS remain the same and can be depicted in Fig. 1. However, as previously mentioned, each GHPS differs in terms of the number and depth of the boreholes, the type of heat pump, and the type of water tank. These characteristics do not affect the installation stages or the heating/cooling process.

2.4. Assumptions

To perform the LCA, we considered the following assumptions.

- GHPS heating capacity and annual consumption for heating and cooling are estimated with respect to real GHPS installations in single-family houses.

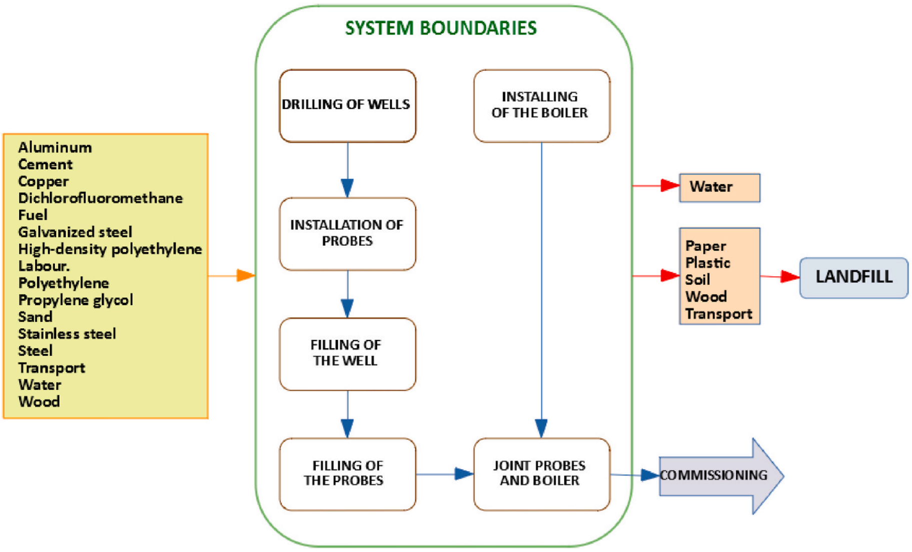

Fig. 1. System boundaries.

- GHPS heating capacity and annual consumption for heating and cooling are estimated as follows:
  - House 1: 10 kW GHPS heating capacity and 14,238 kWh annual demand for heating and cooling.
  - House 2: 15 kW GHPS heating capacity and 16,356 kWh annual demand for heating and cooling.
  - House 3: 45 kW GHPS heating capacity and 35,219 kWh annual demand for heating and cooling.
  - Multipurpose building: 110 kW GHPS heating capacity and 68,500 kWh annual demand for heating and cooling.
  - Residential area: 210 kW GHPS heating capacity and 587,748 kWh annual demand for heating and cooling.
- The installation inside the house or building is not modified. Only regular heaters are replaced by geothermal heat pumps.
- The houses and the multipurpose building are located in La Rioja, Spain. This region belongs to the D2 climate zone, according to Spain's Technical Building Code [19].
- The material needed to install the GHPS is located on-site, thus discarding the need to collect it from warehouses.
- A truck is available for waste management. The truck carries the waste from the construction site to the landfill, which is at a distance of 20 km.

2.5. Building characteristics

The five facilities are located in the Spanish region of Logroño, La Rioja. This region belongs to the D2 climate zone, according to Spain's Technical Building Code [19].

The first house is a two-story single-family house with a 10m × 5m x 8m rectangular design. The house's annual demand for heating and cooling is 14,238 kWh, it has a heatable area of 100 m^2, and low demand for DHW. The GHPS in this house has a heating capacity of 10 kW.

The second house is a detached single-family house with two floors. It has a 10m × 7.5m x 8m rectangular design. Similarly, the house has an annual demand of 16,356 kWh for heating and cooling, low demand for DHW, and a heatable area of 150 m^2. The GHPS has a heating capacity of 15 kW.

The third house is another detached single-family house, having a 45 kW heating capacity GHPS, an annual demand of 35,219 kWh for heating and cooling, a heatable surface of 190 m^2 (a 160 m^2 house and a 30 m^2 garage), and high demand for DHW. This house follows a two-story, 10m × 10 m x 8m rectangular design.

The multipurpose building has an annual demand of 68,500 kWh for heating and cooling, a heatable area of 1000 m^2, and medium-to-high demand for DHW. The GHPS has a heating capacity of 110 kW.

The residential area comprises 42 semi-detached single-family houses (from 65 m^2 to 150 m^2 floor plans) and has an annual demand of 587,748 kWh for heating and cooling. The GHPS has a heating capacity of 210 kW.

2.6. Inventory

To perform the LCA and environmental impact analysis, we created an inventory template file for each GHPS. The document comprises six charts, each listing the materials and resources needed at each phase of the installation process of GHPS.

Phase 1: Drilling of wells. During vertical installation, wells are bored in the ground outside of the houses/building. The number and depth of the boreholes depend on the heating capacity of each GHPS. For each of the three single-family houses, two wells were dug 75m, 90m, and 125m deep, respectively. As for the multipurpose building, 24 holes 80m deep were drilled. Finally, 30 wells, 135m deep each, were drilled to install the GHPS in the residential area. See Table S1 (Supporting Information).

Phase 2: Installation of probes. Geothermal probes are installed vertically within the wells or boreholes. The length of the probes depends on how deep the wells are, and thus on the characteristics of each house/building/residential area. This information is summarized in Table S2 (Supporting Information). Probe pairs in a borehole are bound with a u-shape cross-connector at the bottom of the borehole.

Phase 3: Filling of the well. The space between the wall of the boreholes and the tubes is filled with bentonite grout, thus surrounding the probes to both ensure thermal connection to the surrounding soil and improve heat transfer between the soil and the probes. See Table S3 (Supporting Information).

Phase 4: Filling of the probes. The geothermal probes are filled with a Tyfocor®/water mixture, which acts as a heat transfer fluid. The mixture ensures efficient heat transfer from the energy collection system to the heat pump. See Table S4 (Supporting Information).

Phase 5. Installing of the boiler. This stage involves replacing a traditional boiler with a geothermal heat pump having similar characteristics. Each of the five facilities requires a different heat pump, depending on the heating capacity of the GHPS and the level of demand for DHW. See Table S5 (Supporting Information).

Phase 6: Connection of probes to boiler. The probes ends must be connected to the boiler. This is the last stage in the installation process of the GHPS. Also, this is the last step before performing the LCA. See Table S6 (Supporting Information).

2.7. Lifecycle analysis

We performed the LCA using SimaPro 8.3®, a popular and easy-to-use software for sustainable decision-making (Herrmann and Moltesen 2015). The 11 environmental impact categories include Abiotic Depletion (AD), Abiotic Depletion (fossil fuels) (AD-FF), Global Warming-GWP100 (GWP), Ozone Layer Depletion (ODP), Human Toxicity (HT), Freshwater Aquatic Ecotoxicity (FWAE), Marine Aquatic Ecotoxicity (MAE), Terrestrial Ecotoxicity (TE), Photochemical Oxidation (PO), Acidification (AC), and Eutrophication (EU).

3. Results

This section discusses the results from the LCA analysis and is organized in three subsections.

Table 1
Environmental impact of GHPS installation phases.

Category	Units	Installation	Drilling of wells	Installation of probes	Filling of the well	Filling of probes	Boiler replacement	Connecting probes to the boiler	Total
AD	kg Sb eq	I	6.96E-03	3.12E-03	7.19E-03	1.49E-03	6.07E-02	3.00E-02	1.09E-01
		II	8.35E-03	3.13E-03	8.64E-03	1.79E-03	6.29E-02	3.00E-02	1.15E-01
		III	1.16E-02	3.15E-03	1.20E-02	2.48E-03	1.15E-01	3.00E-02	1.74E-01
		IV	8.90E-02	3.75E-02	9.19E-02	1.91E-02	1.69E-01	5.99E-02	4.66E-01
		V	1.88E-01	4.73E-02	1.94E-01	4.00E-02	3.61E-01	8.99E-02	9.20E-01
AD-FF	MJ	I	2.82E+05	1.38E+04	7.49E+04	8.89E+03	2.12E+04	1.11E+04	4.12E+05
		II	3.38E+05	1.64E+04	9.17E+04	1.07E+04	2.26E+04	1.11E+04	4.90E+05
		III	4.69E+05	2.23E+04	1.24E+05	1.48E+04	4.12E+04	1.11E+04	6.83E+05
		IV	3.60E+06	1.76E+05	9.30E+05	1.14E+05	5.90E+04	2.36E+04	4.91E+06
		V	7.60E+06	3.59E+05	1.93E+06	2.39E+05	1.30E+05	3.49E+04	1.03E+07
GWP	kg CO_2 eq	I	1.85E+04	4.77E+02	1.62E+04	3.61E+02	2.12E+03	6.26E+02	3.83E+04
		II	2.22E+04	5.50E+02	1.94E+04	4.33E+02	2.24E+03	6.26E+02	4.55E+04
		III	3.09E+04	7.18E+02	2.69E+04	6.02E+02	4.09E+03	6.26E+02	6.38E+04
		IV	2.37E+05	6.02E+03	2.07E+05	4.62E+03	5.89E+03	1.29E+03	4.61E+05
		V	5.00E+05	1.15E+04	4.35E+05	9.70E+03	1.29E+04	1.92E+03	9.71E+05
ODP	kg CFC-11 eq	I	3.35E-03	8.51E-06	5.65E-04	1.37E-05	2.16E-04	2.45E-04	4.40E-03
		II	4.02E-03	9.04E-06	7.00E-04	1.64E-05	1.96E-04	2.45E-04	5.19E-03
		III	5.59E-03	1.03E-05	9.30E-04	2.28E-05	3.66E-04	2.45E-04	7.16E-03
		IV	4.29E-02	1.04E-04	6.88E-03	1.75E-04	6.01E-04	4.91E-04	5.12E-02
		V	9.05E-02	1.60E-04	1.42E-02	3.61E-04	1.11E-03	7.36E-04	1.07E-01
HT	kg 1.4-DB eq	I	2.45E+03	1.91E+03	1.53E+03	1.69E+02	1.24E+04	2.64E+03	2.11E+04
		II	2.94E+03	1.91E+03	1.85E+03	2.03E+02	1.99E+04	2.64E+03	2.94E+04
		III	4.08E+03	1.92E+03	2.55E+03	2.82E+02	3.46E+04	2.64E+03	4.61E+04
		IV	3.14E+04	2.29E+04	1.95E+04	2.17E+03	3.45E+04	5.29E+03	1.16E+05
		V	6.62E+04	2.88E+04	4.12E+04	4.56E+03	1.18E+05	7.93E+03	2.67E+05
FWAE	kg 1.4-DB eq	I	9.26E+02	3.58E+02	9.82E+02	8.49E+01	3.77E+03	5.92E+02	6.71E+03
		II	1.11E+03	3.60E+02	1.18E+03	1.02E+02	4.77E+03	5.92E+02	8.11E+03
		III	1.54E+03	3.66E+02	1.64E+03	1.41E+02	8.51E+03	5.92E+02	1.28E+04
		IV	1.19E+04	4.30E+03	1.25E+04	1.09E+03	1.05E+04	1.19E+03	4.14E+04
		V	2.50E+04	5.52E+03	2.64E+04	2.29E+03	2.79E+04	1.78E+03	8.89E+04
MAE	kg 1.4-DB eq	I	2.56E+06	4.41E+05	3.80E+06	3.27E+05	1.86E+07	1.84E+06	2.76E+07
		II	3.08E+06	4.53E+05	4.57E+06	3.92E+05	1.61E+07	1.84E+06	2.65E+07
		III	4.27E+06	4.82E+05	6.33E+06	5.45E+05	3.04E+07	1.84E+06	4.39E+07
		IV	3.28E+07	5.34E+06	4.85E+07	4.18E+06	5.18E+07	3.69E+06	1.46E+08
		V	6.92E+07	7.36E+06	1.02E+08	8.80E+06	9.10E+07	5.53E+06	2.84E+08
TE	kg 1.4-DB eq	I	1.22E+01	2.32E+00	2.01E+01	4.74E-01	1.78E+01	3.71E+00	5.66E+01
		II	1.46E+01	2.33E+00	2.42E+01	5.69E-01	2.62E+01	3.71E+00	7.16E+01
		III	2.03E+01	2.35E+00	3.35E+01	7.90E-01	4.60E+01	3.71E+00	1.07E+02
		IV	1.56E+02	2.79E+01	2.57E+02	6.07E+00	4.96E+01	7.42E+00	5.04E+02
		V	3.29E+02	3.54E+01	5.42E+02	1.27E+01	1.54E+02	1.11E+01	1.08E+03
PO	kg C_2H_4 eq	I	3.14E+00	1.53E-01	1.44E+00	9.92E-02	9.84E-01	3.89E-01	6.20E+00
		II	3.76E+00	1.75E-01	1.74E+00	1.19E-01	9.69E-01	3.89E-01	7.15E+00
		III	5.23E+00	2.28E-01	2.39E+00	1.65E-01	1.79E+00	3.89E-01	1.02E+01
		IV	4.01E+01	1.92E+00	1.82E+01	1.27E+00	2.73E+00	7.89E-01	6.51E+01
		V	8.47E+01	3.64E+00	3.83E+01	2.67E+00	5.54E+00	1.18E+00	1.36E+02
AC	kg SO_2 eq	I	6.25E+01	1.91E+00	3.61E+01	1.45E+00	1.81E+01	5.07E+00	1.25E+02
		II	7.50E+01	2.16E+00	4.35E+01	1.75E+00	1.75E+01	5.07E+00	1.45E+02
		III	1.04E+02	2.73E+00	6.00E+01	2.42E+00	3.24E+01	5.07E+00	2.07E+02
		IV	8.00E+02	2.39E+01	4.59E+02	1.86E+01	5.03E+01	1.03E+01	1.36E+03
		V	1.69E+03	4.34E+01	9.65E+02	3.92E+01	9.97E+01	1.53E+01	2.85E+03
EU	kg PO_4— eq	I	1.34E+01	3.10E-01	8.37E+00	4.61E-01	7.31E+00	3.01E+00	3.28E+01
		II	1.61E+01	3.33E-01	1.01E+01	5.53E-01	6.60E+00	3.01E+00	3.66E+01
		III	2.23E+01	3.85E-01	1.39E+01	7.69E-01	1.24E+01	3.01E+00	5.28E+01
		IV	1.71E+02	3.81E+00	1.07E+02	5.90E+00	2.03E+01	6.03E+00	3.14E+02
		V	3.61E+02	6.00E+00	2.25E+02	1.24E+01	3.74E+01	9.04E+00	6.51E+02

- Comparative analysis per phase per GHPS.
- Comparison among amortization periods per facility.
- Comparison of results per GHPS heating capacity.

3.1. *Comparative analysis per phase per GHPS*

This section discusses the results from the LCA in each of the six phases of the GHPS installation process. Table 1 summarizes such results. We obtained similar results in the same phases across the five GHPS. That is, Phase 1 (Drilling of wells) and Phase 5 (Installing of the boiler) cause the highest environmental impact. Namely, Phase 1 primarily affects categories AD-FF, GWP, ODP, PO, and AC. On the other hand, Phase 2 primarily impacts categories AD, HT, FWAE, and MAE.

Phase 2 (Installation of probes) and Phase 4 (Filling of probes) cause the lowest environmental impact across the first three geothermal systems; that is, GHPS with a capacity lower than 45 kW. Phase 2 has the fewest environmental effects on categories AD, ODP, and EU. Phase 4 causes the lowest environmental impact on AD-FF, GWP, HT, FWAE, MAE, TE, PO, and AC. As for the last two GHPS, whose heating capacity is of 110 kW and 210 kW, respectively, Phase 4 (Filling of probes) and Phase 6 (Connecting probes to the boiler) have the fewest environmental implications. Specifically, Phase 4 has the lowest environmental impact on AD-FF, GWP, HT, FWAE, MAE, TE, PO, and AC, whereas Phase 6 causes the lowest impact on categories AD-FF, GWP, FW8AE, MAE, TE, PO y AC.

The overall results demonstrate that the higher the heating capacity of a GHPS, the greater the environmental impact. Such results allow us to establish correlations between GHPS heating capacity and environmental impact across the 11 environmental impact categories. These correlations are thoroughly discussed in section 3.3.

3.2. *Environmental impact and amortization*

This section discusses the LCA results for the five GHPS in terms of environmental amortization. Amortization periods were calculated with respect to the annual demand for heating and cooling of each facility (see section 2.5).

We found a relatively short amortization period in the majority of the GHPS (see Table 2). In the first two systems (heating capacity of 10 kW and 15 kW, respectively), the amortization period is shorter than 11 years, followed by an eight-year period for the 45 kW GHPS. Similarly, the amortization period for the 210 kW GHPS decreases up to five years. Conversely, the 110 kW GHPS has an 18-year amortization period.

Variability in environmental amortization with respect to GHPS heating capacity can be explained as follows: with low-heating-capacity GHPS (10 kW–45 kW), the environmental amortization period is larger in phase 5 (Boiler replacement), which in turn causes the highest environmental impact on AD and HT. Conversely, with high-heating capacity GHPS (110 kW and 210 kW), the environmental amortization period is larger in phases 1 and 3 (Drilling of well and Filling of the well), which in turn have the highest environmental impact on categories AD-FF, GWP, and ODP.

Fig. 2 introduces a graph of the environmental amortization analysis. As can be observed, environmental impact categories AD and HT show the longest amortization period in low-heating-capacity GHPS, whereas categories AD-FF, GWP, and ODP show the largest amortization period in high-heating capacity GHPS. The graph also demonstrates that the amortization period is not fully dependent on heating capacity, but also on other factors such as building characteristics and annual energy demand. From this perspective, it might be impossible to establish a lineal correlation between GHPS heating capacity and amortization length. However, it is easier to establish such a correlation between heating capacity and the absolute value of each environmental impact category.

3.3. *Relationship between heating capacity and environmental impact. Applications to other GHPS*

This research argues a clear, direct relationship between the eleven environmental impact categories and the heating capacity of GHPS. Such relationship is proven when tracing the tendency lines and is validated when estimating the R^2 values as a measure of the ability of an independent variable to explain the variability of a corresponding dependent variable [20]. Tendency lines help estimate what will be the effects on each impact category with respect to the heating capacity of a GHPS. Our calculations are valid estimations of the environmental impact of GHPS with characteristics similar to those studied in this work. Even though this research focuses on non-industrial applications, the exact value of the relationship depends on the characteristics of the energy collector system. However, estimations can be highly useful when performing environmental impact and lifecycle analyses.

Figs. 3–6 depict the tendency lines of some of the impact categories. For instance, Fig. 5 depicts the relationship between GHPS heating capacity and global warming potential over 100 years (GWP). Since the line shows $R^2 = 0.9809$, we can assume a direct relationship between the two variables. In turn, this relationship helps us estimate the environmental impact of any other similar GHPS, whose heating capacity ranges from 10 kW to 210 kW, in terms of global warming. For instance, a GHPS with 150 kW of heating capacity can cause an environmental impact of around 7.16E+06 kg CO_2 eq in terms of global warming. As another example, our results on the relationship between GHPS heating capacity and abiotic depletion (see Fig. 3) indicate that a geothermal installation with 150 kW of heating capacity has an environmental impact of 6.51E-01 kg Sb eq in terms of abiotic depletion. It is worth mentioning that all the graphs have a five-point line to indicate the valid range of the estimations, from 10 kW to 210 kW of heating capacity.

4. Conclusions

This research analyzes the environmental impact and lifecycle of vertical ground-source GHPS of five different heating capacities – from 10 kW to 210 kW. The installation process of a single GHPS comprises six

Table 2
Environmental amortization across environmental impact categories.

Category	Amortization period (yrs.) (10 kW)	Amortization period (yrs.) (15 kW)	Amortization period (yrs.) (45 kW)	Amortization period (yrs.) (110 kW)	Amortization period (yrs.) (210 kW)
AD	1.03E+01	9.43E+00	6.66E+00	9.14E+00	2.10E+00
AD-FF	7.60E+00	7.88E+00	5.09E+00	1.88E+01	4.61E+00
GWP	7.28E+00	7.53E+00	4.91E+00	1.82E+01	4.48E+00
ODP	6.56E+00	6.73E+00	4.31E+00	1.58E+01	3.86E+00
HT	9.10E+00	1.10E+01	8.03E+00	1.04E+01	2.78E+00
FWAE	1.64E+00	1.73E+00	1.27E+00	2.11E+00	5.27E-01
MAE	2.96E+00	2.47E+00	1.90E+00	3.26E+00	7.37E-01
TE	1.11E+00	1.22E+00	8.46E-01	2.06E+00	5.16E-01
PO	3.97E+00	3.99E+00	2.64E+00	8.67E+00	2.11E+00
AC	3.06E+00	3.09E+00	2.05E+00	6.93E+00	1.69E+00
EU	3.80E+00	3.69E+00	2.47E+00	7.55E+00	1.82E+00

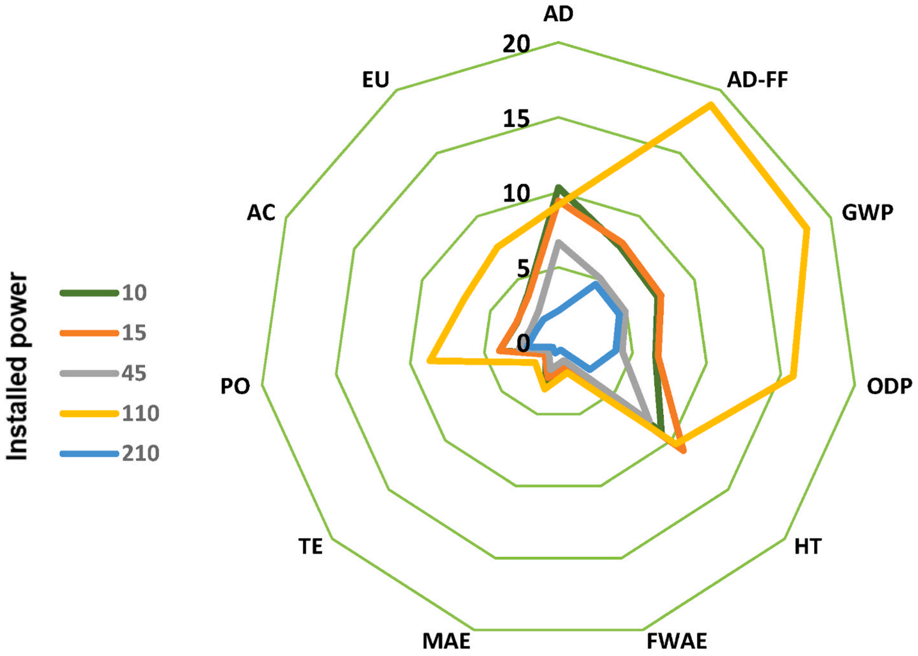

Fig. 2. Environmental amortization per impact categories.

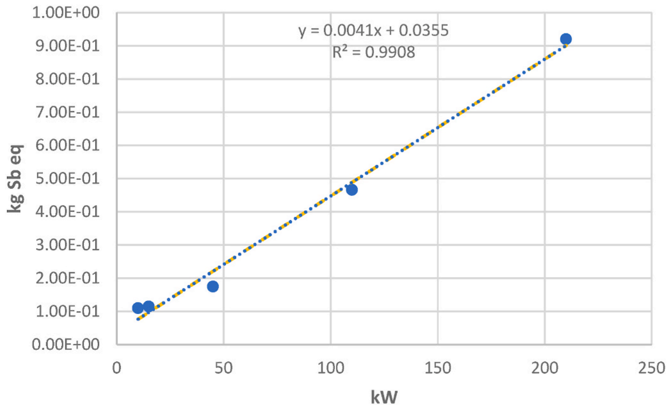

Fig. 3. Tendency line of the relationship between abiotic depletion and heating capacity.

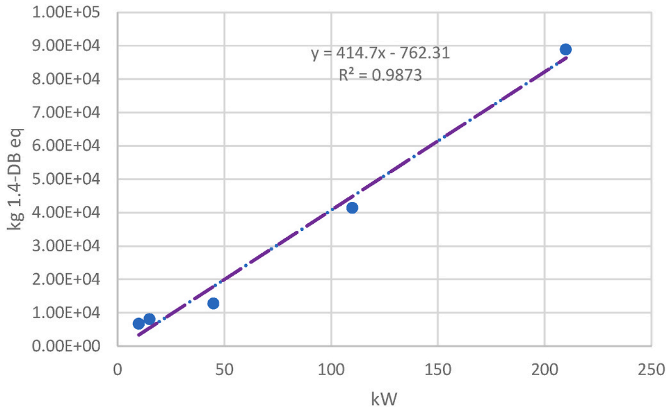

Fig. 4. Tendency line of the relationship between freshwater aquatic ecotoxicity and heating capacity.

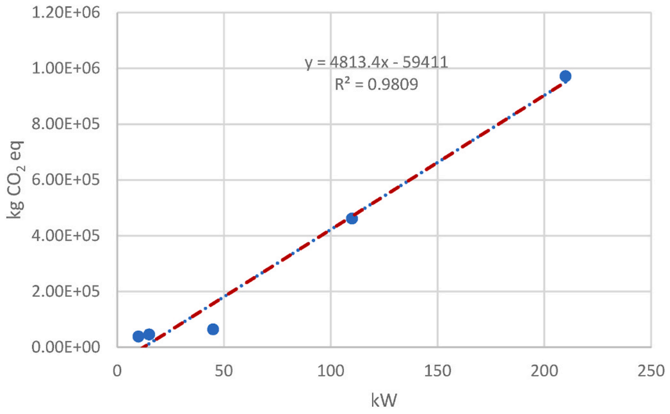

Fig. 5. Tendency line of the relationship between global warming and heating capacity.

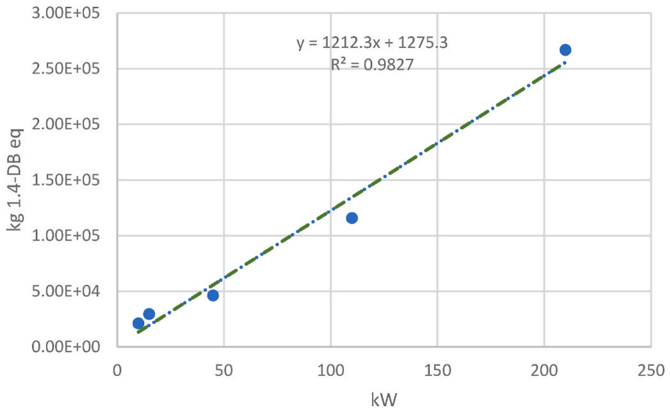

Fig. 6. Tendency line of the relationship between human toxicity and heating capacity.

phases: drilling of wells, installation of probes, filling of the well, filling of probes, boiler replacement and connecting probes to the boiler. The LCA is performed with respect to 11 environmental impact categories: Abiotic Depletion (AD), Abiotic Depletion (fossil fuels) (AD-FF), Global Warming Potential over 100 years (GWP), Ozone Layer Depletion (ODP), Human Toxicity (HT), Freshwater Aquatic Ecotoxicity (FWAE), Marine Aquatic Ecotoxicity (MAE), Terrestrial Ecotoxicity (TE), Photochemical Oxidation (PO), Acidification (AC), and Eutrophication (EU).

Our results demonstrate that, regardless of the heating capacity of the GHPS, the drilling of wells and boiler replacement phases affect the majority of the impact categories. The drilling phase has effects on AD-FF, GWP, ODP, PO, and AC, whereas the pump installation phase affects AD, HT, FWAE, and MAE. On the other hand, we observed mixed results in terms of the phases causing the lowest environmental impact. The installation of probes and filling of probes phases have the lowest impact in low-heating-capacity GHPS. Conversely, the filling of probes and connecting probes to the boiler phases are the least environmentally harmful if the GHPS has a heating capacity of either 110 kW or 210 kW.

It is impossible to establish a correlation between environmental amortization period (in years) and the heating capacity of a GHPS, since amortization length depends on other factors, such as borehole number and depth and energy demand. Overall, amortization periods are short, lasting less than 12 years for 10 kW and 15 kW GHPS, less than 10 years for 45 kW systems, 18 years for 110 kW systems, and eight years for 210 kW GHPS. Categories AD and HT have the greatest influence on amortization with low-heating-capacity systems, whereas AD-FF, GWP, and ODP have the greatest amortization impact in high-heating-capacity GHPS. Finally, our results indicate a direct correlation between GHPS heating capacity and environmental impact across the eleven environmental impact categories. Each correlation is proven with a tendency line, whose R^2 value is close to one. Such results allow us to further estimate the environmental impact of GHPS with similar characteristics.

CRediT authorship contribution statement

C. Lorente-Rubio: Data curation, Investigation, Writing – original draft. **J.L. García-Alcaraz:** Formal analysis, Resources, Supervision, Validation. **J.C. Sáenz-Diez Muro:** Data curation, Investigation, Validation, Visualization. **E. Martínez-Cámara:** Conceptualization, Methodology, Software, Supervision, Writing – review & editing. **A. Bruzzone:** Formal analysis, Supervision, Validation, Visualization. **J. Blanco-Fernández:** Conceptualization, Methodology, Supervision, Visualization, Writing – review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2024.120585.

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