energies

MDPI

Article

Multi-Criteria Study on Ground Source Heat Pump with Different Types of Heat Exchangers

Agnieszka Żelazna, Justyna Gołębiowska * and Dmytro Kosaryha

Faculty of Environmental Engineering, Lublin University of Technology, Nadbystrzycka 40 B Str., 20-618 Lublin, Poland; a.zelazna@pollub.pl (A.Ż.)
* Correspondence: j.golebiowska@pollub.pl

Abstract: Heat pumps are currently one of the most frequently applied heat sources in residential buildings. Ground source heat pumps are more reliable than air source heat pumps in terms of energy efficiency, especially in colder climates. However, they are more expensive and involve increased material inputs; therefore, multi-criteria analyses taking into account environmental and economic aspects seem necessary for the green design of these systems. The aim of this work was to analyze the environmental and economic impacts of the ground source heat pump providing heating for a family house located in eastern Poland, cooperating with three types of ground heat exchangers (each in two sizing options): helix, vertical and horizontal. The multi-criteria analysis was based on the life cycle assessment methodology using IMPACT 2002+ and life cycle costs methods. The lowest environmental impact was reported for the variants with vertical ground heat exchangers, mainly due to their high efficiency in the operation stage. On the other hand, the lowest economic impact was observed for the horizontal heat exchangers, which are not demanding in terms of material and construction costs. Final recommendations based on multi-criteria analysis propose the vertical probes as a sustainable solution, with a weighted sum indicator in the range 0.085–0.297 on 0–1 scale.

Keywords: heat pumps; life cycle assessment; economic efficiency; environmental efficiency

check for updates

Citation: Żelazna, A.; Gołębiowska, J.; Kosaryha, D. Multi-Criteria Study on Ground Source Heat Pump with Different Types of Heat Exchangers. *Energies* **2024**, *17*, 602. https://doi.org/10.3390/en17030602

Academic Editors: Adrián Mota Babiloni and Annunziata D'Orazio

Received: 1 December 2023
Revised: 8 January 2024
Accepted: 24 January 2024
Published: 26 January 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Climate change and environmental degradation are the major threats that are currently receiving a lot of attention [1,2]. Numerous actions have already been taken in order to minimize their negative consequences. The targets set by the European Green Deal [3] are forcing the introduction of major changes into, among others, the residential sector [4–6].

Heating and cooling demand in residential sector accounts for half of the total energy consumption both in Europe and worldwide [7]. Furthermore, the total residential energy consumption is expected to grow in the future on a global scale; thus, decarbonization of this sector is one of the greatest challenges for the upcoming decade [5,8]. Heat pumps (HPs), energy efficient devices utilizing renewable energy inter alia from air or ground sources, are promising options in the upcoming transformation aimed at achieving zero-emission heating systems [9–12].

As a result of numerous efforts toward the reduction of greenhouse gas (GHG) emissions, including government financial support for the investments, and the fluctuating prices of fossil fuels, the market of HPs has grown significantly in recent years [13]. According to the IEA, sales of heat pumps grew by 11% worldwide in 2022 and by nearly 40% in Europe [14]. In the recent years, the HPs market in Poland has been observed to be one of the fastest growing markets in Europe—according to the European Heat Pump Association [15], an overall growth of 120% was reached in 2022. Today, HPs are used as a main heat source in buildings and cover around 10% of heating demand worldwide. However, in order to fulfill all obligations related to climate protection and rational energy

management, HPs should cover nearly 20% of global heating demand in buildings by 2030 [14].

Due to the relatively low investment cost, air source heat pumps (ASHPs) are the most popular choice in Europe among different types of HPs [14,15]. In colder climates, ASHPs are usually a part of hybrid systems cooperating, for example, with gas boilers or supported by an additional electric heater, as their efficiency decreases significantly in the coldest period of the year. Ground source heat pumps (GSHPs) are much more expensive due to the drilling work and materials required for the ground heat exchangers; however, they are more efficient than ASHPs, and they can be used as effective energy sources for buildings even in cold climates [16,17]. However, as the performance of GHPS systems depends strongly on the local geological characteristics, the design of ground heat exchangers is more challenging and requires the proper identification of soil-specific thermal properties such as thermal conductivity and specific heat [18–21] which are strongly related to the moisture content of the soil [22,23].

The main questions that may arise during the selection of the HP for a building are related to the economic and ecological benefits. Life cycle assessment (LCA) can be a useful tool facilitating the selection of the device, as it accounts for and compares many economic as well as ecological factors throughout the entire life cycle of the product. The holistic approach used in LCA, called "from the cradle to the grave", includes the identification and then quantification of the material's consumption, energy and hazardous substances emissions at all stages of the product life cycle, starting from the design phase and obtaining raw materials, through the operation phase, to the final disposal phase [24,25].

The LCA methodology can be applied for the evaluation of a selected HP system working under certain climate conditions in order to determine their advantages, vulnerabilities and possibilities for future improvement [26–30], as well as for comparing different types of HPs in greater detail [17,31,32], in order to select a more profitable/sustainable solution.

The LCA methodology can be also used to compare HPs to other energy sources for a building, for example, comparing air-to-air HPs and biomass boilers [33], hybrid HPs and condensing boilers [34], HPs and gas boilers [35,36], absorption and/or electric water heat pumps compared to gas boilers [37,38], or even photovoltaic (PV)-driven ASHPs and PV-driven absorption systems covering both heating and cooling loads [39]. All the mentioned studies show that HPs present many advantages over more traditional heating devices.

Additionally, there are some studies discussing innovative systems utilizing HPs and showing the potential of their future applications. For example, a prototype of an innovative dual-source HP (a solution that combines both air and ground heat exchangers; the ground thermal storage is a support for the external air main source) was presented in [40] and compared to alternative systems such as standard ASHP and GSHP. In [41], an environmental impact assessment of an absorption solar GSHP was presented and compared to the conventional vapor compression GSHP. Such studies provide important data that can help to direct the development of the discussed technologies.

The scope of analyses covering heat pump performance presented above is broad; however, there are still some areas where the lack of data on life cycle environmental burdens constitutes a barrier to the green designing of GSHP systems. In particular, there is a notable lack of data on the comparison between various options of heat exchangers available for the lower temperature heat source. Therefore, the aim of this work was to perform a multi-criteria analysis (MCA) based on LCA methodology for a GSHP cooperating with various types of ground exchangers (helix, vertical and horizontal) ensuring the effective heating of a residential building located in Poland, in order to select the most favorable variant. The performed analysis was an extended version of the study presented in [42], where the inventory of heat exchangers was completed only for the construction stage. In this analysis, more dimensions options as well as the whole life cycle period were included, and the seasonal coefficients of performance (SCOP) of the systems were considered, which gives a better metric for comparison.

2. Materials and Methods

The conducted MCA of six different variants of ground heat exchangers, in different sizing options, designed as a lower temperature heat source for the GSHP implemented in the selected residential building, was divided into several stages presented in Figure 1. The assumptions for the analysis and the description of all the stages are presented later in this section.

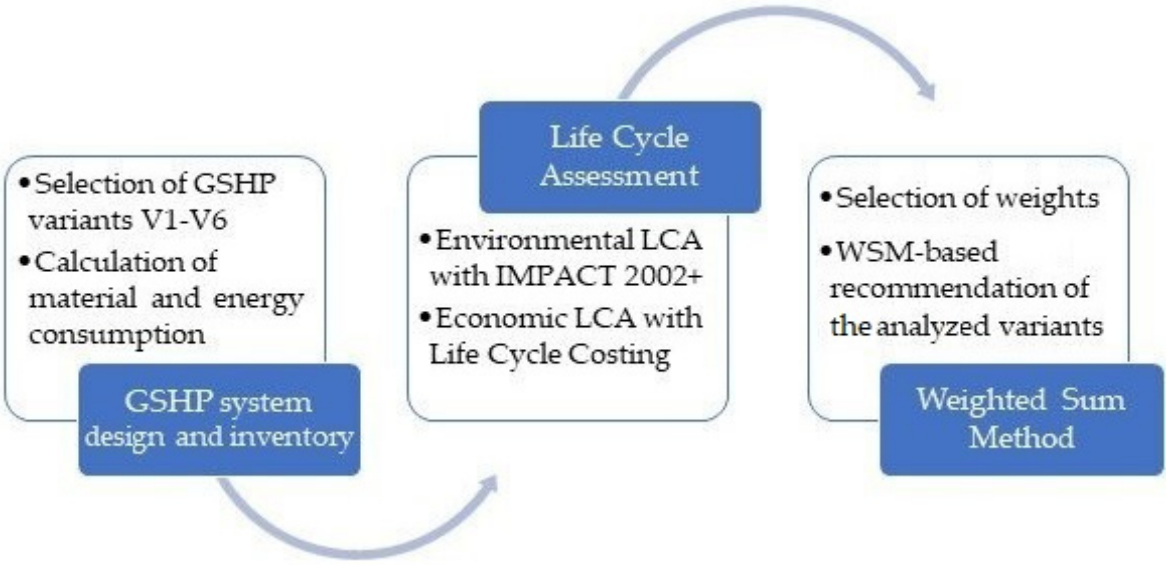


Figure 1. The scheme of research method (own elaboration).

2.1. Object Description

A single-family house located in Kalinówka (Lublin Voivodeship, Poland) was selected for the analysis. The usable area of the building was 193 m^2, the story height was 2.9 m and the total cubic volume was 572 m^3. The energy performance of the building was determined based on the Polish standards included in [43] by using InstalSystem 5.0 software (Instalsoft, Chorzów, Poland). The determined calculated heating power was 5410 W. The 3D model of the building used for the calculation and the overall heat transfer coefficient values for the external barriers are shown in Figure 2.

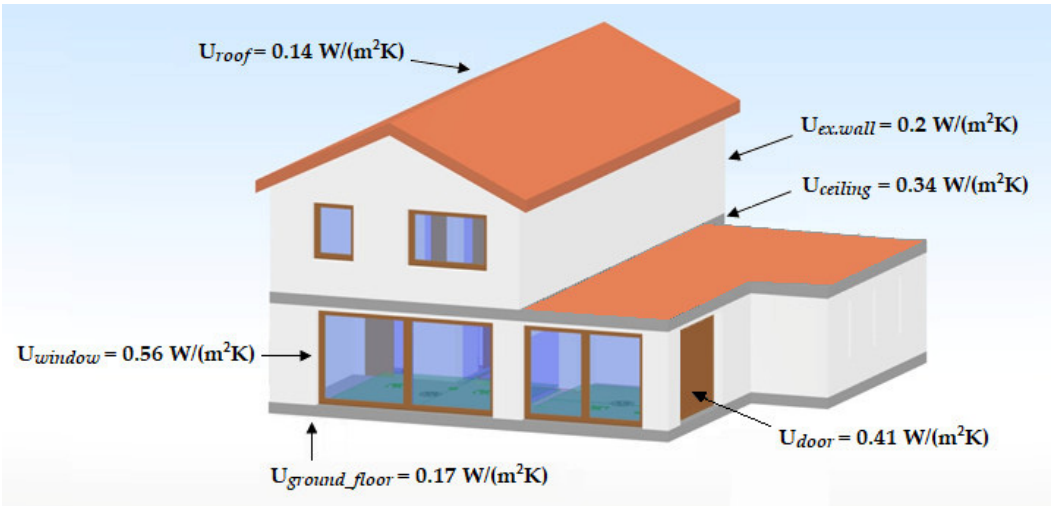


Figure 2. The 3D model of building created in InstalSystem 5 software (own elaboration).

A GSHP with a heating power of 6 kW was selected as the main heat source for the building, covering both the demands of space heating and domestic hot water throughout the whole year. The duration of system operation was assumed to be 30 years. The expected annual operating time of the circulation pump in the ground exchanger was assumed to be 2100 h in all analyzed variants of the system.

2.2. System Description

In the performed analysis, six different variants (V1–V6) of ground heat exchangers were used, including two spiral heat exchangers (helix) of different lengths and heights and two horizontal and two vertical heat exchangers of different pipe diameters. The analyzed versions of heat exchangers were selected on the basis of common engineering practice. Diameters of pipes were selected in a way that minimized the circuit pressure head losses. The variants of ground exchangers used in the MCA are characterized in Figure 3 and Table 1. The dimensions of the exchangers were determined according to the manufacturers' guidelines and engineering practice. The pressure loss as well as the capacity of exchangers were calculated in order to select the circuit pump and determine their energy consumption. All the selected variants were suitable for use in the designed installation; however, they differed in the manner of material consumption for the construction stage, as well as the energy used for pumping during the operation of the system.

Variants of the heat exchangers included in Figure 3a–c show the longitudinal sections of heat pump supply (red pipes) and return (blue pipes, invisible in Figure 3b), brine pipes in the ground below the frost depth and the manhole.

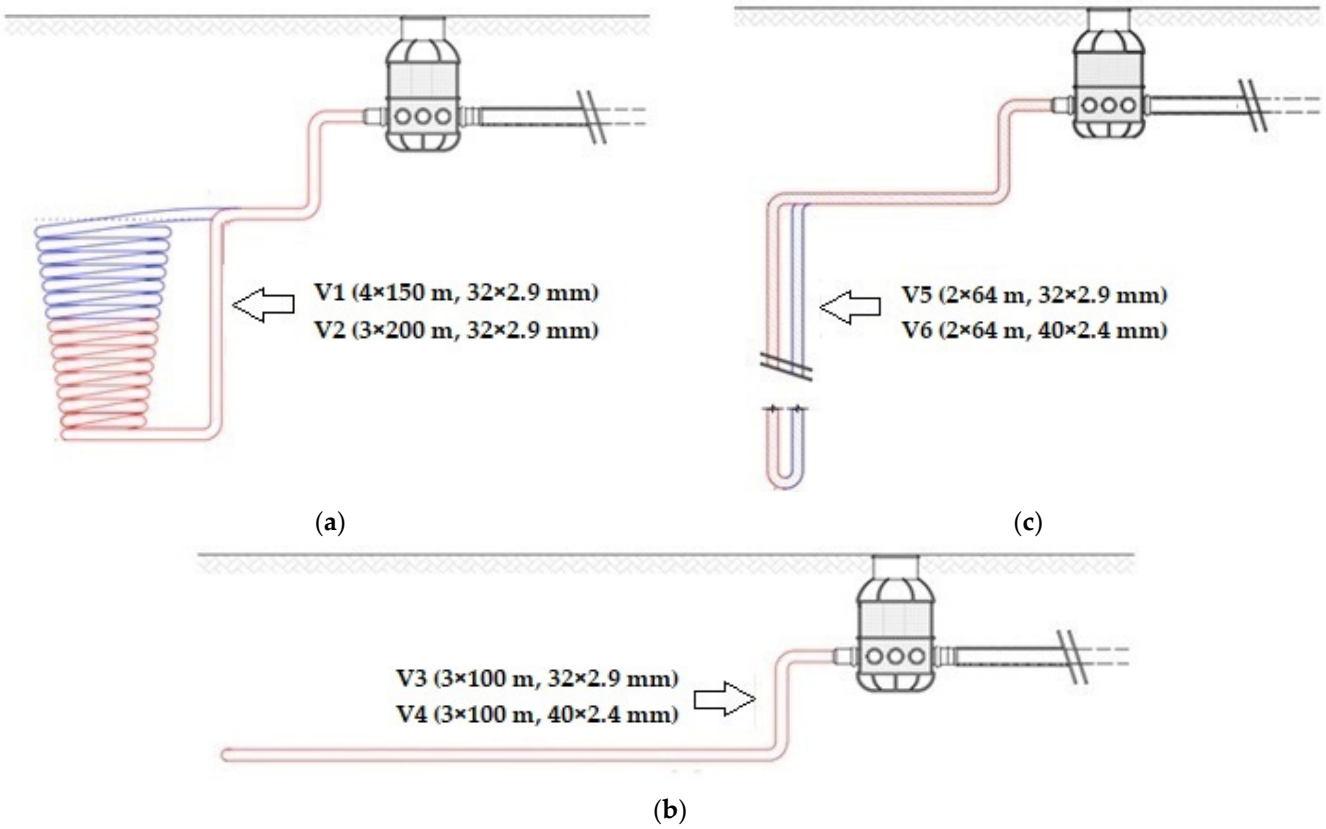


Figure 3. Schematic longitudinal sections of ground heat exchangers (supply—red pipes and return—blue pipes) in the analyzed variants: (**a**) Helix: V1 built from 4 sections and V2 from 3 sections, (**b**) Horizontal built from 3 sections: V3 with diameter 32 × 2.9 mm and V4 with diameter 40 × 2.4 mm and (**c**) Vertical built from 2 sections: V5 with diameter 32 × 2.9 mm and V6 with diameter 40 × 2.4 mm (own elaboration).

Table 1. Characteristics of variants of ground heat exchangers used in the MCA (own elaboration).

		V1	V2	V3	V4	V5	V6
Type of exchanger		helix	helix	horizontal	horizontal	vertical	vertical
Pipe material		PE-XA-UV					
Diameter of pipes between HP and brine distributor	mm	40 × 2.4	40 × 2.4	40 × 2.4	50 × 4.6	40 × 2.4	50 × 4.6
Number of loops		4	3	3	3	2	2
Diameter of pipes after brine distributor (loop)	mm	32 × 2.9	32 × 2.9	32 × 2.9	40 × 2.4	32 × 2.9	40 × 2.4
Length of each loop	m	150	200	100	100	64	64
Total mass of pipes	kg	122	162	66	75	28.08	32.2
Total mass of valves (cast iron)	kg	7.14	7.14	7.14	7.14	7.14	7.14
Volume of heat exchanger (brine)	dm^3	347.1	335.1	181.7	251.22	142.9	202.3
Pressure loss in the circuit	Pa	6947.8	9532.8	6782.8	5792.8	7728.8	6171.2
Pump lifting head	mH_2O	0.71	0.97	0.69	0.59	0.79	0.63
Yearly energy consumption of circulation pump	kWh	29.4	31.5	29.4	29.4	31.5	29.4
Volume of earthworks	m^3	38	34.5	384.75	384.75	9.2	9.2
Length of drilling	m	-	-	-	-	118	118
Mass of PE manhole	kg	85	85	85	85	85	85
SCOP	-	4.54	4.54	4.43	4.43	4.69	4.69
Yearly energy consumption of heat pump	kWh	1580.48	1580.48	1619.72	1619.72	1529.93	1529.93
Circulation pump		40 W, included in Ecoinvent production processes					
Heat pump		6 kW, included in Ecoinvent production processes, adopted from 10 kW					
Expansion vessel		18 dm^3, included in Ecoinvent production processes, adopted from 25 dm^3					

The variants characterized above were simulated in cooperation with GSHP of 6 kW power using the SCOP calculator available in [44]. According to the producer's data, the calculator is based on a program that simulates heating systems with heat pumps, their energy consumption, the annual coefficient of performance and the temperature course of the heat source. The calculation results of these simulation programs were validated (confirmed) by the measurement results in existing facilities, where the reported deviation was between 2% and 6% [45]. The results of these simulations are presented in Table 1. These results were based on soil temperature, which rises and stabilizes in deeper ground layers, leading to the best energy efficiency observed in V5 and V6. The higher energy efficiency of GSHP resulting from the better performance of the vertical heat exchanger is connected with the fact that the average temperature of brine is more stable and in general is higher than in the case of the horizontal heat exchanger. This, among the other parameters, strongly influences the energy efficiency measured by the coefficient of performance (COP), electricity consumption during the heating season and the seasonal coefficient of performance (SCOP). The lowest SCOP was calculated for horizontal heat exchangers, which undergo the largest fluctuations in temperature during the year, with the minimum values corresponding to the peak in energy needed for space heating. Helix exchangers, as a halfway solution between horizontal and vertical, received an SCOP equal to 4.54, between the SCOP values of 4.43 for horizontal and 4.69 for vertical probes.

2.3. Multi-Criteria Analysis

In the performed cradle-to-gate analysis (excluding final disposal phase), two types of criteria were used in order to indicate the most advantageous variant: ecological criteria, based on weighted indicators in four damage categories available in the IMPACT 2002+ method; and economic criteria, based on life cycle cost (LCC). The SimaPro v. 8.1.13 (PRé Consultants B.V., The Netherlands) and the Ecoinvent v. 3 database were used in order to calculate the environmental indicators. Life cycle inventory (LCI) as well as LCC calculations were based on the detailed scheme of systems and its energy balance.

2.3.1. Environmental Criteria

Environmental criteria were measured via the IMPACT 2002+ method, where all the inventoried inputs and outputs of the product system are recalculated into the environmental impact via fourteen midpoint categories grouped into four damage categories, namely human health, ecosystem quality, climate change and resources. The mentioned categories represent the four environmental criteria in the MCA.

The damage category of human health includes the measured human toxicity effects, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, ionizing radiation and damage to the ozone layer. The effects are measured first in kg of reference substances at midpoint category levels, i.e., kg PM 2.5 emitted into the air is a measure in the respiratory inorganics midpoint category. At the damage category level, more general units are used. Disability-adjusted life years (DALY) is a unit in the human health category.

The damage category of ecosystem quality includes the measured aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acidification/nutrification, land occupation and water turbined. The damage category is measured in units of potentially disappeared fraction (PDF·m^2·y) expressing the damage by a species in a certain area over one year.

The damage category of climate change includes only one midpoint category, namely global warming, where the measurement of kg CO_2 emitted into the air is used as a unit.

The damage category of resources includes non-renewable energy consumption and mineral extraction, measured in MJ of additional (surplus) energy possibly used in the future to extract the resources from deeper layers or less concentrated ores. Additional impacts, like water consumption in m^3, are included in human health, ecosystem quality and resources categories. The results of the normalized (referred to yearly impact of one European) indicator calculation are expressed in points (Pt) [46]. The higher the IMPACT 2002+ indicator, the greater the harmful effect to the natural environment.

In order to assess the uncertainty of the received results, MonteCarlo analysis was applied to all the analyzed variants of the system. The SimaPro uncertainty analysis tool allowed the performance of a probabilistic calculation with a fixed number of runs set at 1000, using random changes in input data not exceeding 1% of the inventory results. Infrastructure processes were excluded from the model due to the lack of uncertainty data. The assumed confidence interval was 90%.

2.3.2. Economic Criterion

The LCC method includes all costs that will be incurred during the lifetime of the system. To calculate all the costs related to investment and operations, the following formula was applied [47]:

$$LCC = C_i + \sum_{1}^{n} \frac{C_o \cdot (1 + r_e)^n}{(1 + i)^n} [\text{Euro}] \quad (1)$$

where

C_i is the investment cost (Euro),

C_o is the annual cost of operation and maintenance (Euro),

n is the year of system operation, from 1 to 30 (years),
r_e is the energy price growth rate assumed to be 4.5% and
i is the discount rate assumed to be 6.85%.

2.3.3. Weighted Sum Method

Furthermore, to simplify the selection of the most favorable variant, the weighted sum method (WSM) was used. The WSM score is the sum of the normalized indicators multiplied by their corresponding weights. It varies between zero (minimal impact) and one (maximal impact in the given category) or may be expressed as a percentage.

The formulae used for the calculation of normalized multi-criteria results according to the weighted sum method (WSM) are as follows [48]:

$$a_{ij} = \frac{Indicator - Indicator_{min}}{Indicator_{max} - Indicator_{min}} \quad (2)$$

$$A_i = \sum_{1}^{i} (a_{ij} \cdot w_j) \quad (3)$$

where

A_i is the WSM score of alternative i,
a_{ij} is the normalized value of jth indicator,
w_j is the weighting factor for jth indicator and
i is the number of alternatives.

The weighting factors were assigned to the criteria equally in the basic option, and additional calculations were performed including 50% and 70% weights for the economic criterion to ensure the relevant understanding of the weighting process as well as to provide a broader comparison perspective for investors.

3. Results and Discussion

This section presents the results of calculations divided into three main groups: environmental impact, LCC and the final comparison of the analyzed variants by the use of WSM. The results are discussed with information found in the literature that covers a similar scope of analysis.

3.1. Life Cycle Impact Assessment by the Use of IMPACT 2002+

The first stage of calculations in the environmental impact assessment criterion is called characterization, where all the fourteen midpoint categories are used to gather various materials and emissions with measurable environmental impacts in a certain area. The indicators in the impact categories presented in Figure 4 have varying units; therefore, the comparison is presented as the percentage of maximal value in the category (100% is related to the highest results obtained in certain category). As can be noticed, V5 and V6 reported the lowest impact in all the categories, while V3 and V4 reported high scores in 13 of 14 categories. The most similar results were observed in the category of ozone layer depletion, since the heat pump used in all variants was the same; therefore, only a small portion of the emissions related to this category come from processes other than the refrigerant used in the HP circuit. At the same time, the most diverse results were obtained for the respiratory inorganics impact category. This is due to the location of the system in Poland, where the energy mix is still largely based on non-renewable energy. Lower energy consumption obtained for a highly efficient ground-sourced heat pump with the vertical probes characterized by the highest SCOP allowed for the reduction of PM 2.5 emissions and other inorganic pollutants, such as sulfur and nitrogen oxides, which are typical byproducts of the energy industry.

Other categories with the most differing results for the selected variants were respiratory organics and carcinogens, which are related, among others, to the emission of benzo-a-pyrene. This differentiation is again mostly related to the amounts of energy used

during the 30-year operation, but it also includes various amounts and types of materials used for the construction of heat exchangers. It has to be emphasized that the results obtained in this stage of calculation differ by no more than 15.5% across all variants.

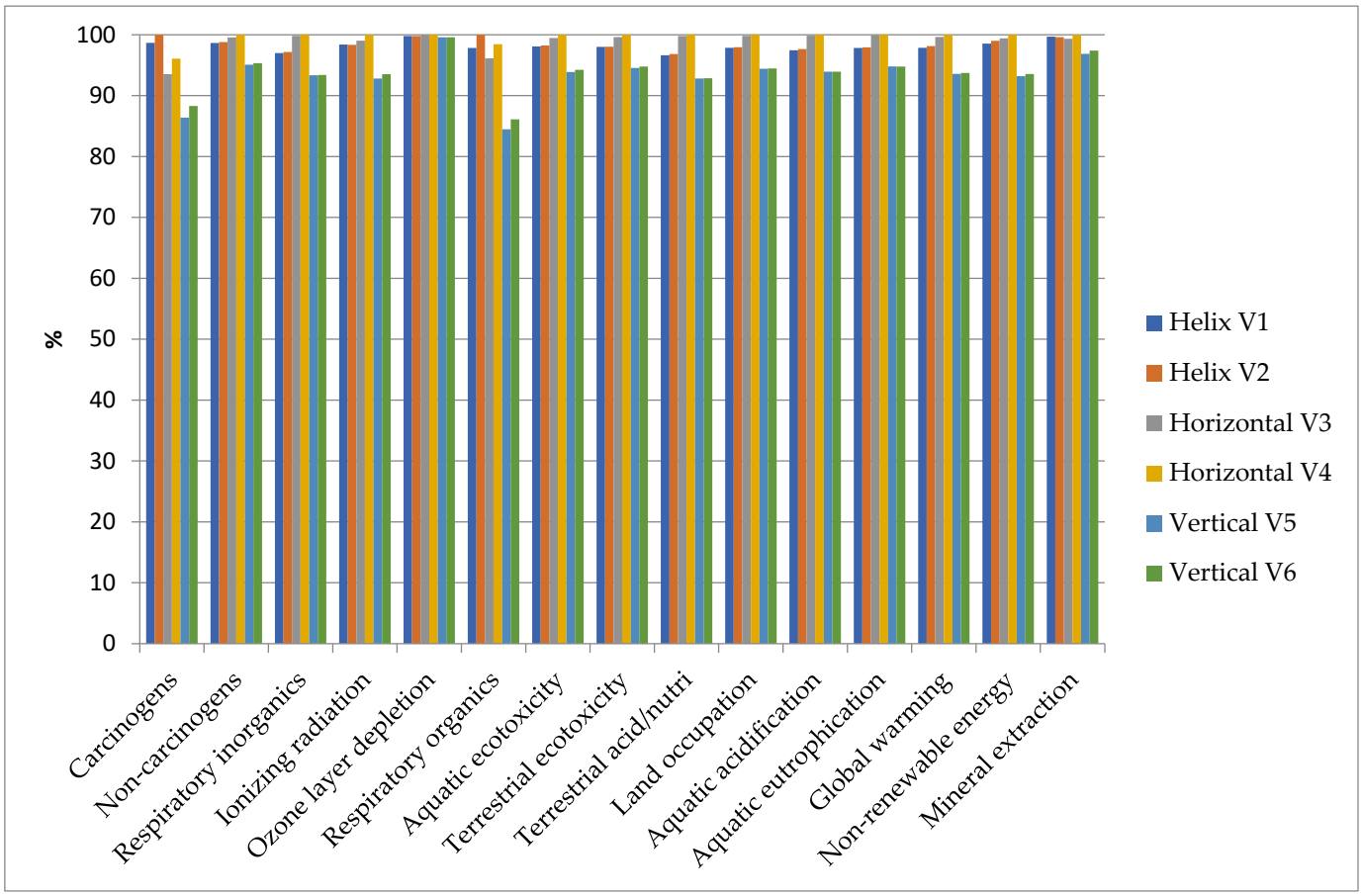


Figure 4. Comparison of characterization results from the IMPACT 2002+ method (own elaboration).

A more complex comparison can be made based on the single score calculated via the IMPACT 2002+ method, as presented in Figure 5 (impact categories equally weighted).

As can be noticed, the highest results of 13.18 Pt and 13.13 Pt are reported for V4 and V3, respectively, which conforms to the previously discussed characterization results. The minimum value of the indicator reported for V5 corresponded to 93.34% of the highest score and equaled 12.31 Pt. The 6.66% difference between variants contributes to the possible environmental benefits in the case of V5 selection. A deeper analysis of the results leads to the processes of energy consumption during the operation of the heat pump which are strongly related to the energy efficiency of the GSHP. It has to be mentioned that the values of the indicators are dependent on the kind of energy mix (Polish low voltage network in this study, updated on the basis of Ecoinvent database); therefore, the results may differ for other locations that use the same system.

In all the cases, human health and resources were the most important categories, followed by climate change. An additional share analysis performed for all the analyzed variants shows that the most important life cycle stage is operation, responsible for about 95% of the indicator for V1–4 and 96% for V5–6. This confirms the previous results with the shares near or exceeding 90% as published in [26,49,50].

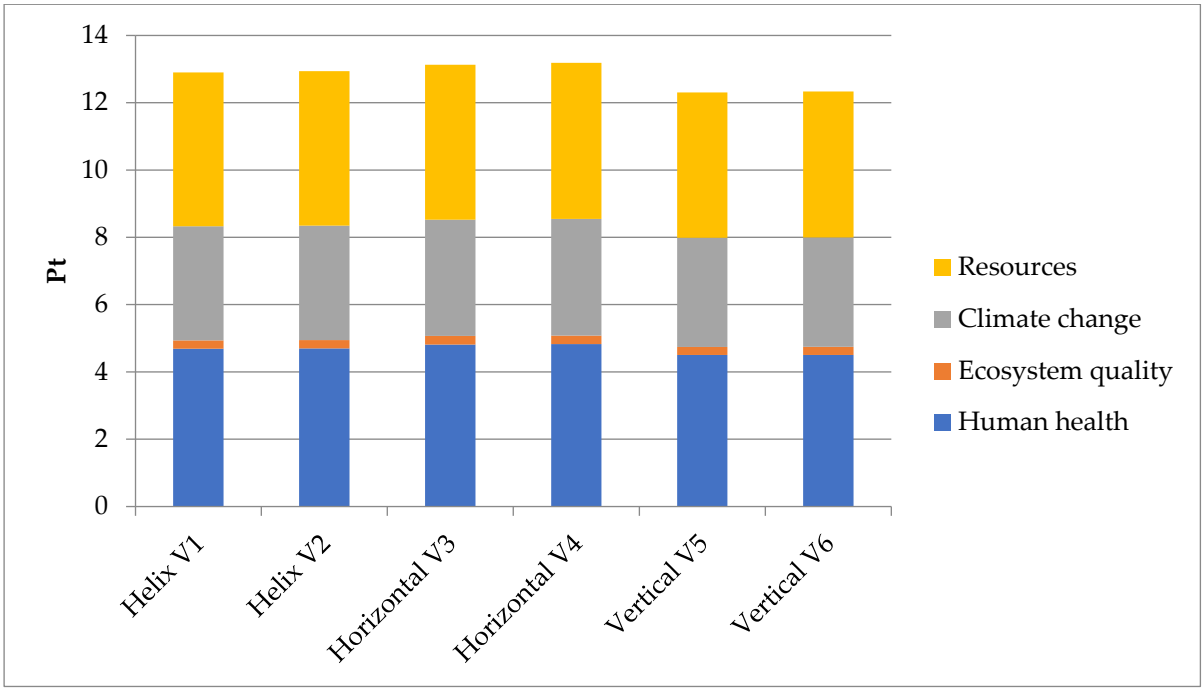


Figure 5. Comparison of the IMPACT 2002+ indicators in damage categories (own elaboration).

In order to assess the reliability of the received results, Monte Carlo analysis was used within the probabilistic model including 1% changes in input values (Table 2). The range of results received in the 90% confidence interval indicates the consistency of the differential trend between horizontal and vertical heat exchangers. The ranges of results obtained for helix heat exchangers overlapped to some extent with the results of the statistical distribution produced by the IMPACT 2002+ indicator for other types of exchangers; therefore, the usefulness of the obtained data when making decisions is limited since V1 and V2 versions are close to both horizontal and vertical heat exchangers.

Table 2. Results of Monte Carlo analysis of single score calculated via IMPACT 2002+ method with 90% confidence interval.

Variant	V1	V2	V3	V4	V5	V6
Type of exchanger	helix	helix	horizontal	horizontal	vertical	vertical
5%	12.540	12.564	12.774	12.828	11.980	11.984
Mean	12.892	12.918	13.118	13.164	12.307	12.324
95%	13.355	13.374	13.550	13.577	12.717	12.805

3.2. LCC Results

Investment costs as well as operation costs were calculated for each proposed variant included in the conducted analyses. The investment costs cover costs of the materials (i.e., heat pump, PE-XA-UV premium pipes for ground exchanger, valves, filters, expansion vessel, brine distributor and distributor manhole) and the costs of construction (borehole/trench). The operation costs cover the costs of energy required for the operation of the heat pumps and circulation pumps in the ground circuits. The investment and annual operation costs as well as the results of the LCC calculations for each proposed variant are presented in Table 3.

Table 3. The comparison of investment costs, annual costs of operation and maintenance and LCC for the analyzed variants.

Variant		V1	V2	V3	V4	V5	V6
Type of exchanger		helix	helix	horizontal	horizontal	vertical	vertical
C_i	Euro	14,490.44	14,350.67	10,386	11,244.89	12,756.44	13,349.11
C_o	Euro	430.22	464.89	438.89	426.67	418.89	409.11
LCC	Euro	24,013.78	24,641.56	20,100.89	20,689.11	22,028.89	22,405.56

According to the results obtained from the calculation, the investment costs related to the V1 and V2 helix ground heat exchangers were the most significant, which is connected with the cost of helix exchanger itself (a prefabricated element consisting of pipes and a special frame). The four other variants (V4–6) with less complex exchangers were less expensive. The difference in investment cost between variants with horizontal (V3–4) and vertical exchangers (V5–6) is caused by the costs of construction, since due to their volume as well as the required equipment and manpower, excavations are generally more expensive for vertical boreholes. The highest operating costs were related to the use of the helix heat exchanger in V2. This is due to the fact that the energy demand for the operation of the brine circulation pump in V2 is higher than in the other variants. The lowest operation costs were reported for V6 due to the lowest pressure losses in the ground circuit and the highest SCOP value achieved by the heat pump—the temperature of the ground in layers deeper than 15 m is stable through the whole year, providing better operation results of the system.

The lowest LCC was obtained for the variants with a horizontal exchanger, specifically for the variant V3 with a smaller pipe diameter, i.e., 32 × 2.9 mm. The vertical exchangers were in the middle of the LCC comparisons, wherein the variant V5 is more preferable due to the smaller pipe diameter (32 × 2.9 mm). As mentioned in the previous paragraph, the difference between horizontal and vertical exchangers is related mainly to the cost of construction. The variants with helix exchangers are characterized by the highest LCC indicators. The greatest value of LCC was observed for V2 where three helix exchangers of larger size were used.

3.3. WSM Results

The results of the MCA comparison for each studied variant of ground heat exchangers are presented in Figure 6.

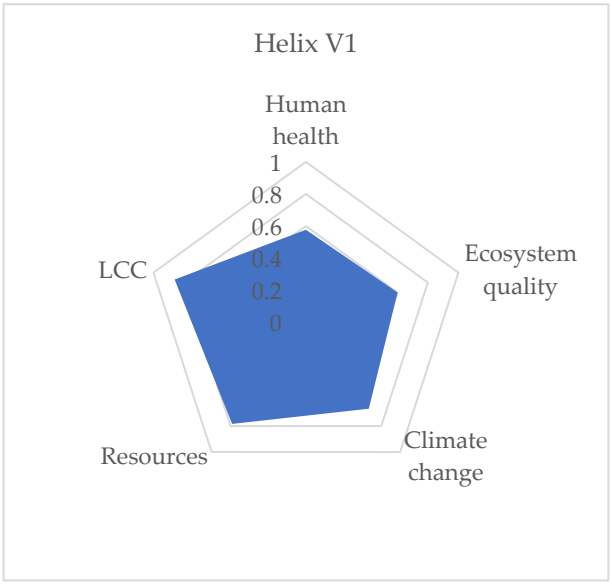
According to the presented radar graphs (Figure 6), based on the normalized a_{ij} indicators, the broadest area of influence can be noticed for the V2 and V1 variants (utilizing a helix heat exchanger) due to the highest costs and relatively high environmental burdens. At the same time, V5 and V6 (variants with a vertical heat exchanger) are represented by the smallest areas, mainly due to the economic criterion.

The final recommendation of a system should be based on the weighted sum indicator A_i, comprising the importance of the selected criteria. The commonly used system is to apply equal weights [48] or 50% weight to the economic criterion [51]. In this paper, the authors decided to use an additional 70% weight for the economic criterion as the "game changer"—the limit value leading to a change in the recommendation and moving it to another solution.

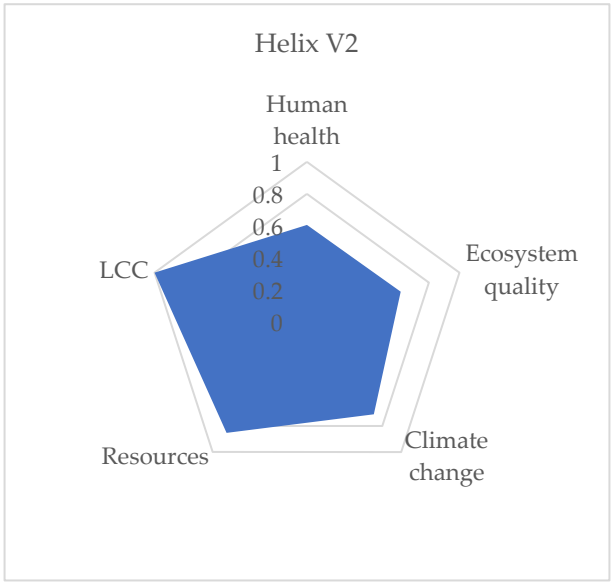
As visible in Figure 7, for both 20% and 50% weights allocated to the economic criterion, V5 and V6 are the recommended options with the lowest environmental burdens and life cycle cost. However, in the case of 70% allocation of weight to the LCC, the horizontal heat exchanger V3 is characterized by the lowest WSM result, which changes the recommendation to this type of exchanger. In most cases, the helix heat exchanger (applied in variants V1 and V2) is characterized by the highest WSM index, compared to V3 and V4 only in the case of the 20% weight scenario.

The results obtained in this part of the study lead to the conclusion that the general type of heat exchanger is more important than other parameters, like the number and length of loops or the diameter of the pipes. It can be easily observed that the differences between types of heat exchangers are more visible, reaching 74% in the case of V4 to V5, compared to a 4% difference between V6 and V5 in the 20% weight scenario. Therefore, the recommended option should be the vertical heat exchanger due to the highest SCOP caused by the temperature of the deep ground layers (lower energy consumption in operation stage), as well as lower material consumption during the construction of the exchanger.

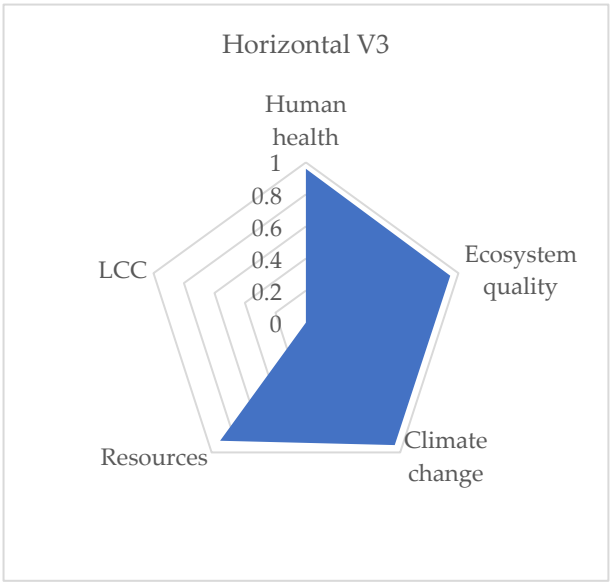
This recommendation varies from the literature [42], where only the construction aspect of ground heat exchangers (GHEs) operating in the same location was analyzed. The focus on the operation stage is crucial for the holistic perspective of LCA results; therefore, the current study supplements the scope of the former analysis with key issues that were not originally fully developed.



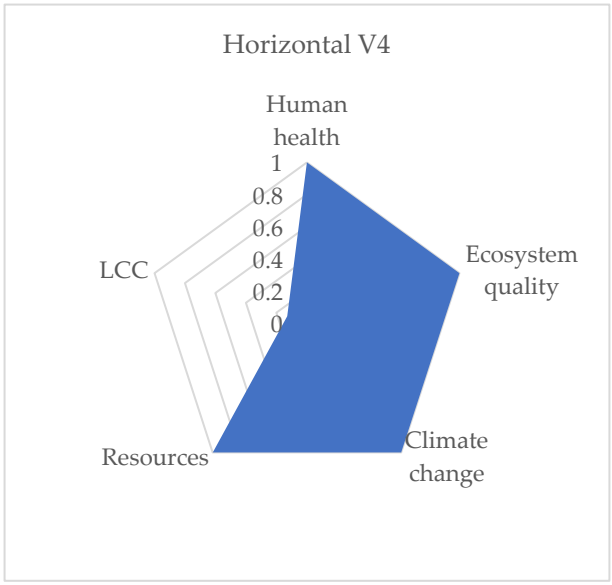
(**a**)



(**b**)

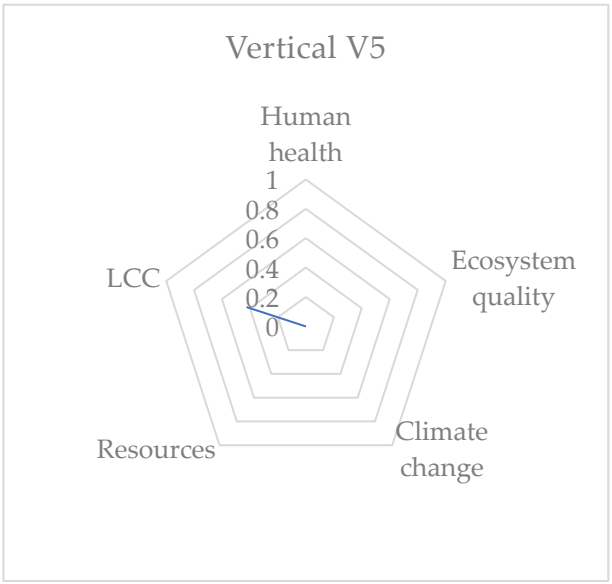


(**c**)

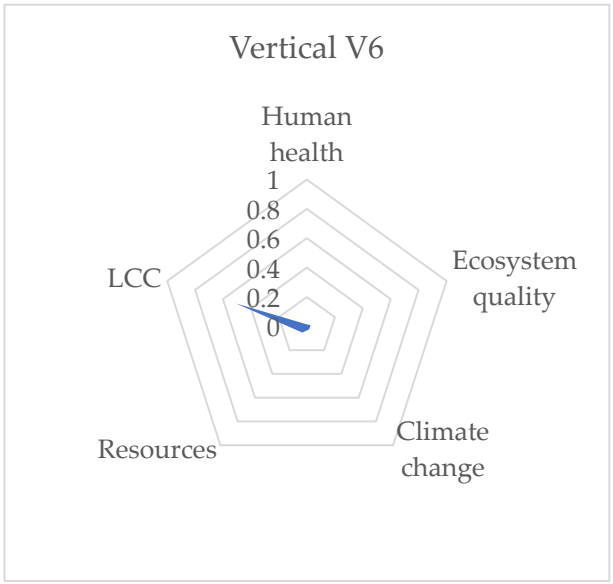


(**d**)

Figure 6. *Cont.*



(**e**)



(**f**)

Figure 6. MCA normalized indicators: (**a**) V1, (**b**) V2, (**c**) V3, (**d**) V4, (**e**) V5, (**f**) V6 (own elaboration).

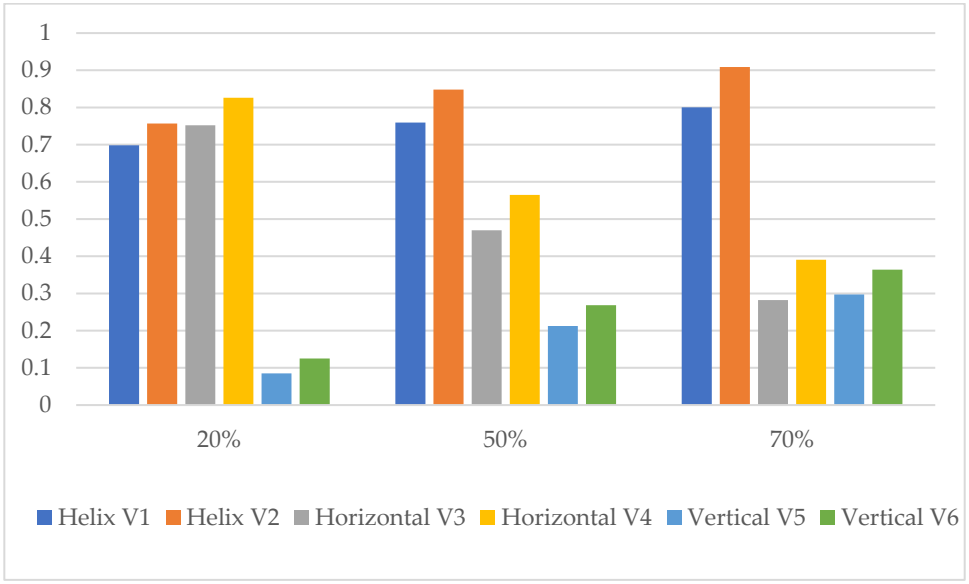


Figure 7. MCA weighted indicators in three variants of weights (20%, 50%, 70%) allocated to the economic criterion LCC (own elaboration).

Another study on LCA of the several configurations of GHEs can be found in [52], where an ASHP is compared to six variants of horizontal and vertical heat exchangers used by a GSHP in Cyprus. As in the current study, the systems' operation processes had the highest contribution (at least 83%) to the impact indicators calculated via the Ecoinvent'99 method (the precursor of the IMPACT 2002+ method); hence, the higher the efficiency of the system, the lower the impact indicators. Therefore, the GSHP analyzed in this paper has an advantage over ASHP due to the COP of the device. However, it has to be emphasized that the authors based their calculation on the catalogue COP given by producer and did not include any changes in soil temperature nor the air temperature changes. Therefore, the recommendation of a horizontal type heat exchanger cannot be treated as exhaustive, because it does not take into account the soil temperature profile or its influence on the seasonal performance of the heat pump.

It should be emphasized that the type of heat exchanger and its temperature are not the only parameters influencing the energy efficiency of GSHP. Within this study, the authors focused on the mentioned parameters, while the temperature of the upper heat source was constant. Changes in the type of installation supplied by GSHP, i.e., the introduction of surface heating with lower supply temperatures, should also be examined, since its influence on the overall COP is also important and leads to energy savings. What is more, LCA was performed on the basis of the selected location in Poland and the specific soil profile composition and its moisture conditions. Further analyses should cover more locations, both in the case of the dimensions of ground heat exchangers and the type of energy mix used in the life cycle inventory, so that the results can be more widely applicable.

4. Conclusions

Heat pumps powered by geothermal energy are a commonly known and modern solution for providing a heat source. Although they have been available on the market for a long time, not all of the construction elements have yet been carefully analyzed and discussed. One of the important factors affecting the operation stage of a heat pump is the kind of geothermal heat exchanger used in the system, which may be built in several manners. Within the presented paper, the authors analyzed the influence of the ground source heat exchanger type on the life cycle environmental and economic performance of the heat pump. The highest results in the environmental assessment are reported for variants with horizontal heat exchangers (V4 and V3) due to the lowest temperature of the lower heat source. The lowest value of the IMPACT 2002+ indicator was reported for the vertical heat exchanger (V5) due to its small material consumption and high SCOP based on the ground temperatures. The possible environmental benefits in the case of the selection of V5 was estimated to be 6.66% of the total environmental impact measured by the IMPACT 2002+ indicator. The most important life cycle stage is operation, responsible for up to 96% of this score for vertical heat exchangers (V5 and V6).

In the case of LCC, the best results were achieved for variants with horizontal heat exchangers (V3 and V4) as the heat exchanger is not complex and is located in relatively shallow layers of the ground, therefore the required construction operations are not costly. Nevertheless, in many cases, there is not the available space required for the construction of the horizontal exchanger. When the building plot area is limited, vertical exchangers or helix exchangers can be selected. The implementation of horizontal exchangers is associated with obtaining better results in terms of LCC.

The final recommendation of a system was based on the weighted sum indicator, comprising the importance of selected criteria (between 20% and 70% for economic criterion). According to the results obtained, the vertical type of heat exchanger V5 is the recommended option in most scenarios. In future research, more attention should be paid to the location and type of the system, as well as issues like the kind of refrigerant, which is subject to the restrictions of the European Union and can lead to serious changes in the heat pump market.

Author Contributions: Conceptualization, A.Ż. and J.G.; methodology, A.Ż., D.K. and J.G.; software, A.Ż. and D.K.; validation, A.Ż. and J.G.; formal analysis, A.Ż. and J.G.; investigation, A.Ż., D.K. and J.G.; data curation, A.Ż.; writing—original draft preparation, A.Ż. and J.G.; writing—review and editing, A.Ż. and J.G.; visualization, A.Ż. and J.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by internal project of Lublin University of Technology, Poland number FN-20.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

ASHP	Air source heat pump
COP	Coefficient of Performance
GHE	Ground heat exchanger
GHG	Greenhouse gases
GSHP	Ground source heat pump
HP	Heat pump
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCC	Life Cycle Cost
MCA	Multi-criteria analysis
PE-XA-UV	Cross linked polyethylene pipe with an anti-UV layer
Pt	Points
PV	Photovoltaic
SCOP	Seasonal Coefficient of Performance

References

1. Ahmed, N.; Khan, T.I.; Augustine, A. Climate change and environmental degradation: A serious threat to global security. *Eur. J. Soc. Sci.* **2018**, *3*, 161–172. [CrossRef]
2. Fawzy, S.; Osman, A.I.; Doran, J.; Rooney, D.W. Strategies for mitigation of climate change: A review. *Environ. Chem. Lett.* **2020**, *18*, 2069–2094. [CrossRef]
3. European Commission. A European Green Deal. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal (accessed on 5 November 2023).
4. Leibowicz, B.D.; Lanham, C.M.; Brozynski, M.T.; Vázquez-Canteli, J.R.; Castejón, N.C.; Nagy, Z. Optimal decarbonization pathways for urban residential building energy services. *Appl. Energy* **2018**, *230*, 1311–1325. [CrossRef]
5. Berrill, P.; Wilson, E.J.; Reyna, J.L.; Fontanini, A.D.; Hertwich, E.G. Decarbonization pathways for the residential sector in the United States. *Nat. Clim. Chang.* **2022**, *12*, 712–718. [CrossRef]
6. Elavarasan, R.M.; Pugazhendhi, R.; Irfan, M.; Mihet-Popa, L.; Khan, I.A.; Campana, P.E. State-of-the-art sustainable approaches for deeper decarbonization in Europe–An endowment to climate neutral vision. *Renew. Sustain. Energy Rev.* **2022**, *159*, 112204. [CrossRef]
7. International Renewable Energy Agency (IRENA). Available online: https://www.irena.org/Innovation-landscape-for-smart-electrification/Power-to-heat-and-cooling/Status (accessed on 12 November 2023).
8. Güneralp, B.; Zhou, Y.; Ürge-Vorsatz, D.; Gupta, M.; Yu, S.; Patel, P.L.; Fragkias, M.; Li, X.; Seto, K.C. Global scenarios of urban density and its impacts on building energy use through 2050. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 8945–8950. [CrossRef] [PubMed]
9. Connolly, D.; Lund, H.; Mathiesen, B.V. Smart energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1634–1653. [CrossRef]
10. Yan, H.; Wang, R.; Zhang, C.; Xu, Z.; Hu, B.; Shao, Z. The role of heat pump in heating decarbonization for China carbon neutrality. *Carbon Neutrality* **2022**, *1*, 40. [CrossRef]
11. Dong, S.; Zhao, H.; Zheng, Y.; Ni, L. Carbon reduction analysis of electric heat pumps in carbon neutrality in China. *Sustain. Cities Soc.* **2023**, *97*, 104758. [CrossRef]
12. Borge-Diez, D.; Icaza, D.; Trujillo-Cueva, D.F.; Açıkkalp, E. Renewable energy driven heat pumps decarbonization potential in existing residential buildings: Roadmap and case study of Spain. *Energy* **2022**, *247*, 123481. [CrossRef]
13. Witkowska, A.; Krawczyk, D.A.; Rodero, A. Analysis of the Heat Pump Market in Europe with a Special Regard to France, Spain, Poland and Lithuania. *Environ. Clim. Technol.* **2021**, *25*, 840–852. [CrossRef]
14. International Energy Agency (IEA). Available online: https://www.iea.org/commentaries/global-heat-pump-sales-continue-double-digit-growth (accessed on 12 November 2023).
15. European Heat Pump Association (EHPA). Available online: https://www.ehpa.org/2023/02/08/ehpa_news/port-pc-2022-was-the-year-of-heat-pumps-in-poland/ (accessed on 15 November 2023).
16. Valancius, R.; Singh, R.M.; Jurelionis, A.; Vaiciunas, J. A review of heat pump systems and applications in cold climates: Evidence from Lithuania. *Energies* **2019**, *12*, 4331. [CrossRef]
17. Sewastianik, S.; Gajewski, A. Energetic and ecologic heat pumps evaluation in Poland. *Energies* **2020**, *13*, 4980. [CrossRef]
18. Wang, Z.; Wang, F.; Ma, Z.; Wang, X.; Wu, X. Research of heat and moisture transfer influence on the characteristics of the ground heat pump exchangers in unsaturated soil. *Energy Build.* **2016**, *130*, 140–149. [CrossRef]
19. Noorollahi, Y.; Saeidi, R.; Mohammadi, M.; Amiri, A.; Hosseinzadeh, M. The effects of ground heat exchanger parameters changes on geothermal heat pump performance—A review. *Appl. Therm. Eng.* **2018**, *129*, 1645–1658. [CrossRef]
20. Li, B.; Han, Z.; Bai, C.; Hu, H. The influence of soil thermal properties on the operation performance on ground source heat pump system. *Renew. Energy* **2019**, *141*, 903–913. [CrossRef]

21. Torres-Rodríguez, A.; Morillón-Gálvez, D.; Aldama-Ávalos, D.; Morales-Ramírez, J.D.; Kerdan, I.G. Predicting the thermal behaviour of sands considering its moisture content and grain size with applications to geothermal heat pump installations. *Energy Build.* **2019**, *194*, 85–104. [CrossRef]
22. Çetin, G.; Özkaraca, O.; Keçebaş, A. Development of PID based control strategy in maximum exergy efficiency of a geothermal power plant. *Renew. Sust. Energy Rev.* **2021**, *137*, 110623. [CrossRef]
23. Liu, Z.; Du, Y.; Song, C.; Yang, X.; Yan, J. Effect of soil moisture content on thermal performance of ground source heat exchangers: An electromagnetism topology-based analysis. *Energy Rep.* **2023**, *10*, 3914–3928. [CrossRef]
24. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
25. Gundes, S. The use of life cycle techniques in the assessment of sustainability. *Procedia Soc. Behav. Sci.* **2016**, *216*, 916–922. [CrossRef]
26. Bonamente, E.; Aquino, A. Life-cycle assessment of an innovative ground-source heat pump system with upstream thermal storage. *Energies* **2017**, *10*, 1854. [CrossRef]
27. Biglarian, H.; Saidi, M.H.; Abbaspour, M. Economic and environmental assessment of a solar-assisted ground source heat pump system in a heating-dominated climate. *Int. J. Sci. Environ. Technol.* **2019**, *16*, 3091–3098. [CrossRef]
28. Smith, M.; Bevacqua, A.; Tembe, S.; Lal, P. Life cycle analysis (LCA) of residential ground source heat pump systems: A comparative analysis of energy efficiency in New Jersey. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101364. [CrossRef]
29. Eguiarte, O.; Garrido-Marijuán, A.; de Agustín-Camacho, P.; del Portillo, L.; Romero-Amorrortu, A. Energy, environmental and economic analysis of air-to-air heat pumps as an alternative to heating electrification in Europe. *Energies* **2020**, *13*, 3939. [CrossRef]
30. Panagiotidou, M.; Aye, L.; Rismanchi, B. Alternative Heating and Cooling Systems for the Retrofit of Medium-Rise Residential Buildings in Greece. *Energy Technol.* **2021**, *9*, 2100377. [CrossRef]
31. Violante, A.C.; Donato, F.; Guidi, G.; Proposito, M. Comparative life cycle assessment of the ground source heat pump vs air source heat pump. *Renew. Energy* **2022**, *188*, 1029–1037. [CrossRef]
32. Sewastianik, S.; Gajewski, A. An Environmental Assessment of Heat Pumps in Poland. *Energies* **2021**, *14*, 8104. [CrossRef]
33. Miralles, J.A.L.; García, R.L.; Carnicero, J.M.P.; Martínez, F.J.R. Comparative study of heat pump system and biomass boiler system to a tertiary building using the Life Cycle Assessment (LCA). *Renew. Energy* **2020**, *152*, 1439–1450. [CrossRef]
34. Lin, H.; Clavreul, J.; Jeandaux, C.; Crawley, J.; Butnar, I. Environmental life cycle assessment of heating systems in the UK: Comparative assessment of hybrid heat pumps vs. condensing gas boilers. *Energy Build.* **2021**, *240*, 110865. [CrossRef]
35. Sevindik, S.; Spataru, C.; Domenech Aparisi, T.; Bleischwitz, R. A comparative environmental assessment of heat pumps and gas boilers towards a circular economy in the UK. *Energies* **2021**, *14*, 3027. [CrossRef]
36. Naumann, G.; Schropp, E.; Gaderer, M. Life cycle assessment of an air-source heat pump and a condensing gas boiler using an attributional and a consequential approach. *Procedia CIRP* **2022**, *105*, 351–356. [CrossRef]
37. Nitkiewicz, A.; Sekret, R. Comparison of LCA results of low temperature heat plant using electric heat pump, absorption heat pump and gas-fired boiler. *Energy Convers. Manag.* **2014**, *87*, 647–652. [CrossRef]
38. Famiglietti, J.; Toppi, T.; Pistocchini, L.; Scoccia, R.; Motta, M. A comparative environmental life cycle assessment between a condensing boiler and a gas driven absorption heat pump. *Sci. Total Environ.* **2021**, *762*, 144392. [CrossRef]
39. Riva, C.; Roumpedakis, T.C.; Kallis, G.; Rocco, M.V.; Karellas, S. Life cycle analysis of a photovoltaic driven reversible heat pump. *Energy Build.* **2021**, *240*, 110894. [CrossRef]
40. Marinelli, S.; Lolli, F.; Butturi, M.A.; Rimini, B.; Gamberini, R. Environmental performance analysis of a dual-source heat pump system. *Energy Build.* **2020**, *223*, 110180. [CrossRef]
41. Li, H.; Bi, Y.; Qin, L.; Zang, G. Absorption solar-ground source heat pump: Life cycle environmental profile and comparisons. *Geothermics* **2020**, *87*, 101850. [CrossRef]
42. Żelazna, A.; Kosaryha, D. The influence of the type of heat exchanger on the environmental and economic efficiency of brine-to-water heat pump. *AIP Conf. Proc.* **2023**, *2887*, 020016. [CrossRef]
43. *PN-EN 12831-1:2017-08*; Energy Performance of Buildings—Method for Calculating the Design Thermal Load—Part 1: Thermal Load, Module M3-3. PKN: Warsaw, Poland, 2017.
44. Available online: https://portpc.pl (accessed on 10 September 2023).
45. Available online: http://www.wp-opt.pl/walidacja.html (accessed on 26 September 2023).
46. Jolliet, O.; Margni, M.; Charles, R.; Humbert, S.; Payet, J.; Rebitzer, G.; Rosenbaum, R. IMPACT 2002+: A new life cycle impact assessment methodology. *Int. J. LCA* **2003**, *8*, 324. [CrossRef]
47. Lee, M.; Ham, S.H.; Lee, S.; Kim, J.; Kim, Y. Multi-objective optimization of solar-assisted ground-source heat pumps for minimizing life-cycle cost and climate performance in heating-dominated regions. *Energy* **2023**, *270*, 126868. [CrossRef]
48. Shaaban, M.; Scheffran, J.; Böhner, J.; Elsobki, M.S. Sustainability Assessment of Electricity Generation Technologies in Egypt Using Multi-Criteria Decision Analysis. *Energies* **2018**, *11*, 1117. [CrossRef]
49. Rey Martínez, F.R.; Velasco Gómez, E.; Navas García, L.M.; Sanz Requena, J.F.; Navas Gracia, L.M.; Hernández Navarro, S.; Correa Guimaraes, A.; Martín Gil, J. Life cycle assessment of a semi-indirect ceramic evaporative cooler vs. a heat pump in two climate areas of Spain. *Appl. Energy* **2011**, *88*, 914–921. [CrossRef]
50. Aresti, L.; Florides, G.A.; Skaliontas, A.; Christodoulides, P. Environmental Impact of Ground Source Heat Pump Systems: A Comparative Investigation From South to North Europe. *Front. Built Environ.* **2022**, *8*, 914227. [CrossRef]

51. D'Agostino, D.; Parker, D.; Melià, P. Environmental and economic implications of energy efficiency in new residential buildings: A multi-criteria selection approach. *Energy Strategy Rev.* **2019**, *26*, 100412. [CrossRef]
52. Aresti, L.; Christodoulides, P.; Florides, G.A. An investigation on the environmental impact of various Ground Heat Exchangers configurations. *Renew. Energy* **2021**, *171*, 592–605. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.