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Primary Energy Resources and Environmental Impacts of Various Heating Systems Based on Life Cycle Assessment

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Abstract: This paper utilizes a life cycle assessment (LCA) to evaluate three heating systems' energy resources and environmental impacts. The first system uses an electric heat pump that exclusively relies on geothermal energy. The second system operates on a gas boiler system that utilizes non-renewable electricity and natural gas. Lastly, the third system incorporates an absorption heat pump utilizing geothermal energy and natural gas. In the first step, cradle-to-gate assessments were prepared for the renewable, conventional, and mixed systems. The second step involved comparing the system scenarios based on their loads and energy resources. Primary energy, material resources, emissions, and impact categories were normalized and weighted using the CML, ReCiPe, and EF 3.0 methods. Finally, models for environmental reliability and complex decision support were developed. The novelty of this research lies in analyzing the ecological burden and energy usage of a mixed energy system that incorporates both renewable and non-renewable energy sources. The results show that the gas boiler system has a higher load, primarily due to the depletion of abiotic fossil fuels. However, the acidification is higher when an electric heat pump is used. The absorption heat pump system falls between the renewable and conventional systems in terms of both fossil depletion and acidification.

Keywords: heating systems; life cycle assessment; environmental impact; primary energy; environmental reliability model; complex decision-support model

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1. Introduction

1.1. Research Background

Today's global concerns are energy supply difficulties caused by the energy crisis, escalating energy costs, growing environmental impacts from fossil fuels and greenhouse gases, and sustainability compliance. Given the development targets for reducing greenhouse gas emissions, there is an increasing need today to utilize renewable energy sources [1]. In recent years, there has been a significant interest within the scientific community in utilizing renewable energy sources and integrating both renewable and non-renewable energy systems. This interest has also extended to the construction industry in Europe, as this sector is responsible for most greenhouse gas emissions, accounting for nearly 40% of global energy consumption [2]. Considering this, it is essential to highlight the regulations for nearly zero-energy buildings (nZEBs). The number of studies on near-zero-energy buildings [3–5] has increased dramatically, indicating a shared vision and commitment to zero-emission buildings. For example, Moran et al. [3] investigated the optimal retrofit packages for improving thermal efficiency and reducing the energy demand of gas-fired homes, taking into consideration the significant role of the Irish electricity mix. The essential aspects of nZEBs include a high heating performance, efficient energy system installation, and the application of renewable energy sources [4]. According to the European Union (EU), only buildings that meet near-zero energy requirements will be eligible to obtain a building permit starting in 2021 [6].

A building that does not meet the nZEB requirements may consume significantly more energy during its operation. Regardless of the energy source used to meet the eergy demand, a near-zero-energy building improves and enhances the efficiency of mechanical systems. This leads to a lower overall energy performance rating and increased utilization of renewable energy. This contrasts with a facility that only meets cost-optimized expectations. At the COP27 Conference (27th Conference of the Parties to the United Nations Framework Convention on Climate Change) in November 2022 in Sharm-el-Sheikh, Egypt, WorldGBC emphasized energy efficiency's importance in addressing lifecycle CO_2 emissions [7] while highlighting additional solutions. Therefore, applying a lifecycle-based holistic methodology is essential throughout the whole lifecycle of buildings.

Many environmental indicators have been developed for assessing a building's sustainability and measuring its performance throughout its lifecycle [4]. Since energy efficiency and environmental impact are crucial considerations throughout the life cycle of buildings, especially during the operation and use phases, it is essential to compare different heating systems using LCA and to develop comprehensive models. Based on a life cycle approach, accurate engineering models can be created to reduce the environmental impact of energy systems while meeting the necessary primary energy demand for heating in the residential and industrial sectors [8].

This research study falls within the context of energy efficiency and environmental impact in the life cycle approach. It compares three heating systems. The first examined system utilizes pure renewable energy inputs from geothermal sources. The second system relies solely on non-renewable energy inputs, specifically electricity from the public grid in Hungary and natural gas. The third system combines renewable and non-renewable sources, utilizing geothermal energy and natural gas. The novelty of the research lies in conducting life cycle assessments to analyze the parallel environmental impacts and primary energy resources.

1.2. The Literature Review

Ground-source heat pumps (GSHPs) are a popular renewable energy technology used for heating buildings. This technology is attractive and widely used in many countries worldwide [9–12]. The GSHP system is highly efficient, with lower energy consumption and CO_2 emissions (up to 80%) during its lifecycle compared to other systems, such as natural gas-GF systems [9]. In Canada, geothermal heat pumps have effectively reduced energy consumption, emissions, and economic costs for households, small businesses, and large commercial enterprises [10]. In Cyprus, a comparison was made between GSHPs and conventional systems for single- and multi-family reference buildings. The results, in terms of energy consumption, favored GSHPs [11].

Energy consumption varies from 1% to 7.3% in hot climates, from 18.4% to 23.5% in temperate climates, and reaches 33.6% in cold climates. Regarding carbon emissions from single-family homes, the use of ground-source heat pumps instead of conventional systems has resulted in a decrease of from 19% to 24% in carbon emissions. For multi-family homes, carbon emission results vary by climate, with the highest increase reaching 10%. It was 5% in the Saittas region, and the lowest reduction was −4.7% in the temperate Nicosia region [11]. In Spain, the use of a GSHP (ground-source heat pump) reduced carbon dioxide emissions into the atmosphere by approximately 54.3% compared to a conventional heating system, specifically a diesel boiler [12]. In China, the acidification, eutrophication, and global warming potentials of the life cycle phases of GSHPs were calculated and assessed. Approximately 16 RMB/m^2 was spent on pollution prevention during the production phase, while 5 RMB/m^2 was spent during the operational phase. The type of residential building and the atmospheric climate also influence the energy, environmental, and economic impacts of GSHP systems [13].

Earth–air heat exchangers (EAHXs), which utilize geothermal energy, are sustainable and renewable systems that produce no greenhouse gas emissions. EAHXs have a remarkable ability to provide indoor thermal comfort and save primary energy. Several studies [14–17] have reported that ground-source heat pumps significantly reduce greenhouse gas emissions as renewable energy technologies improve the electricity mix. According to a study conducted by Tariq et al. [15], annual CO_2 emissions were reduced by 2878 tons compared to natural gas, 4883 tons compared to fuel oil, and 6646 tons compared to coal. In addition to improving the electricity mix, an EAHX allows for drilling wells and laying pipes in the ground, resulting in minimal environmental impacts during the construction phase [15,16]. Furthermore, an EAHX does not use refrigerants [17].

Comparative studies [18,19] have been conducted to compare traditional and sustainable technical heating systems based on the results of life cycle assessments. A research study conducted in the United States [18] compared gas boilers to air-source, ground-source, and water-source heat pumps (ASHPs, GSHPs, and WSHPs) for residential buildings. The results showed that heat pumps have a greater environmental impact than gas boilers because they consume electricity. However, if the energy mix is sufficiently decentralized, the life cycle impacts of heat pumps could be improved.

In a study conducted by researchers from Mexico and Norway [19], the performance of an electric heat pump, an absorption heat pump, and natural gas boilers was compared. According to the results, the absorption heat pump had a lower environmental impact than the electric heat pump. Although gas boilers have significant environmental impacts, they pose less risk to human health. According to a study by Greening et al. [20], heat pumps have a greater environmental impact than gas boilers. APS and WSPS are 73% higher, and ASPS is 82% higher than a conventional boiler system. However, this study excluded certain environmental categories, including global warming, fossil resource depletion, and the impacts of summer smog. These categories are considered less relevant for heat pumps compared to boilers. Nitkiewicz and Sekret [21] evaluated the environmental life cycle of three heating systems by utilizing the Ecoinvent database. The tested heating systems included an electric heat pump (water–water), an absorption heat pump (water–water), and a natural gas boiler. The researchers discovered that all the heat pumps drew their heat from the ground below 20 degrees Celsius. According to the results of this study, the electric heat pump had a higher environmental impact than the absorption heat pump. In contrast, the gas boiler had the greatest environmental impact. These results are practically identical to those of the Mexican–Norwegian study [19].

Another study [22] from Germany compared an ASHP with a gas-condensing boiler. The study found that eight out of the eleven analyzed environmental impact categories showed significant environmental consequences. The main reason was the electricity consumption of the ASHP. In contrast, the primary sources of emissions from gas condensing boilers are the production and combustion of natural gas. This study also found that the modelling approach did not influence the overall trend of the environmental impacts of the ASHP and CGB. However, it was observed that the global warming potential of ASHPs is only one-third of that of gas-condensing boilers.

Sevindik et al. [23] compared the potential environmental impacts of heat pumps and gas boilers and conducted a life cycle analysis for three scenarios: a circular economy, resource efficiency, and limited growth. Their results showed that the use and production phases were responsible for an average of 74% and 14% of the total environmental impact, respectively. The circular economy scenario showed a 44% reduction in heat pumps and a 27% reduction in gas boilers.

In Gaziantep, Turkey, an environmental study [24] was conducted on three residential heating systems: coal, gas, and a geothermal heat pump. Regarding the environmental impact, the geothermal heat pump system had the least significant impact. This was due to the production of copper and R134a refrigerant during the construction phase, the production of polyethylene pipes, and the drilling of wells during the installation phase, as well as the process of maintaining and charging the refrigerant in the use phase.

Although there is already a substantial amount of literature on this research topic, very few cases explicitly link the results of LCA calculations to energy efficiency by comparing different heating systems. At the same time, the heating system of each building must now be investigated using three-dimensional models. This means that the ecological aspect must also be considered. Kim et al. [25] designed survey items to assess business activities and energy consumption in hospital buildings as well as to develop an energy benchmark. Lee et al. [26] conducted calculations to forecast the ideal maintenance intervals for air-conditioning units. They found that the energy consumption of these units increased by approximately 41% in the 15th year compared to the initial energy consumption.

Bolteya et al. [27] conducted a study on the energy savings of buildings by utilizing thermal insulation materials for the building envelope. However, their research specifically focused on reducing energy consumption for cooling purposes. Banks et al. [28] reported the results of their research on heat-pump water-heating systems. Of interest is the research conducted by Zhang et al. [29], which compares the primary energy consumption, environmental impact, and heating costs of coal-fired and wall-fired gas boiler heating systems, direct electric heating systems, and air-source heat pump systems using a life cycle analysis. The study by AlAli et al. [30] exclusively focused on the United Arab Emirates and examined the energy efficiency of mosque buildings.

In Minnesota, a comprehensive analysis [31] was conducted comparing geothermal systems with conventional methods such as gas boilers and air conditioners. The analysis was based on a life cycle assessment. Different scenarios for geothermal systems were tested. Most scenarios had a lower carbon footprint. In a research study by Shirazi and Ashuri [32], life cycle assessments were conducted for buildings requiring retrofit measures. The main results of this study showed that retrofitting the thermal system had the greatest environmental impact. The results showed that for buildings constructed before the 1970s, the time required to recover grey energy ranged from 5 to 3 years, whereas for buildings constructed after the 1970s, it ranged from 1.6 to 3.2 years. In Italy, the ENEA Casaccia Research Centre compared an experimental GSHP (ground-source heat pump) geothermal system with a conventional ASHP (air-source heat pump) system for a life cycle comparison. The SimaPro 9.0 software was used to assess the environmental impacts on the four damage criteria at each stage of the entire life cycle (manufacturing, installation, commissioning, and end-of-life) in accordance with ISO standards. Compared to other ASHP systems, the GSHP system had more significant impacts during production and installation. On the other hand, the operational phase of the ASHP system showed slightly higher impacts [33].

Asdrubali and Grazieschi [34] argue that in order to decrease the operational energy of systems, it is necessary to increase the utilization of grey systems. These systems have the ability to generate the necessary energy required to achieve improved energy efficiency in buildings. Non-renewable primary energy can be reduced by 63% and greenhouse gas emissions by 60% if a comprehensive life cycle assessment of thermal systems is conducted. The most important factors for evaluating thermal systems from an environmental and economic perspective are, on the one hand, the regional electricity fuel mix, and, on the other hand, fluctuating energy prices. From a life cycle energy perspective, a low-energy design of an autonomous building outperformed a near-zero-energy building when various configurations of different building designs were tested in a case study conducted in the Italian context [35]. A new study [36] conducted in Poland analyzed the source of heat (geothermal energy) and the technical and economic market in the country. The goal was to verify the feasibility of building a dual power station that operates on low-temperature geothermal resources in Poland. The study yielded promising results. The study also confirmed that conducting an economic analysis is necessary for the next step to determine the most suitable location for constructing a power station in Poland. Table 1 provides a comprehensive summary of the reviewed literature. This comprehensive table primarily focuses on renewable and conventional primary energy sources. It includes information on environmental and energy analyses related to the literature.

Table 1. Previous studies related to renewable and conventional primary energy sources.

Authors	Ref. Number	Renewable Energy Sources	Country	Conventional Energy Sources	Environmental Impact Analysis	Energy Analysis
Huang, B. and Mauerhofer, V.	[11]	geothermic	Cyprus	n. gas	yes	yes
Michopoulos, A. et al.	[12]	geothermic	Spain	n. gas	yes	no
Bristow, D. and Kennedy, C.	[13]	geothermic	China	n. gas	yes	yes
Tariq, S. et al.	[15]	solar energy	Korea	coal, fuel oil, and n. gas	yes	yes
Milousi, M. et al.	[16]	geothermic	Greece	-	yes	no
Clark, C. et al.	[18]	geothermic, thermal water	USA	n. gas, electricity	yes	yes
Martínez-Corona, J.I. et al.	[19]	-	Norway and Mexico	n. gas, electricity	yes	no
Greening, B. and Azapagic, A	[20]	-	United Kingdom	n. gas, electricity	yes	no
Nitkiewicz, A. and Sekret, R.	[21]	thermal water	Poland	n. gas, electricity	yes	no
Naumann, G. et al.	[22]	-	Germany	n. gas, electricity	yes	no
Sevindik, S. et al.	[23]	-	United Kingdom	n. gas, electricity	yes	yes
Abusoglu, A. and Sedeeq, M.S	[24]	-	Türkiye	electricity, coal, n. gas	yes	no
Kim, H. et al.	[25]	-	Korea	electricity	no	yes
Lee, J.-H. et al.	[26]	-	Korea	electricity	no	yes
Bolteya, A. et al.	[27]	phase-change materials	Cairo	-	no	yes
Zhang, Z. et al.	[29]	-	China	electricity, n. gas, coal	yes	yes
AlAli, M. et al.	[30]	-	UAE	-	no	yes
Li, Mo.	[31]	geothermic	Munsta, Canada	n. gas, electricity	yes	yes
Asdrubali, F. and Grazieschi, G.	[34]	-	Italy	n. gas, electricity	yes	yes
Ziółkowski, P. et al.	[36]	geothermic	Poland	-	yes	yes

There has been a lot of discussion in European Union countries over the past five years regarding the need to increase the number of buildings with near-zero energy demand, retrofit existing buildings, and evaluate the life cycle stages of buildings [37]. The research results of Asdrubali et al. [38] show that buildings converted into near-zero-energy buildings have a shorter environmental recovery time throughout their life cycle.

1.3. Research Aims

Through life cycle assessment, an investigation was conducted on three thermal engineering systems considering inputs of both renewable and non-renewable energy. The systems selected for analysis are well-known and commonly found in households.

The primary objective of these research paper is to quantify and compare the environmental impact and primary energy resources of renewable and non-renewable thermal systems. Since building design, construction, operation, and building energy regulations have constantly changed over the past decade, the first step involved reviewing various reports [1,6,7] on environmental impacts and the professional literature on nZEB buildings.

In the second step, a life cycle assessment of an office building was conducted to estimate the primary energy and measurable environmental impact values for two heat pump systems (electric and absorption) using pure geothermal and combined energy inputs. Additionally, the values for a gas boiler system (using natural gas and electricity) were also estimated. The numerical results of the applied life cycle assessment were evaluated to identify areas for intervention.

In addition, a model for assessing environmental reliability and a complex three-point decision-support model (which incorporates environmental, energy, and economic factors) were developed.

The reason for conducting this research is that consumers are increasingly seeking more advanced, environmentally friendly, and cost-effective home heating systems amidst the current energy crisis.

2. Materials and Methods

2.1. Life Cycle Assessment Method and System Boundary

The applied LCA method was based on the descriptions of the ISO 14040:2006 and 14044:2006 standards [39,40], which include the life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation phases. The life cycle models allowed for the assessment of the environmental impacts and primary energy resources associated with heating a 110 kW information technology building. The cradle-to-gate assessments included energy supply, transportation, energy generation, and energy use in operations. Figure 1 shows the phases of the life cycle assessment.

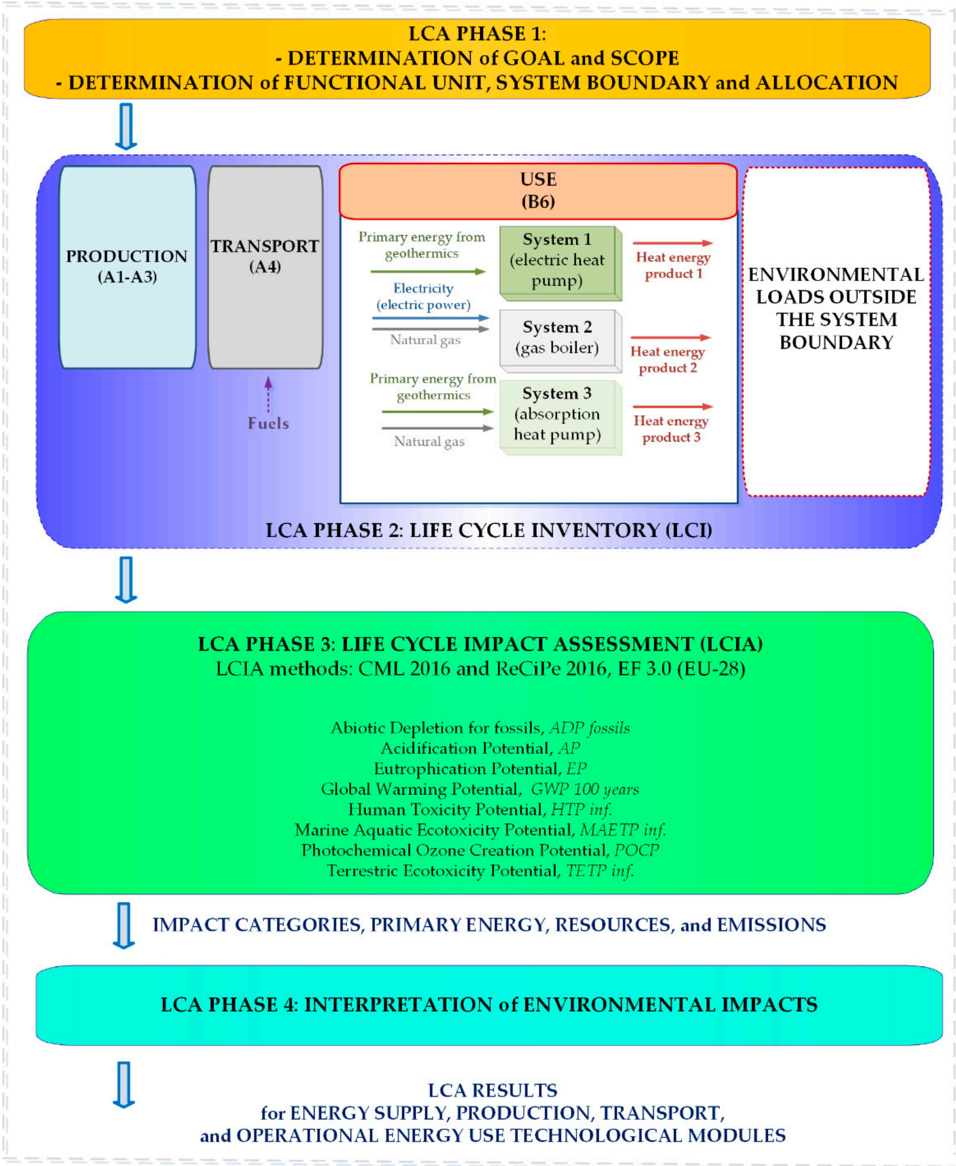

Figure 1. The phases of the life cycle assessment.

The scope of the LCA method included creating life cycle models for three different heating systems, covering the entire life cycle from cradle to gate. System 1 utilizes an electric heat pump and harnesses clean geothermal energy. System 2 operates by utilizing a gas boiler as well as injecting electricity and gas. System 3 operates with an absorption heat pump, which utilizes both electricity and gas as input energy sources. The system boundary of the LCA extended from energy provision, energy transport, and energy generation to operational energy use. The modules included in this boundary were A1-A4 and B6. The system boundary did not include the environmental and energy impacts of the entire operation and maintenance module of the heating system. The selection of values and the conditions for the use of optional elements were developed based on national and EU regulations. Figure 2 shows the system boundary of the LCA. One of the critical points of the analysis was that the analysis did not cover the B7 module, so we calculated water use values in the impact assessment phase by applying the EF 3.0 method. It can also be mentioned as a critical point that the C modules shown in Figure 2 were not considered either.

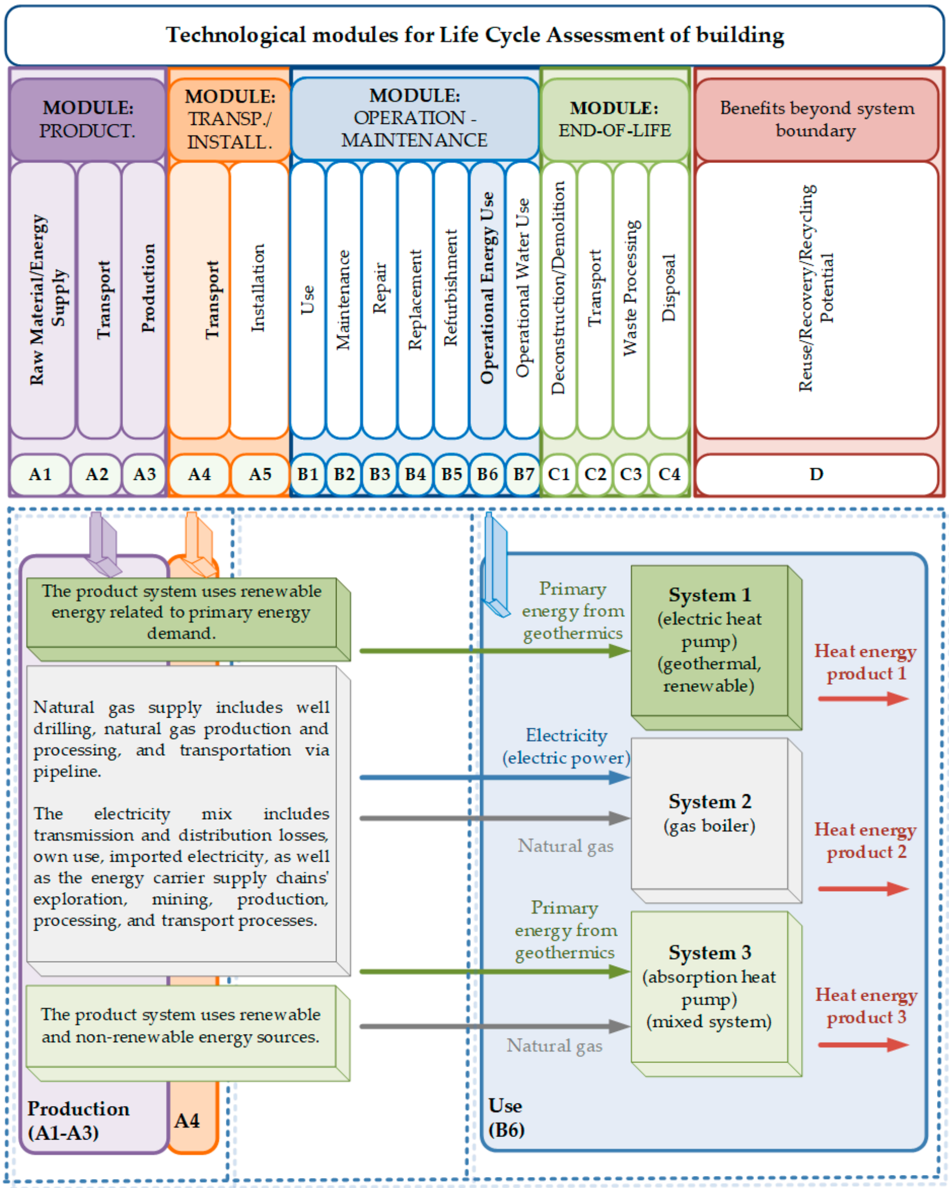

Figure 2. The system boundary of the cradle-to-gate life cycle assessment.

2.2. Life Cycle Inventory and Functional Unit

Data transparency and clarity were essential in this research study. The life cycle inventory contained data on energy consumption for each heating process. In the life cycle inventory, the output products were created using a combination of heating systems, including both renewable and non-renewable energy sources. Additional equipment, such as electric and absorption heat pumps as well as a gas boiler, was also used. The input flows were provided for the systems involved in producing targeted thermal energy for heating systems with a supply temperature of 50 degrees Celsius and a return temperature of 40 degrees Celsius in a 110 kW (heating energy) IT building. For all the three systems studied, the energy flows required to produce 1 GJ of specific heat energy were calculated in advance. For the creation of the LCA plan for System 1, the utilization of geothermal energy aligns with the current situation in the European Union. For the preparation of System 2, the electricity grid mix represents the situation in the European Union, while natural gas represents the situation in Hungary. For System 3, the geothermal electricity comes from the EU, and natural gas comes from Hungary.

All major energy flows were quantified, but only the energy used for heating was included within the system boundary of this inventory. The life cycle inventory was based on the 2021 industrial dataset, excluding the electricity grid mix. The life cycle inventory did not include capital assets and materials in the thermal plants that were studied. The efficiency of thermal energy generation was directly related to the input energy from the corresponding energy source. All relevant and well-known transport processes were taken into consideration. Sea and inland waterway transportation, as well as rail, truck, and pipeline transportation, were considered for the transportation of bulk goods. Table 2 lists all the energy inputs for the systems studied to generate an LCI for operational energy consumption. Table 3 summarizes the background information on the system inputs. Figure 3 depicts the electricity mix used in the EU, as shown in a pie chart. The data are based on the GaBi software database source for 2018.

Table 2. Inputs and outputs related to thermal systems during the operational energy use phase.

Flow Type	Process Flow Name	Plan Flow Name	Amount
System 1			
Input	Primary energy from geothermics (renewable energy)	Electricity from geothermal (European Union)	75.2 MJ 20.9 kWh
Output	Thermal energy from heating (thermal energy)	Product heat energy	75.2 MJ
System 2			
Input	Natural gas (at consumer Hungary)	Natural gas mix (Hungary)	8.8 kg 412 MJ 114.4 kWh
Input	Electricity (electric power)	Electricity grid mix (production mix, Hungary)	7.92 MJ 2.2 kWh
Output	Thermal energy from heating (thermal energy)	Product heat energy	419.92 MJ
System 3			
Input	Natural gas (at consumer Hungary)	Natural gas mix (Hungary)	4.82 kg 226 MJ 62.7 kWh
Input	Primary energy from geothermics (renewable energy)	Electricity from geothermal (European Union)	11.9 MJ 3.3 kWh
Output	Thermal energy from heating (thermal energy)	Product heat energy	237.9 MJ

Table 3. Background of system inputs.

Input Names	Background of System Inputs
Natural gas	The LCI dataset covers the entire natural gas supply chain. This includes drilling, natural gas production, processing, and transportation via pipelines. The main technologies in Hungary include conventional (primary, secondary, and tertiary) and unconventional production (shale gas, tight gas, and coal seam gas). These technologies encompass various parameters, including energy consumption, transport distances, and gas processing technologies. Pipeline transportation between the gas field and the coast was considered. Hungarian natural gas consumption consists of a combination of domestically produced natural gas and imported natural gas from the respective producing countries. An average regional distribution (via pipelines) was estimated for the total supply of natural gas, including domestic production and imports. The inventory was primarily based on secondary data.
Electricity	Electricity was modelled according to the specific circumstances of the European Union. The modelling of the electricity mix included accounting for transmission and distribution losses as well as self-consumption by energy producers such as power plants and other sources like pumped-storage power plants. It also took into consideration the importing of electricity. Secondly, the national emission and efficiency standards of power plants were modelled as well as the proportion of electricity plants and combined heat and power (CHP) plants. Thirdly, the analysis considered the supply of specific energy carriers, taking into account both imported and domestically produced energy sources. This included examining the properties of the energy carriers, such as their composition and energy content. The exploration, extraction, production, processing, and transportation processes of the energy carrier supply chains were modelled according to the EU situation.
Geothermal energy	The product system used renewable-energy-related primary energy demand; for 1 MJ of electricity from geothermal power, 1.98 MJ of primary geothermal power was used. The product system utilized renewable energy sources, which resulted in a primary energy demand related to renewable energy. For every 1 MJ of electricity generated from geothermal power, 1.98 MJ of primary geothermal power was consumed.
Energy carriers and refinery products	The energy carriers were modelled based on the specific supply situation (refer to the electricity section above). A parameterized refinery model simulated diesel fuel, gasoline, technical gases, fuel oils, lubricants, and residues, such as bitumen, using specific models for each country. The refinery model represents the current national standard in refining techniques, including emission levels, internal energy consumption, and other factors. It also took into consideration the specific product output spectrum of each country, which can vary from one country to another. The supply of crude oil was modelled based on the specific situation of each country and the properties of the available resources.

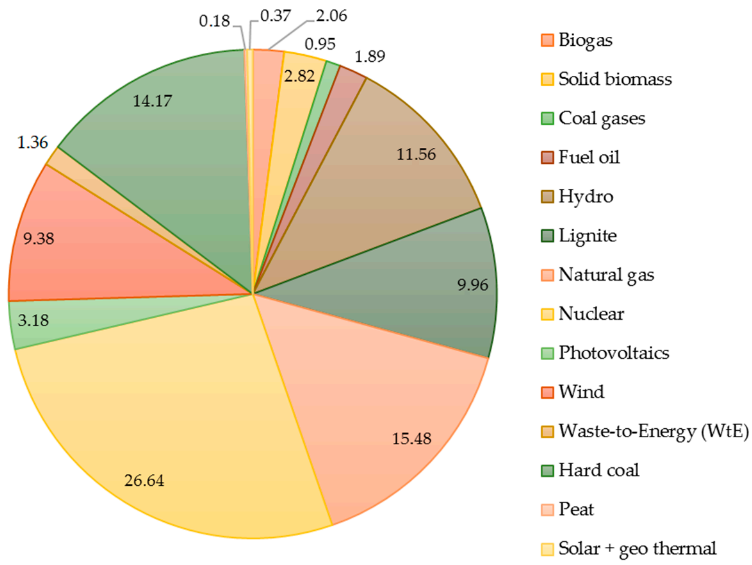

Figure 3. Energy mix in the European Union (based on the GaBi professional database and the GaBi extension database "Energy").

2.3. Life Cycle Impact Assessment Method

A life cycle impact assessment converts inventory data from a life cycle assessment into potential impacts, allowing one to comprehend the environmental burdens. The LCIA refers to the third phase of the LCA, which primarily evaluated the environmental effects of the examined energy systems. The environmental impact of the three systems can be assessed using various techniques and approaches. As LCIA methods, the ReCiPe 2016 method (developed collaboratively by the Dutch National Institute for Public Health and the Environment (RIVM), Radboud University Nijmegen, the Norwegian University of Science and Technology, and PRé) and the CML 2016 method (developed by the Centre for Environmental Science at Leiden University) were applied [41,42]. The ReCiPe and CML methods are often used in the European Union. These applied methods align with international standardization processes and cover all phases of life cycle assessment [43]. The ReCiPe method calculates endpoint indicators and incorporates factors derived from a hierarchical consensus perspective. The applied ReCiPe 2016 perspective includes climate change, human health, fossil depletion, and human toxicity (cancer). The CML 2016 method measures various environmental potentials, such as abiotic depletion for fossils and elements (ADPF and ADPE), photochemical ozone creation (POCP), freshwater and marine aquatic ecotoxicity (FAETP and MAETP), terrestrial ecotoxicity (TETP), human toxicity (HTP), global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP). ReciPe and CML normalization and weighting processes were used to calculate nanogram data.

2.4. Empirical Method for the Development of an Environmental Reliability Model

The importance of energy efficiency and environmental impact in thermal engineering systems is no longer questioned today. Examining the energy demand and environmental impact of thermal engineering systems and electricity supply is essential for optimizing building operations. The primary reason for this is the environmental impact of different energy supply methods and the increasing energy demand for buildings. However, optimizing construction facilities is closely linked to the structural integrity and environmental performance of the building. Facilities' environmental reliability also involves comparing individual building design processes and operational options. Still, it is rarely discussed how the optimization process and life cycle assessment can work together to inform design decision-making for building thermal engineering systems. Different scenarios can be considered when examining thermal systems using life cycle assessment to determine installations' energy consumption and ecological burden. To draw comprehensive conclusions, it is advisable to conduct a modelling process that takes into account various parameters. These parameters should include the primary energy resource, the environmental impact categories, and the ecological loads associated with renewable and non-renewable energy supplies.

An empirical model for assessing environmental reliability was developed to achieve the research objective. The developed model is primarily based on quantitative methods that establish quantitative indicators. The environmental reliability model relies on calculated data for primary energy resources, emissions, climate change, and ecological impact categories. Therefore, the LCA method was considered authoritative during the development of the model, especially when examining heating systems from ecological and energetic perspectives. The reliability modelling depends on the results of the LCA calculation. The development objective included collecting data for the LCI and creating single-operation processes. The provided model theoretically incorporates various LCA technological modules throughout the life cycle stages of the building, as illustrated in Figure 4.

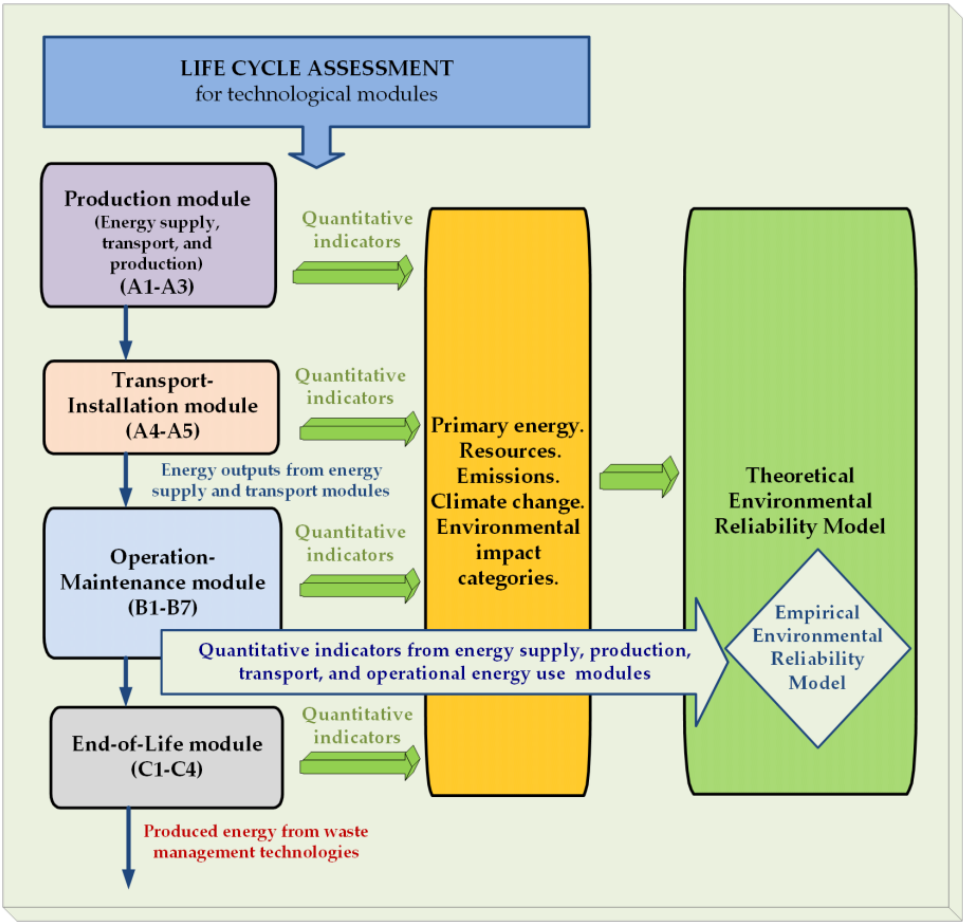

Figure 4. Technological modules for developing theoretical and empirical environmental reliability models.

As shown in Figure 4, it is recommended to conduct the life cycle assessment of buildings using the following technological modules:

- Production module: The composition of the individual system elements and material components is crucial. The LCA can be more precise by considering each system unit's exact place of origin.
- Transport–installation module: To determine the environmental loads, it is advisable to assess the energy demand and environmental impact of the materials used for transporting, installing, and assembling the thermal system units. This includes considering the packaging and subsequent waste. Conducting a life cycle assessment and specifying the distance, utilization, and method of transportation is advisable. It is recommended to design the most optimal heating system.
- Operational module: During the operational phase, it is crucial to prioritize the energy consumption of the thermal units. It is recommended to minimize the amount of energy being consumed. Modern types of heat generation equipment today include gas-condensing boilers and renewable-energy-based heat production. In terms of heat exchange surfaces, heating surfaces with lower temperatures offer energy-efficient heating. For this module, it is advisable to use a computerized building management system (BMS). A BMS automatically controls and monitors heating systems, security systems, electrical units, and other BMSs, reducing energy costs. A building monitoring system enables checking the entire building from a single point. With well-planned building management, higher energy efficiency, lower operating costs, improved comfort, and increased productivity can be achieved.

- Maintenance module: Facility management services related to buildings are now more emphasized, particularly in building maintenance, energy management, and work-related services. It is recommended to perform major maintenance on heating technology once a year. All entrances and exits of an apartment or building must be thoroughly inspected. During the life cycle of a building, the components of the thermal system may need to be repaired and replaced multiple times. This implies that purchasing, transporting, installing, and replacing worn-out materials and components require energy. The discarded units or elements create an environmental burden as waste, which is managed at the end of their lifecycle. The use of a BMS is also recommended for this module.
- End-of-life module: If the examined system boundaries are well defined, a more accurate life cycle inventory and impact assessment can be established for the end-of-life stage. This module primarily consists of either landfilling or processing.

This research only considered and summarized some life cycle phases' actual environmental and energetic results. The newly developed model was empirical for the energy supply, production, transport, and operational energy use phases and provided accurate LCA results. In the case of the other life cycle stages of the building, the environmental reliability model was only developed theoretically.

2.5. Theoretical Method for the Development of a Complex Decision-Support Model

The environmental reliability model under development requires further refinement to integrate economic considerations, as well as environmental and energy-related impacts, into the selection process of the building's thermal engineering system. A tabular theoretical complex decision-support model was developed to integrate life cycle assessment and life cycle cost (LCC) at the building's design, installation, and operational phases. This model introduces environmental, economic, and energy-related aspects. The newly developed complex decision-support model, which is currently in the design phase of the building heating system, enables the establishment of sustainability objectives from the viewpoints of energy resources, environmental impacts, and economic efficiency. It is necessary to support the theoretical complex decision-support model with the results of the life cycle assessment, including energy resources, primary energy, and environmental potentials. These results should be obtained for the empirical environmental reliability model.

Additionally, if possible, it would be beneficial to formulate several hypotheses. The null hypothesis states that there are no deviations or changes that occur during the life cycle phases of a building. The complex decision-support model can shed light on the challenges of implementing a multicriteria evaluation for complex and ambiguous problems, thereby establishing a process based on a comprehensive research model. During the practical application of the theoretical model, it is worthwhile to examine the parameters for each of the three aspects individually as well as to observe how they are interconnected and build upon each other. Figure 5 illustrates the primary steps involved in developing a complex decision-support model.

Table 4 summarizes the most critical economic, environmental, and energy-related aspects of developing the comprehensive decision-support model for heating systems.

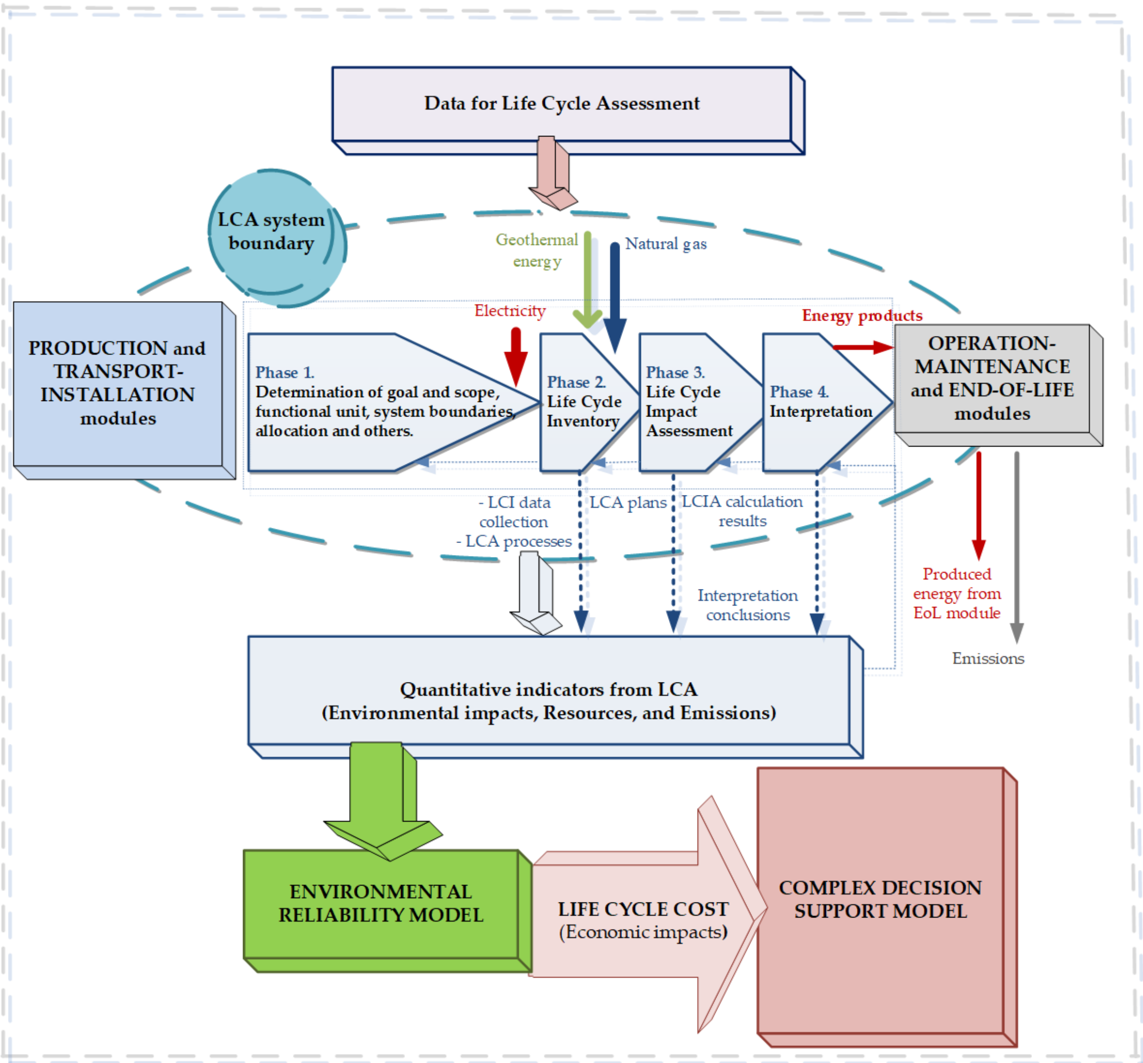

Figure 5. Steps for developing theoretical complex decision-support models.

Table 4. Complex decision-support model.

	Name of Parameters
Economic aspects	Productivity
	Delivery, installation, operation, and maintenance costs
	Energy costs, decommissioning costs during replacement, operational, and life-cycle costs
	The management cost of system units that have become waste
	Method and safety of energy supply, type of energy, and type of fuel used
	Rate and unit price of energy and water consumption
	Primary energy saving and energy transmission loss
	Power generation method and utilization of generated heat
	The life cycle of thermal engineering units, downtime, and amortization
	Property, work and fire protection, and safety technology
	Building value, financing options, and innovation

Table 4. *Cont.*

	Name of Parameters
Environmental aspects	Reduction in energy and material resources
	Lifetime and life cycle of the building
	Emissions, carbon footprint, environmental impact categories, and reduction
	Primary energy savings
	Inspection and control of heat engineering units and utilities
	Indoor air quality and thermal comfort
	Environmental building assessment system and building environmental performance
	Environmental impact of installation, use, and end-of-life stages
	Use of low-carbon, renewable technologies
	Polluting substances, type of waste, amount, and treatment method
Energetic aspects	Method of energy supply and heating system
	Energy/primary energy consumption and savings
	Percentage of use of renewable and fossil energy sources
	Building technical systems and system design
	Building energy requirements
	Energy efficiency and its improvement, energy efficiency measures, and certificates
	Energy transmission loss
	Peak winter heating performance and reduction
	Off-peak heating performance and its increase
	Application of storage tanks and temperature control
	Reduction in the mass flow of primary district heating water
	Utilization and recovery rate of heat generated during electricity and energy production
	Energy and waste heat utilization technology from the treatment of units that have become waste
	Type and efficiency of thermal energy storage techniques
	Building energy performance
	Building qualification and certification system

3. Results

The life cycle assessment examined the environmental and energy effects of the production stage (A1–A3 module), the transport phase (A4 module), and the operational energy use phase (B6 module) to develop an empirical environmental reliability model. The environmental impacts were measured during the life cycle assessment using various LCIA methods. Table 5 presents the calculated environmental impacts for the three thermal systems in nanograms using the CML 2016 life cycle impact assessment method. With the application of the ReCiPe 2016 endpoint (H) method and Environmental Footprint 3.0, Table 6 presents the analyzed environmental quantities in person equivalents. Both tables summarize normalized and weighted values.

According to the calculated values shown in Tables 4 and 5 for both LCIA methods, the environmental impact quantities for the use of gas boilers were higher than those for heat pumps. The exceptions were the acidification potential and water use, which showed exceptional values when using an electric heat pump. Acidification refers to the degree to which different compounds contribute to the occurrence of acid rain. This primarily includes sulfur dioxide (SO_2), nitrogen oxides (NOx), nitrogen monoxide (NO), and nitrogen dioxide (NO_2), resulting in a larger number of substances in the case of

System 1. In the case of System 2, the abiotic depletion of fossil fuels was exceptionally high because the examined system incorporated electric power and natural gas, with fossil energy sources being predominantly utilized. Here, the proportion of renewable energy sources was only as much as the electricity mix shown in Figure 3. Table 7 summarizes the amount of primary energy. According to this table, the primary energy values from renewable sources were significantly higher in the heat pump systems compared to the gas boiler systems. In particular, the proportion of renewable energy was higher for System 1. Here, the net primary energy value was 341 MJ compared to the 3.56 MJ characteristic of System 2 and the 54 MJ value of System 3. This was because, in the first case, pure geothermal energy, which is a renewable source, was used as an input. Furthermore, this table shows that the gross caloric value of the primary energy demand from renewable and non-renewable resources was very high for System 2 (552 MJ). Figures 6–8 present the measurable normalized and weighted environmental impact categories as percentages.

Table 5. Environmental quantities regarding the thermal systems based on the CML 2001–August 2016 method in nanograms. Normalization: EU 25 + 3, 2000, excl. biogenic carbon (region equivalents). Weighting: Sphera LCIA Survey, 2012, Europe, excl. biogenic carbon (region equivalents weighted). Environmental quantities related to thermal systems based on the CML 2001–August 2016 method measured in nanograms. Normalization: EU 25 + 3, 2000, excluding biogenic carbon. Weighting: Sphera LCIA Survey, 2012, Europe, excluding biogenic carbon (regionally weighted equivalents).

Environmental Impact Quantities (CML 2016)	System 1 (Electric Heat Pump)	System 2 (Gas Boiler)	System 3 (Absorption Heat Pump)
Abiotic Depletion ADP fossils	0.09	88.20	47.4
Acidification Potential AP	62.90	2.41	11.0
Eutrophication Potential EP	0.01	0.516	0.24
Global Warming Pot. GWP 100 years	2.28	9.0	4.55
Human Toxicity Potential HTP inf.	0.46	6.38	3.32
Marine A. Ecotox. Pot. MAETP inf.	0.47	28.9	5.54
Photochem. Ozone Creat. Pot. POCP	0.02	5.11	2.57
Terrestrial Ecotoxicity Pot. TETP inf.	0.02	3.36	1.80

Table 6. Environmental quantities related to thermal systems were determined using the ReCiPe 2016 endpoint (H) method and the Environmental Footprint 3.0 database, measured in person equivalents. Normalization: ReCiPe 2016 v1.1 (H), endpoint, world, excluding biogenic carbon, and EF 3.0 (person equivalents). Weighting: ReCiPe 2016 v1.1 (H/H), excluding biogenic carbon, and EF 3.0.

Environmental Impact Quantities (ReCiPe 2016)	System 1	System 2	System 3
Climate change human health (default)	0.0508	0.216	0.11
Fossil depletion	0.00423	3.6	1.95
Human toxicity (cancer)	0.0148	0.0159	0.00813
Environmental Impact Quantities (EF 3.0)	**System 1**	**System 2**	**System 3**
Climate change-total	0.00352	0.0151	0.00767
Land use	1.92×10^{-6}	6.67×10^{-6}	5.56×10^{-6}
Particulate matter	3.88×10^{-5}	1200×10^{-5}	585×10^{-5}
Water use	482×10^{-5}	3.09×10^{-5}	76.8×10^{-5}

Table 7. Primary energy values regarding the examined thermal systems in MJ.

Primary Energy Quantities	System 1	System 2	System 3
Primary energy demand from ren. and non-ren. resources (gross cal. value)	341	552	343
Primary energy demand from ren. and non-ren. resources (net cal. value)	341	499	314
Primary energy from non-renewable resources (gross cal. value)	0.556	548	289
Primary energy from non-renewable resources (net cal. value)	0.52	496	260
Primary energy from renewable resources (gross cal. value)	341	3.56	54
Primary energy from renewable resources (net cal. value)	341	3.56	54

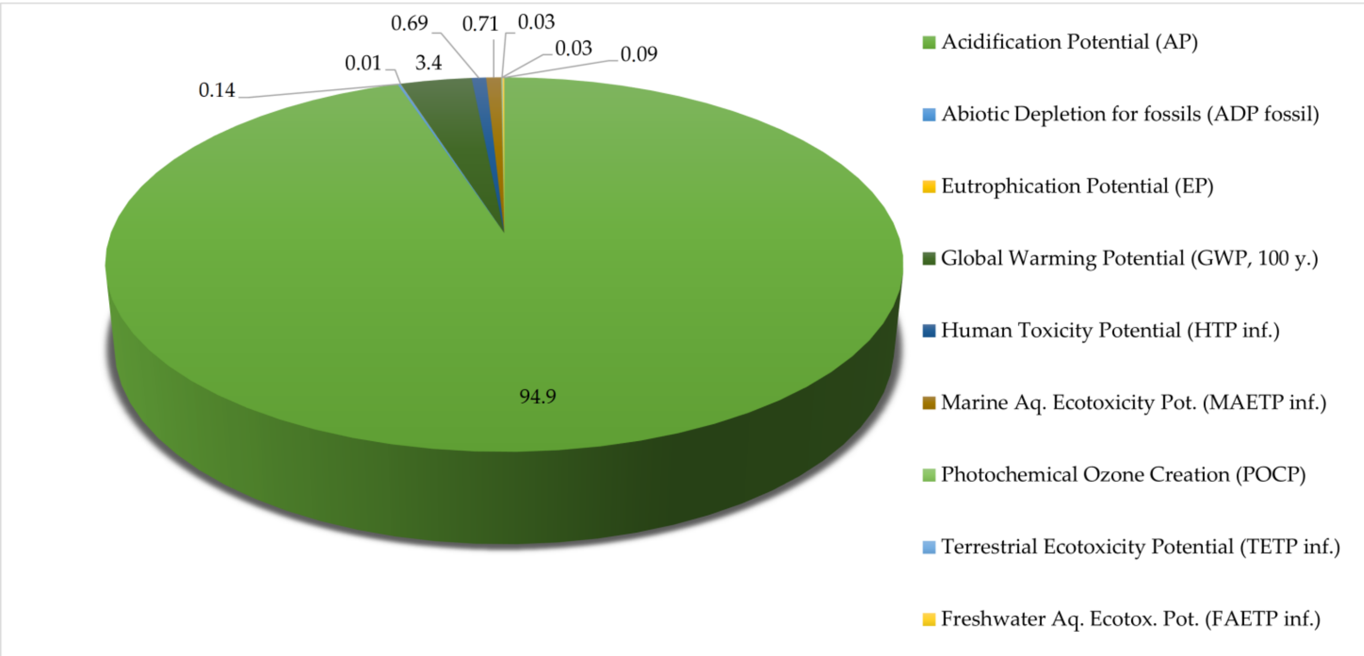

Figure 6. The measurable nine impact categories for System 1, expressed as percentages. (Normalization reference: CML 2016, EU 25 + 3, year 2000, excluding biogenic carbon. Weighting method: thinkstep LCIA Survey 2012, Europe, CML 2016, excluding biogenic carbon.)

Several conclusions can be drawn based on Figures 6–8. For System 1, where only renewable energy was used, the results of the CML 2016 method showed a significant increase in acidification potential, reaching 95%. At the same time, greenhouse gases also contributed significantly to emissions, resulting in a global warming potential value of 3.4%. In this case, the geothermal heat pump utilized the available geothermal energy. Achieving the operating temperature of the heating system requires drilling to a significant depth in the earth's crust to ensure efficient heat transfer. Simultaneously, the processes involved in manufacturing ground heat exchange pipes and transporting dust from drilling operations at the drilling site resulted in increased levels of acidification and greenhouse gas emissions. This led to increased AP and GWP quotients. The results of the CML 2016 method yielded very similar outcomes for Systems 2 and 3 in terms of various environmental impact categories. The ADP values were 61.18% in System 2 and 62.15% in System 3.

Meanwhile, the GWP was 6.2% in System 2 and 5.91% in System 3. The HTP values ranged from 4.31% to 4.4%, and the POCP values ranged from 3.3% to 3.5% for both systems. In general, the gas boiler and absorption heat pump systems had a higher impact in these categories due to various factors, such as the use of non-renewable resources and the transportation equipment involved. However, there was a significant discrepancy that was noted in one crucial category, namely the potential for acidification. In System 2, the value was 1.7%, whereas in System 3, it was 14%. The high ratio was related to the production of lithium bromide and ammonia in the absorption heat pump system, which generates a significant amount of acidic substances. Here, nitrogen and hydrogen are produced from natural or industrial gas using various methods, each requiring specific temperatures and pressures. The AP value was primarily determined by the emission of nitrogen oxides into the environment, as mentioned previously. Table 8 summarizes the quantities of material and energy resources, as well as the corresponding emission values, in kilograms.

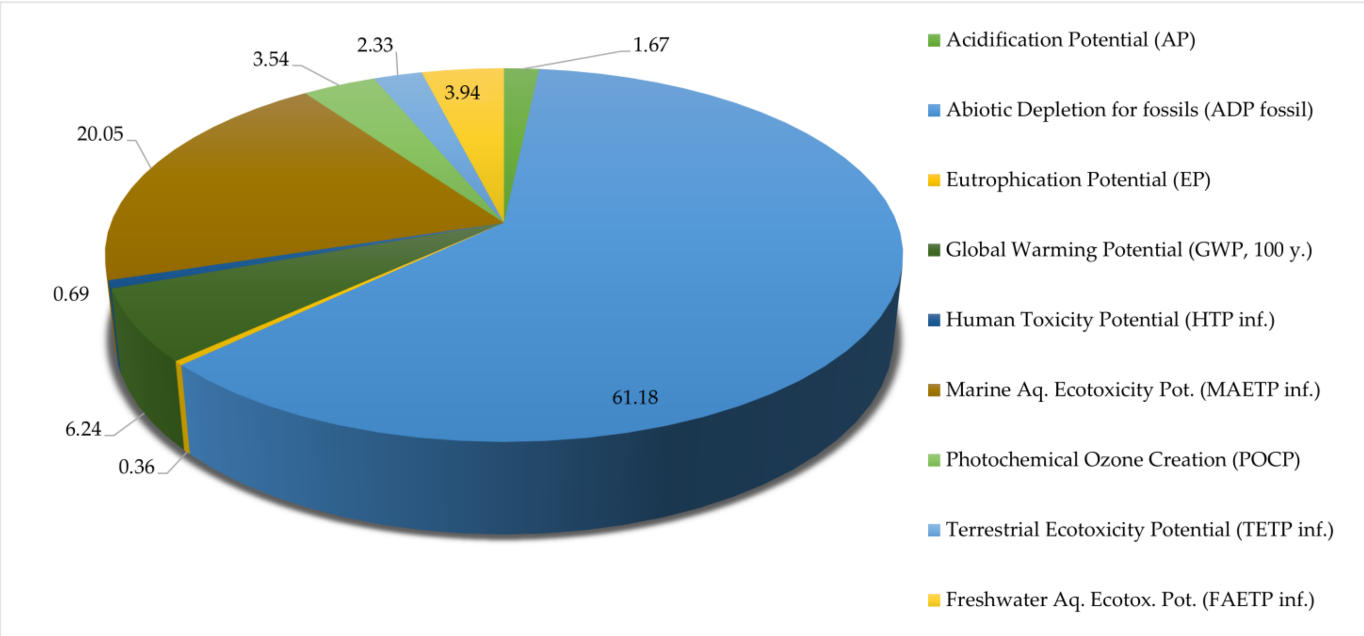

Figure 7. The measurable nine impact categories for System 2, expressed as percentages. (Normalization reference: CML 2016, EU 25 + 3, year 2000, excluding biogenic carbon. Weighting method: thinkstep LCIA Survey 2012, Europe, CML 2016, excluding biogenic carbon.)

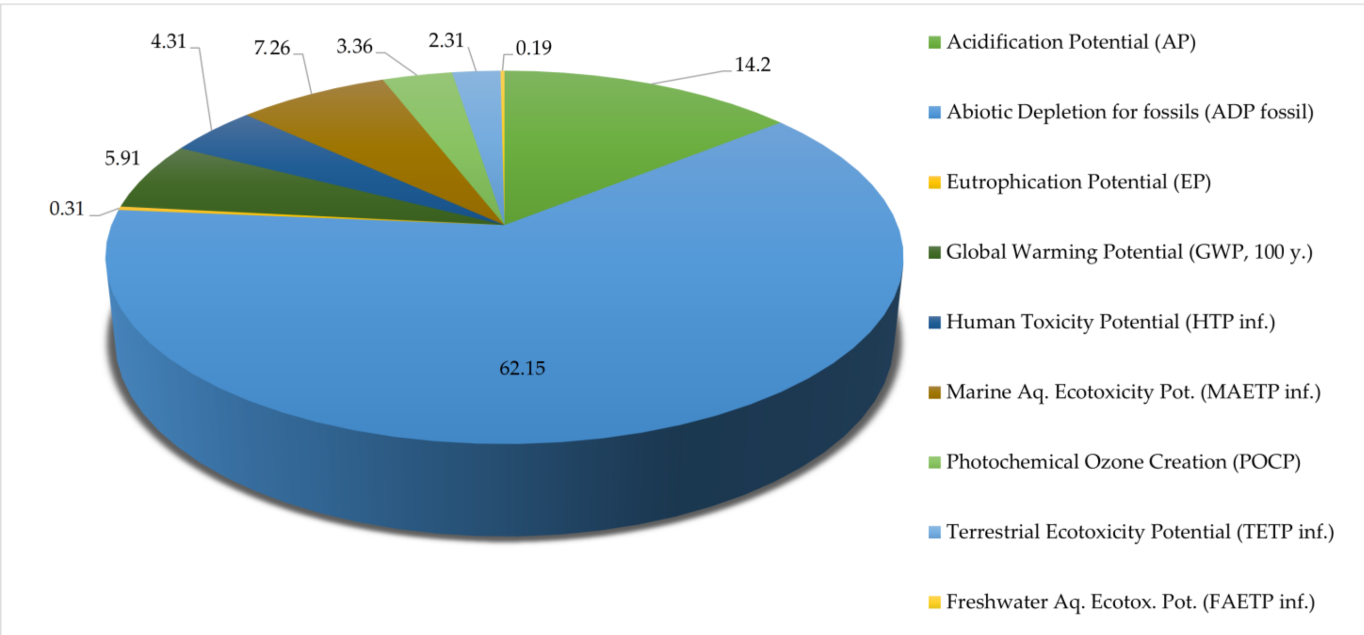

Figure 8. The measurable nine impact categories for System 3, expressed as percentages. (Normalization reference: CML 2016, EU 25 + 3, year 2000, excluding biogenic carbon. Weighting method: thinkstep LCIA Survey 2012, Europe, CML 2016, excluding biogenic carbon.)

Table 8. Resources and emissions regarding the energy systems in kilograms.

Resources and Emissions	System 1	System 2	System 3
Energy resources	0.0142	11.3	5.93
Energy resources from electricity mix	-	0.5	-
Energy resources from Hungarian natural gas	-	10.8	5.9278
Energy resources from geothermal	0.0142	-	0.0022
Material resources	173	1240	183
Material resources from non-renewable resources	0.089	40	15
Material resources from renewable resources	172.91	1200	168
Emissions to air	153	29.5	28.5
Emissions to fresh water	17.9	1500	145
Emissions to sea water	0.041	1.02	0.535

Based on the data in Table 7, it can be concluded that the gas boiler system had a higher resource load and emissions compared to the heat pump systems, except for emissions into the air. Table 9 shows the primary normalized and weighted environmental impacts using the Environmental Footprint 3.0 method as a percentage.

Table 9. Environmental impacts related to thermal systems are determined using the EF 3.0 database as a percentage. Normalization method: EF 3.0 (person equivalents). Weighting method: EF 3.0.

Environmental Impacts (EF 3.0)	System 1	System 2	System 3
Climate change-total	4	17	13
Ecotoxicity freshwater-total	90	0.65	21
Human toxicity (non-cancer)-total	0.019	2.7	2.1
Water use	5.5	0.035	1.3
Resource use, fossils	0.076	72	57

Table 9 shows that the use of the gas boiler system (System 2) affected human toxicity, climate change, and fossil resource use to the greatest extent. In the case of the renewable system (System 1), geothermal energy affected only 4% of the value of climate change but a relatively high (90%) of the value of freshwater ecotoxicity. It contributed to the effect on human health only to an insignificant extent. As for the combination of geothermal energy and natural gas, we saw a change of 12% in the value of freshwater ecotoxicity, 13% in the value of climate change, and a 57% change in the value of fossil resource use. A total of 90% of the use of geothermal energy affected freshwater ecotoxicity; in contrast, the use of natural gas in this system affected only 0.25% of the value of freshwater use. At the same time, geothermal energy in this system affected climate change by 4% and natural gas by 16%.

4. Discussion

This study aimed to determine the environmental effects and primary energy requirements of renewable, conventional, and mixed heating systems. The LCA analyses were complemented by establishing two newly developed models, which can already be used in the planning phase of buildings. The developed empirical model for environmental reliability utilized life cycle assessment calculations. The theoretical complex decision-support model also integrated the environmental LCA with energetic and economic aspects. During this research, the different life cycle results for the three energy systems were compared separately by considering the ecological effects and primary energies. The applied software database was continuously updated, which helped to determine the potential environmental impacts.

The research results showed that the environmental impact of gas boiler heating systems was higher than that of geothermal systems. This was because the assessment considered the energy inputs and associated loads. Comparing the three heating systems, the significant differences in the results regarding the total impact quantities were based on the ReCiPe and EF 3.0 LCIA approaches. In the case of the CML method, the differences were higher for the abiotic depletion of fossil fuels, mainly when using a gas boiler and the impact of acidification when applying an electric heat pump. The life cycle assessment results from Figures 6–8 showed that fossil–abiotic depletion, global warming, and acidification had a higher environmental impact. The main factors influencing emissions were natural gas and electricity. However, it should be noted that the survey was conducted for Hungarian natural gas and the electricity mix of the European Union. Using different natural gas sources, electricity mixes, and varying geographical locations could impact the validity of the research [44,45].

The difference in the primary energy demand between renewable and non-renewable resources was also significant. The primary energy values from renewable resources for the geothermal heating system (examined in System 1) were 6-10 times higher. A previously mentioned research study [19] also compared electric heat pumps, absorption heat pumps, and gas boilers, similar to our research. The study's results were consistent with ours, which indicates that the environmental impact of absorption heat pumps is smaller than that of electric heat pumps.

Gas boilers impose a significant ecological burden. With a gas boiler system, the effect of natural gas on human toxicity is precisely twice as much as the effect of electricity. While electricity contributes 34%, natural gas contributes 16% to the higher value of climate change. As for the value of fossil resource use, 43% of electricity and 75% of natural gas influence it. The use of electricity for this system contributes 5.8% to the value of freshwater ecotoxicity and contributes precisely twice as much to acidification as gas.

Nowadays, building design primarily focuses on the environmental, energy, and economic impacts of heating and cooling systems throughout the operational life cycle of buildings. Therefore, reviewing and interpreting the literature on building thermal systems' environmental loads and energy efficiency is essential. Each building energy system requires a unique assessment to identify opportunities for optimizing environmental loads and improving energy efficiency. A conducted life cycle assessment of a building's energy system can provide essential information and a fundamental element of its sustainability to achieve nearly zero-energy buildings in the future [46,47]. The life cycle assessment results enable the optimization of various impact parameters, primarily during the operational stage. This optimization aims to achieve energy efficiency when using buildings while minimizing environmental impacts [48–50].

5. Conclusions

This study integrated environmental impacts and primary energy resources through the use of a life cycle assessment. It is helpful to calculate the life cycle factors for three heating systems, including electric and absorption heat pumps as well as a gas boiler. In conclusion, it can be said that gas boiler and absorption heat pump systems have higher rates of environmental impact in various categories. The proposed models are essential for improving energy efficiency and reducing environmental burdens through building design. When an environmental reliability model and a complex decision-support model accurately predict the parameters, it becomes possible to reduce the environmental loads of buildings. The application of these models and their further development will be a possible research direction in the future in relation to building design.

From this study, several recommendations can be formulated to reduce environmental impacts based on life cycle assessment.

- The emissions associated with the use of electricity and natural gas can be reduced by changing the composition of the electricity grid and the source of natural gas.

- The impacts of energy transport can be reduced by using low-emission transportation methods.
- Greenhouse gas emissions and acidification can be reduced by modifying the procedures for manufacturing the materials required for ground heat exchange pipes and improving the method of transporting dust from drilling operations.

This research work provides new information about renewable and non-renewable thermal systems. The results can be used to develop sustainable heating systems that have reduced environmental impacts and enhanced energy efficiency. The research results can benefit the construction industry by facilitating the integration of building information modelling and life cycle assessment. Hungary, as Poland's neighbor, has significant resources for geothermal energy. Still, there needs to be a thriving market for geothermal heat pumps. Planning has begun to address the current energy crisis in Europe and the need for additional energy resources. Numerous projects in Hungary and all European Union countries aim to harness renewable energy for heating and electricity generation [51]. Nearly 60% of the primary energy required and 90% of the associated CO_2 emissions in Europe for 2050 could be mitigated by replacing traditional building space heating systems with high-efficiency geothermal heat pumps.

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

Abbreviations

ADPE	Abiotic depletion potential for elements
ADPF	Abiotic depletion potential for fossils
AP	Acidification potential
ASHP	Air-source heat pump
CE	Circular economy
CGB	Condensing gas boiler
EAHX	Earth-to-air heat pump
EGD	European Green Deal
EP	Eutrophication potential
EU	European Union
FAETP	Freshwater aquatic ecotoxicity potential
GSHP	Groundsource heat pump
GWP	Global warming potential
HTP	Human toxicity potential
HVAC	Heating, ventilation, and air conditioning
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MAETP	Marine aquatic ecotoxicity potential

nZEB	Nearly zero-energy building
POCP	Photochemical ozone creation potential
SDGs	Sustainable development goals
TETP	Terrestrial ecotoxicity potential
WSHP	Water-source heat pump

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