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Article

Energy Resources and Environmental Impacts of Heating Systems

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Abstract: This paper utilizes a life cycle assessment to evaluate the energy resources and environmental impacts of three heating systems. In the first step, life cycle assessments (LCAs) are prepared for the renewable, conventional, and combined systems. The system boundary of the LCA method is "cradle to gate," which means it includes the entire life cycle of a product or process. This includes energy supply, transport, energy generation, and operational energy use. The system scenarios were compared based on ecological and energy loads in the second step. Primary energy, resources, emissions, and environmental potentials are calculated for the system scenarios using the life cycle assessment methods CML 2016 and ReCiPe 2016. Finally, models for environmental reliability and complex decision-support tools have been developed. This work addresses two main questions: how to characterize the environmental and energy impacts of the systems under study, and what is the optimal scenario for the system? The research results show that the gas boiler system has a greater environmental impact. The most significant differences between the systems relate to the degradation of abiotic fossil fuels when using a gas boiler and the process of acidification when using an electric heat pump. The results can be used to develop sustainable heating systems with reduced environmental impacts and enhanced energy efficiency.

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

The global problem of primary energy supply difficulties is a cause for concern worldwide today. At the same time, the use of fossil fuels, the ever-increasing energy costs, and the growing environmental impact are raising concerns about sustainability. The European construction industry is responsible for most greenhouse gas emissions, comprising nearly 40% of global energy consumption [1]. Considering this, it is important to highlight the regulations for nearly Zero Energy Buildings (nZEBs). According to European Union (EU) requirements, only buildings that meet near-zero energy requirements will be eligible to obtain a building permit starting in 2021 [2]. 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 energy demand, a near-zero energy building improves the efficiency of mechanical systems, leading to a lower overall energy performance rating and greater 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 also emphasized solutions that address energy efficiency and life-cycle CO_2 emissions [3].

The number of studies on near-zero-energy buildings [4–6] has increased dramatically, indicating a shared vision and commitment to zero-emission buildings. In Ireland, Moran et al. [4] investigated the optimal retrofit packages for improving thermal efficiency and reducing the energy demand of gas-fired homes. They found that the cost-optimal approach was effective in determining the best retrofit package. However, the environmental impact of the Irish electricity mix played a significant role. Many environmental indicators have been developed for assessing building sustainability and measuring their performance throughout their life cycle [5]. However, applying holistic methodologies and constructing comprehensive models for sustainable development are important. Essential aspects of nZEB include high heating performance, efficient energy system installation, and the use of renewable energy technologies [5].

Given the ambitious targets for reducing greenhouse gas emissions, the achievable development goals, and the importance of adopting holistic methods and models, there is an increasing need to utilize renewable energy sources in a holistic life-cycle approach [7]. In recent years, the concept and implementation of renewable energy sources have garnered the attention of the scientific community, particularly in the integration of thermal engineering systems and renewable energy technologies. Based on the life cycle approach, accurate engineering models can be created to reduce the environmental impact of thermomechanical systems while meeting the necessary primary energy demand for heating in the residential and industrial sectors [8]. Since energy efficiency and environmental impact are crucial considerations throughout the life cycle of buildings, particularly during the operation and use phases, it is essential to compare various heating systems using life cycle analysis and the development of comprehensive models.

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 the GSHP and conventional systems for single- and multi-family reference buildings. The results, in terms of energy consumption, favoured the GSHP [11].

Energy consumption varied from 1% to 7.3% in hot climates, 18.4% to 23.5% in temperate climates, and 33.6% in cold climates. Regarding carbon emissions from single-family homes, the use of ground-source heat pumps instead of conventional systems resulted in a decrease of 19% to 24% in carbon emissions. For multi-family homes, carbon emission results varied 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 in 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 evaluated. Approximately 16 RMB/m^2 was spent on pollution prevention during the production phase, while 5 RMB/m^2 was spent during the operation phase. The type of residential building and the atmospheric climate also influence the energy, environmental, and economic impacts of the GSHP system [13].

The Earth-Air Heat Exchanger (EAHX), which utilizes geothermal energy, is a sustainable and renewable system that produces no greenhouse gas emissions. EAHX has 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 2,878 tons compared to natural gas, 4,883 tons compared to fuel oil, and 6,646 tons compared to coal. In addition to improving the electricity mix, EAHX allows for drilling wells and laying pipes in the ground, resulting in minimal environmental impacts during the construction phase [15,16] EAHX does not use refrigerant [17].

Comparative studies [18,19] have been conducted to compare traditional and sustainable technical heating systems based on the results of life cycle assessments (LCAs). A research study conducted in the United States [18] compared gas boilers to air-source, ground-source, and water-source heat pumps (ASHP, GSHP, and WSHP) for residential buildings. The results showed that heat

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pumps have a greater environmental impact than gas boilers because they consume electricity. However, if the energy mix is sufficiently decentralized, the life cycle effects 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 were compared. According to the results, the absorption heat pump has a lower environmental impact than an 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 has a higher environmental impact than the absorption heat pump. In contrast, the gas boiler has the greatest environmental impact. These results are practically identical to those of the Mexican-Norwegian study [19].

Another study [22] from Germany compared the ASHP with a gas-condensing boiler. The study found that eight out of the 11 analysed 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 ASHP and CGB. However, it was observed that the global warming potential of ASHP is only one-third 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: circular economy, resource efficiency, and limited growth. Their results showed that the use and production phases are responsible for an average of 74% and 14% of the total environmental impact, respectively. The circular economy scenario shows 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 geothermal heat pump. Regarding environmental impact, the geothermal heat pump system had the least significant impact. This is due to the production of copper and R134a refrigerant during the construction phase, the production of polyethene 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 the 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 taken into account. 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 cooling energy consumption. 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 a research study [31], 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.

Asdrubali and Grazieschi [32] argue that to reduce the operational energy of systems, it is necessary to increase the use of grey systems, which can produce the required energy needed to achieve higher 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 [33].

In Minnesota, a comprehensive analysis [34] was conducted to compare GSHP systems with conventional methods such as gas boilers and air conditioners. The analysis was based on a life cycle assessment. Different scenarios for GSHP systems were tested, including vertical and horizontal heat exchangers, high-efficiency and low-efficiency factors, and hybrid systems with natural gas heat support. Most scenarios had a lower carbon footprint. Greenhouse gas emissions increased when low-efficiency horizontal heat exchangers and hybridization were used.

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 [35]. The research results of Asdrubali et al. [36] show that buildings converted into near-zero energy buildings have a shorter environmental recovery time during their life cycle.

1.3. Research Aims

Through life cycle assessment, an investigation was conducted on three distinct systems (with renewable and non-renewable energy inputs). The primary objective of the research paper is to quantify the amounts of primary energy involved and assess their associated environmental impacts. The selected thermal engineering systems for investigation are well-known and available in households.

Since building design, construction, operation, and building energy regulations have constantly changed over the past decade, different reports [2,3,7] relating to environmental impacts and some professional literature about nZEB buildings were reviewed in the first step.

In the second phase, the primary energy and the measurable environmental impact values for two heat pump systems (with electric and absorption heat pumps) using pure geothermal and combined energy inputs and for a gas boiler system (using natural gas and electricity) with the help of a life cycle assessment for an office building were estimated and compared. The applied life cycle assessment's numerical results were evaluated to identify intervention areas.

In addition, a model for environmental reliability and a complex three-point decision support model (incorporating environmental, energy, and economic factors) were developed. The research primarily compares renewable and non-renewable thermal systems' environmental impact and energy efficiency. The reason for conducting this research is that in the current energy crisis, consumers are increasingly seeking more advanced, environmentally friendly, and cost-effective home heating systems.

2. Materials and Methods

2.1. Life Cycle Assessment Method and System Boundary

The applied LCA method is based on the descriptions of the ISO 14040:2006 and 14044:2006 standards [37,38] which include the life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation phases. The life cycle models allow for the assessment of the environmental impacts and primary energy resources associated with heating a 110-kW information technology building. **Figure 1** shows the phases of the Life Cycle Assessment.

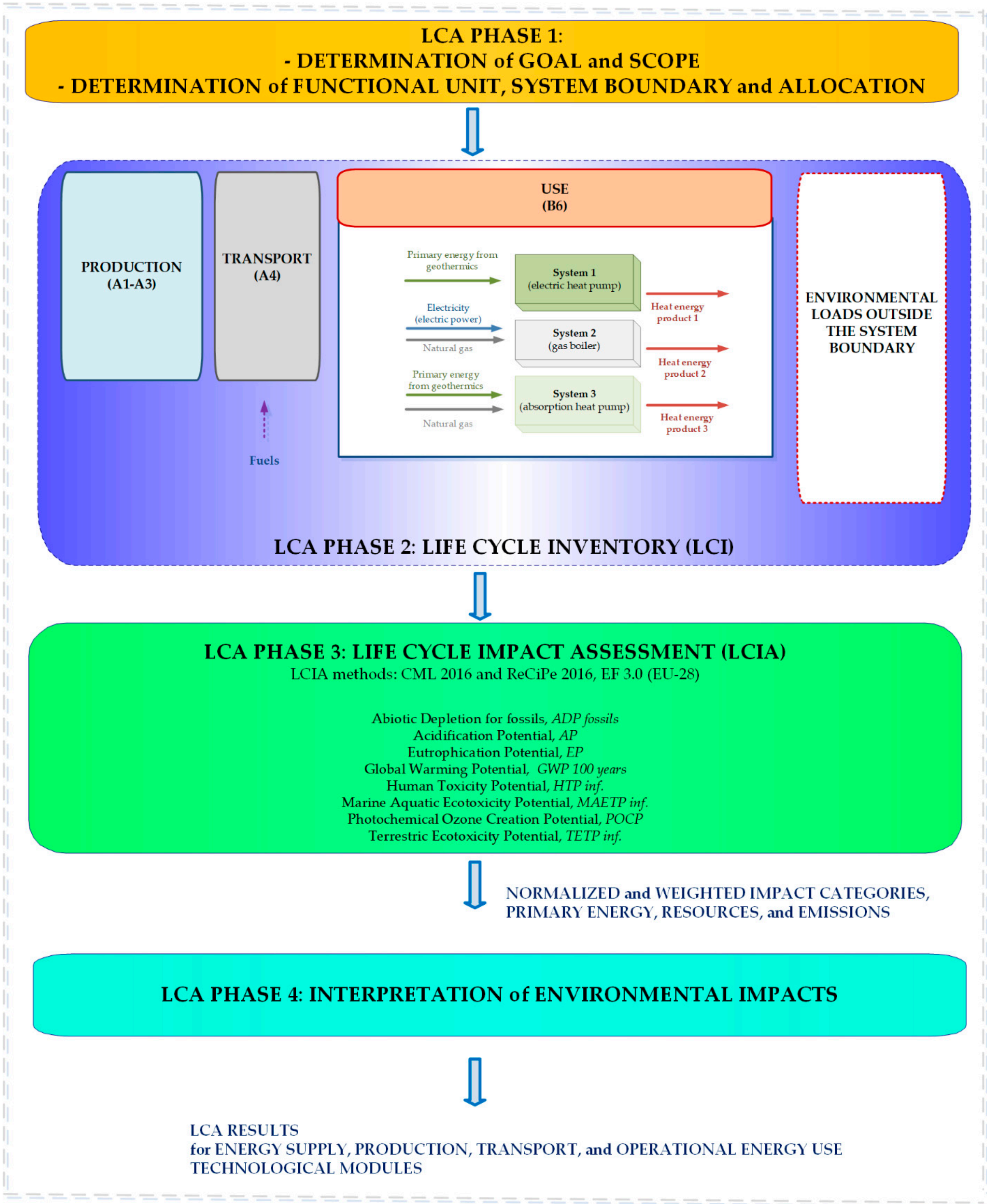

Figure 1. The phases of the life cycle assessment.

The scope of the LCA method includes 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

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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 extends from energy provision, energy transport, and energy generation to operational energy use. The modules included in this boundary are A1-A4 and B6. The system boundary does 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.

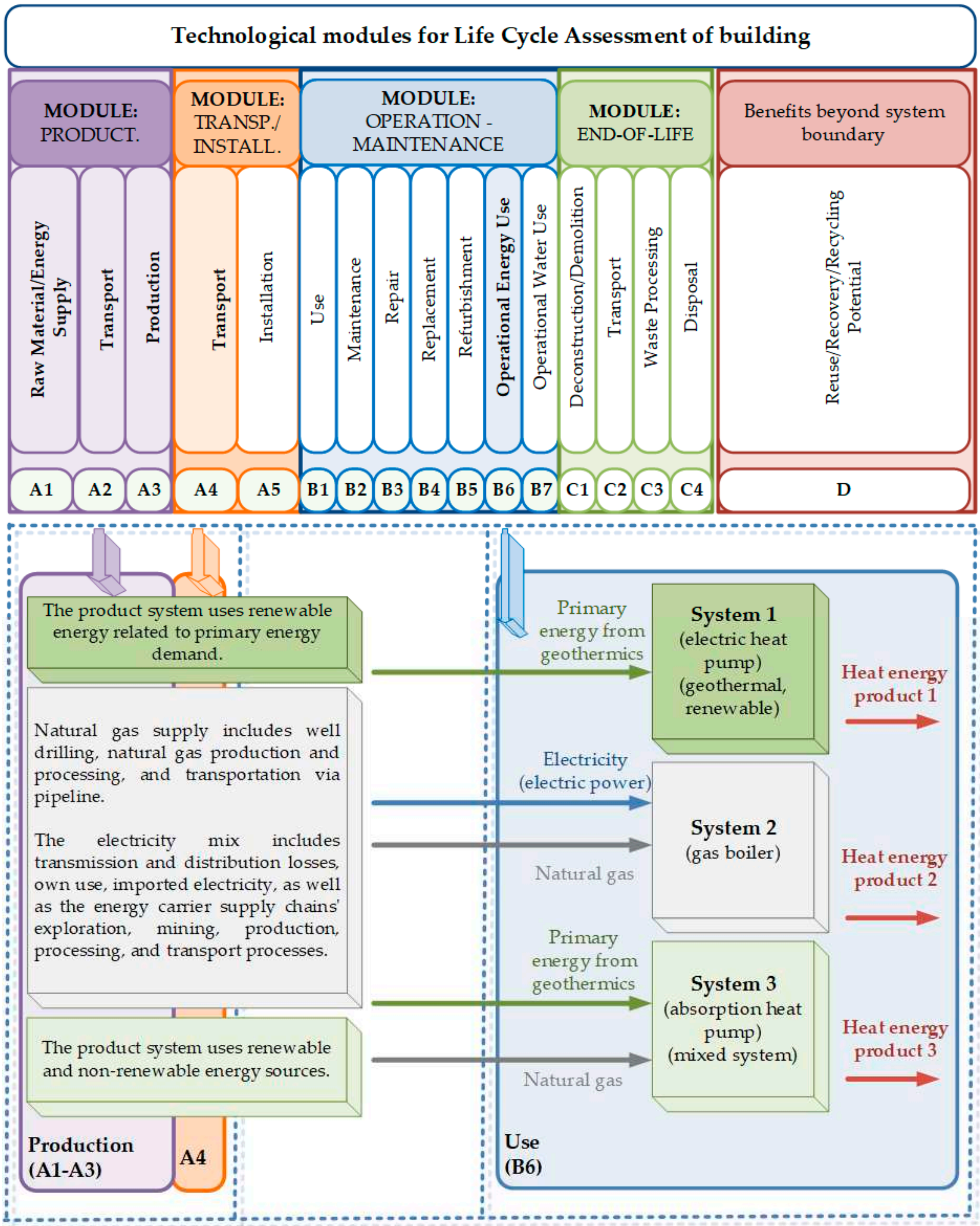

Figure 2. The system boundary of the cradle-to-gate life cycle assessment.

2.2. Life Cycle Inventory and Functional Unit

Data transparency and clarity are essential in this research study. The life cycle inventory contains data on energy consumption for each heating process. In the life cycle inventory, the output products are 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, is also used. The input flows are 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 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, geothermal electricity comes from the EU, and natural gas comes from Hungary.

All major energy flows are quantified, but only the energy used for heating has been included within the system boundary of this inventory. The life cycle inventory is 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 is directly related to the input energy from the corresponding energy source. All relevant and well-known transport processes are taken into consideration. Sea and inland waterway transportation, as well as rail, truck, and pipeline transportation, are considered for the transportation of bulk goods. **Table 1** lists all energy inputs for the systems studied to generate a LCI for operational energy consumption. **Table 2** 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 is based on the GaBi software database source for 2018.

Table 1. Inputs-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

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Table 2. 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, coal seam gas). These technologies encompass various parameters such as energy consumption, transport distances, and gas processing technologies. Pipeline transportation between the gas field and the coast is being 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) is estimated for the total supply of natural gas, including domestic production and imports. The inventory is primarily based on secondary data.
Electricity	Electricity is modelled according to the specific circumstances of the European Union. The modelling of the electricity mix includes 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 takes into consideration imported electricity. Secondly, the national emission and efficiency standards of power plants are modelled, as well as the proportion of electricity plants and combined heat and power (CHP) plants. Thirdly, the analysis considers the supply of specific energy carriers, considering both imported and domestically produced energy sources. This includes examining the properties of the energy carriers, such as their composition and energy content. The exploration, extraction, production, processing, and transport processes of the energy carrier supply chains are modelled according to the EU situation.
Geothermal energy	The product system uses renewable energy-related primary energy demand; for 1 MJ of electricity from geothermal power, 1.98 MJ of primary geothermal power is used.
Energy carriers and refinery products	The energy carriers are modelled based on the specific supply situation (refer to the electricity section above). A parameterized refinery model simulates diesel fuel, gasoline, technical gases, fuel oils, lubricants, and residues, such as bitumen, with 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 takes into consideration the specific product output spectrum of each country, which can vary from one country to another. The supply of crude oil is modelled based on the specific situation of each country and the properties of the available resources.

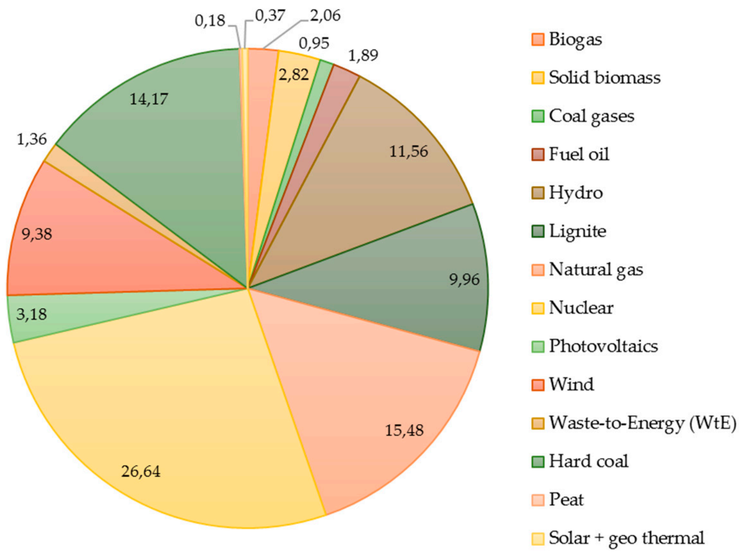

Figure 3. Energy mix in the European Union (based on the GaBi professional database and the GaBi extension database "Energy").

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 LCA, which primarily evaluates 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 [39,40]. 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 [41]. 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 measured 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 is 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 includes 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**.

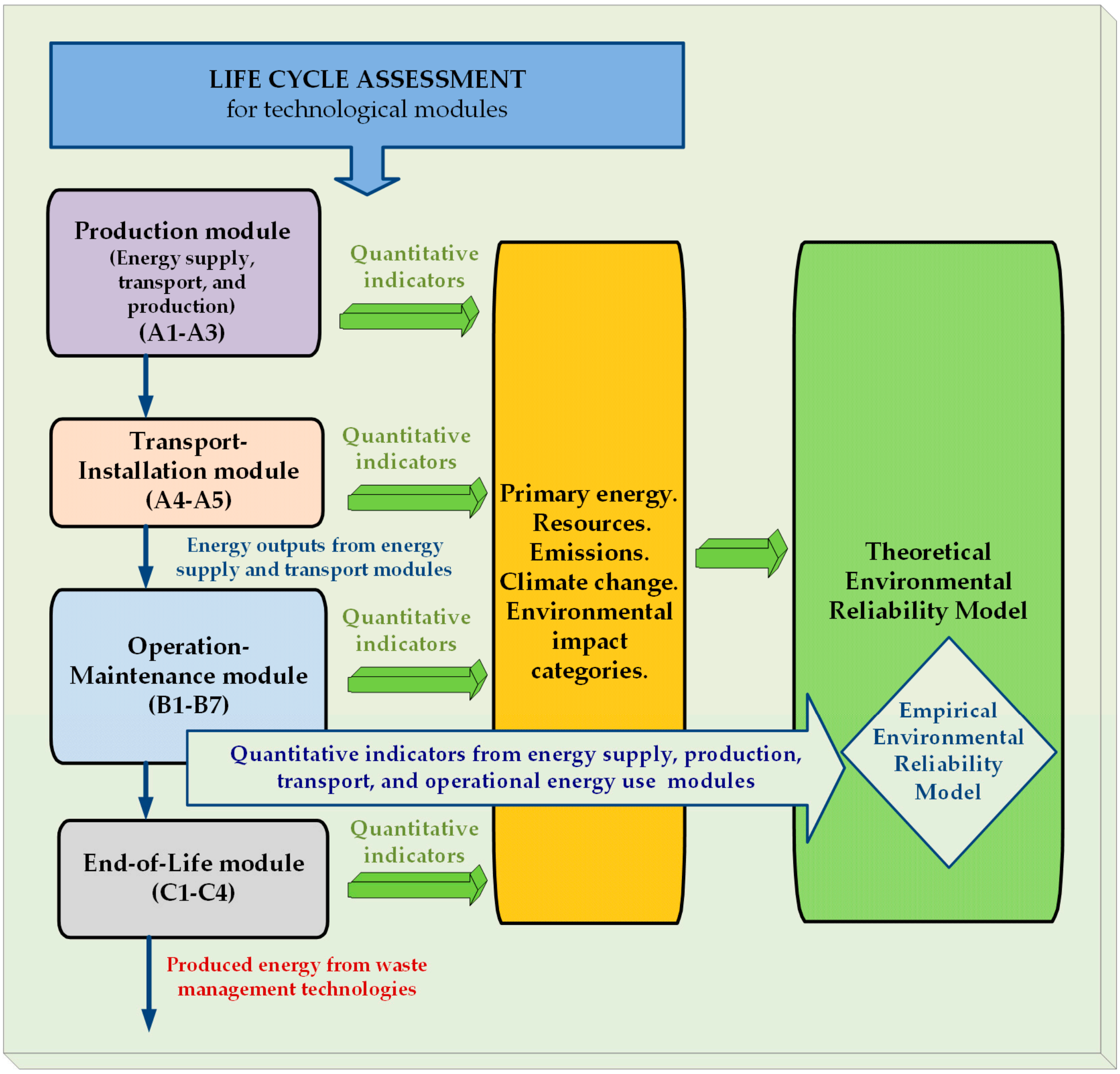

Figure 4. Technological modules for developing theoretical and empirical environmental reliability models.

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

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• 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 the 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 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.

The research only considers and summarizes some life cycle phases' actual environmental and energetic results. The newly developed model is empirical for the energy supply, production, transport, and operational energy use phases and provides accurate LCA results. In the case of the other life cycle stages of the building, the environmental reliability model has only been 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 the building. The complex decision-support model can shed light on the challenges of implementing multicriteria evaluation for complex and ambiguous problems, thereby establishing a process based

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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 observe how they are interconnected and build upon each other. **Figure 5** illustrates the primary steps involved in developing a complex decision-support model.

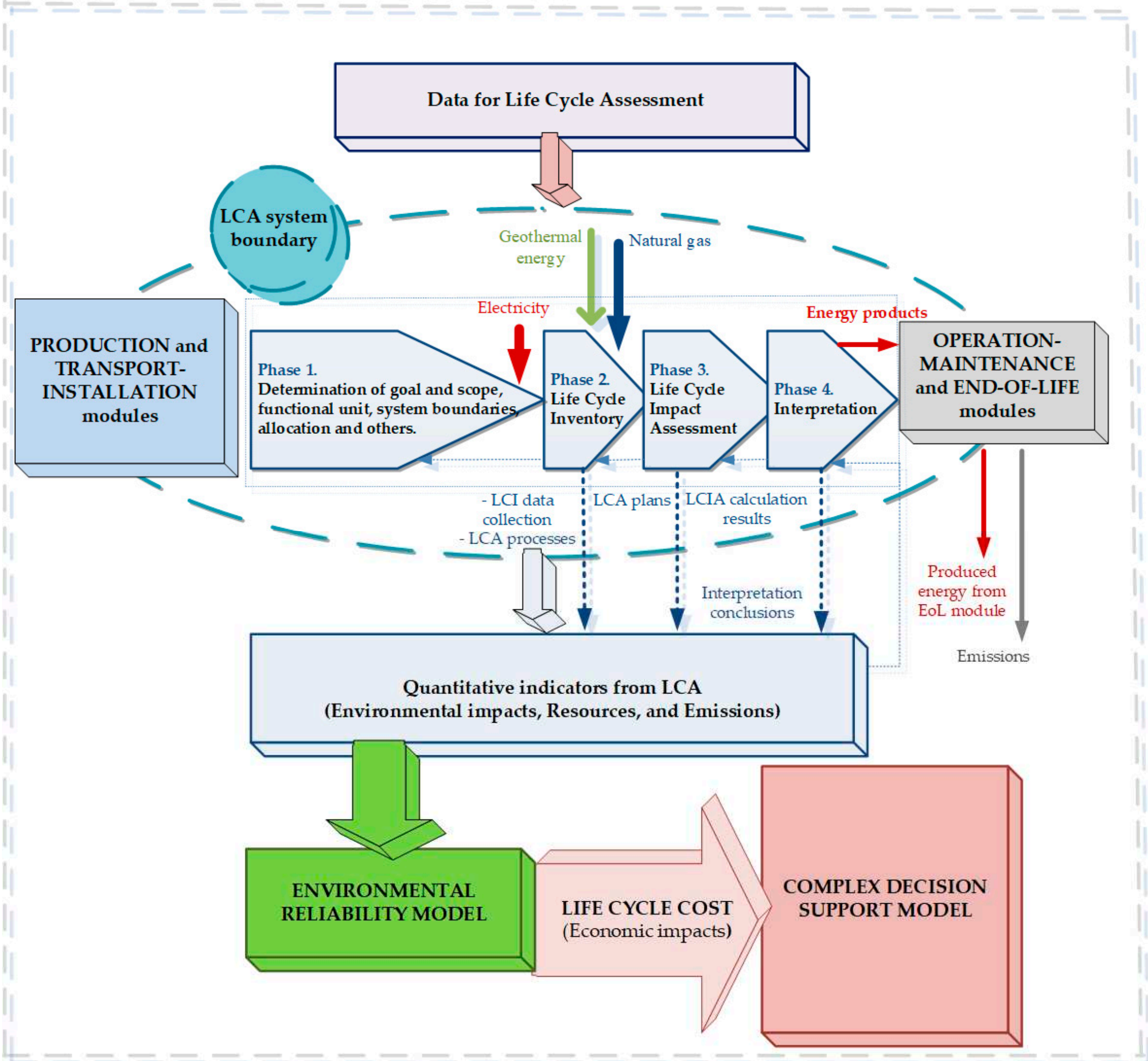

Figure 5. Steps for developing theoretical complex decision-support models.

Table 3 summarizes the most critical economic, environmental, and energy-related aspects of developing the comprehensive decision-support model for heating systems.

Table 3. 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, type of used fuel
	Rate and unit price of energy and water consumption
	Primary energy saving, energy transmission loss
	Power generation method, utilization of generated heat
	The life cycle of thermal engineering units, downtime, amortization
	Property, work and fire protection, safety technology

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	Building value, financing options, and innovation
Environmental aspects	Reduction of 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, thermal comfort
	Environmental building assessment system, 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, 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 of 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 examines 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 4** 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 5** presents the analyzed environmental quantities in person equivalents. Both tables summarize normalized and weighted values.

Table 4. 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 is 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

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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
Terrestric Ecotoxicity Pot. *TETP inf.*	0.02	3.36	1.80

Table 5. Environmental quantities related to thermal systems are 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. 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	0.0813
Environmental impact quantities (EF 3.0)	**System 1**	**System 2**	**System 3**
Climate change - total	0.00352	0.0151	0.00767
Land Use	1.92E-006	6.67E-006	5.56E-006
Particulate matter	3.88E-005	1200E-005	585E-005
Water use	482E-005	3.09E-005	76.8E-005

According to the calculated values in Tables 4 and 5 for both LCIA methods, the environmental impact quantities for the use of gas boilers are higher than those for heat pumps. Exceptions are the acidification potential and water use, which show 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 sulphur 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 is exceptionally high because this examined system incorporates electric power and natural gas, with fossil energy sources being predominantly utilized. Here, the proportion of renewable energy sources is only as much as the electricity mix in Figure 3. **Table 6** summarizes the amount of primary energy. According to this table, the primary energy values from renewable sources are significantly higher in heat pump systems compared to gas boiler systems. In particular, the proportion of renewable energy is higher for System 1. Here, the net primary energy value is 341 MJ, compared to the 3.56 MJ characteristic of System 2 and the 54 MJ value of System 3. This is 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 primary energy demand from renewable and non-renewable resources is very high for System 2 (552 MJ). **Figures 6–8** present the measurable normalized and weighted environmental impact categories as percentages.

Table 6. 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

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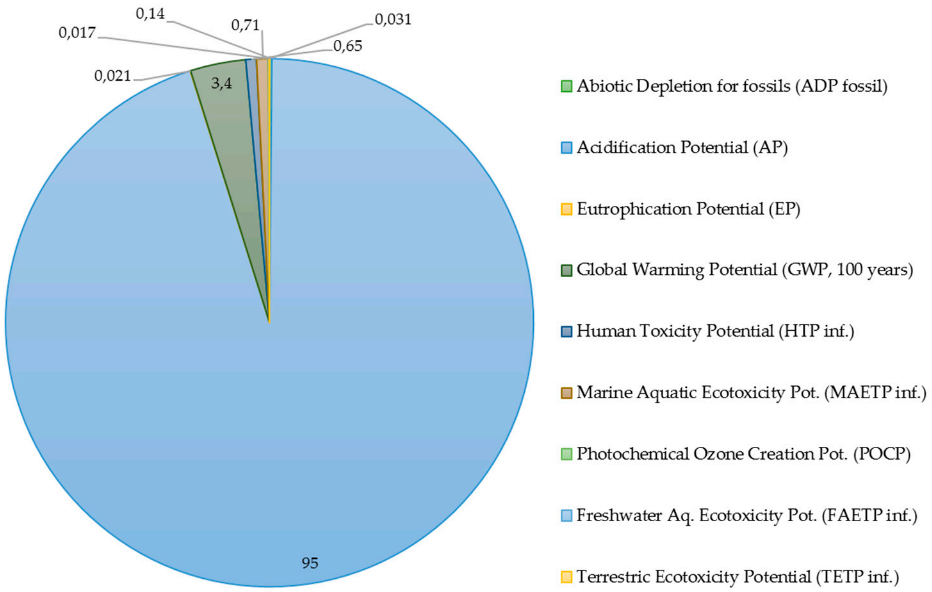

Figure 6. The measurable nine impact categories for System 1, expressed as percentages. (Normalization reference: CML 2016, EU 25 + 3, year 2000, excluding biogenic carbon. Weighting method: thinkstep LCIA Survey 2012, Europe, CML 2016, excluding biogenic carbon).

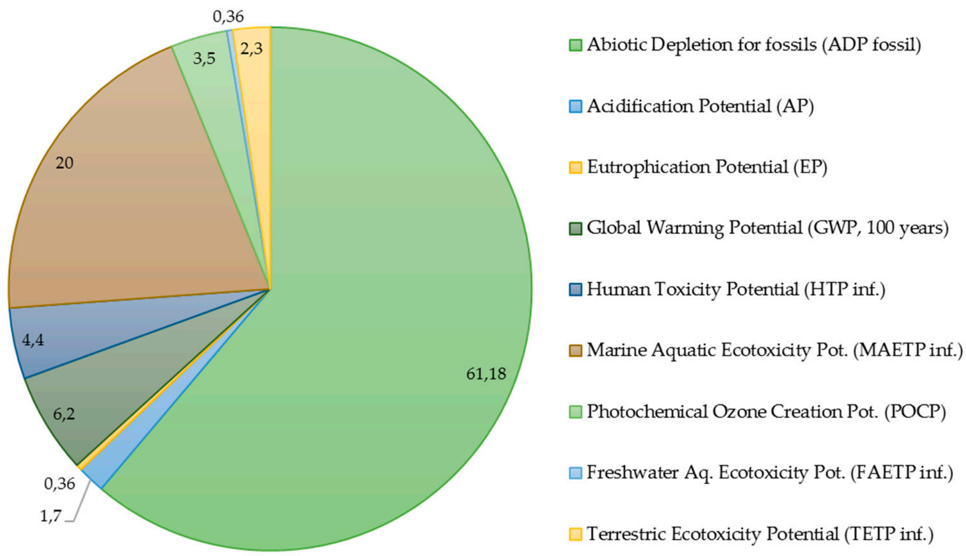

Figure 7. The measurable nine impact categories for System 2, expressed as percentages. (Normalization reference: CML 2016, EU 25 + 3, year 2000, excluding biogenic carbon. Weighting method: thinkstep LCIA Survey 2012, Europe, CML 2016, excluding biogenic carbon).

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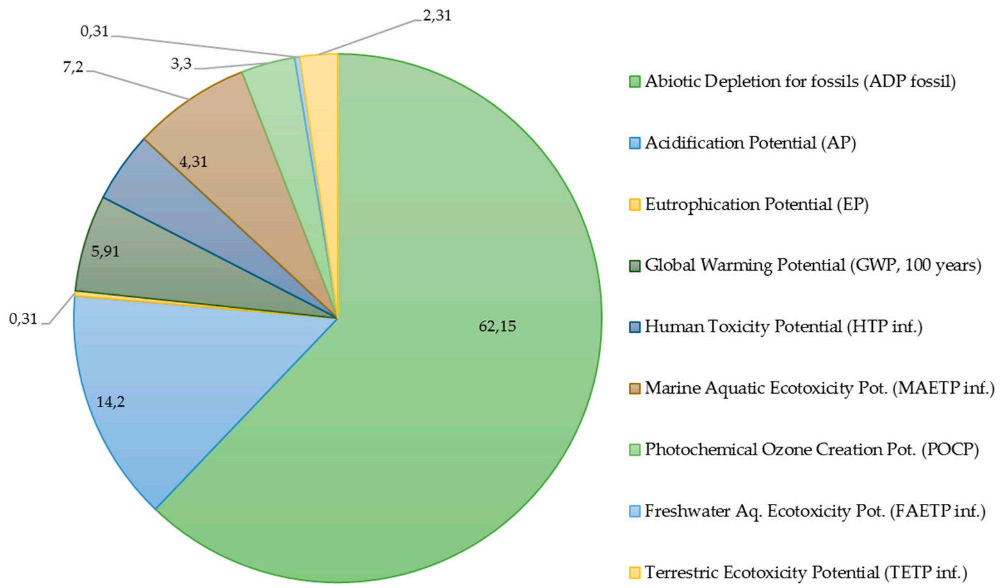

Figure 8. The measurable nine impact categories for System 3, expressed as percentages. (Normalization reference: CML 2016, EU 25 + 3, year 2000, excluding biogenic carbon. Weighting method: thinkstep LCIA Survey 2012, Europe, CML 2016, excluding biogenic carbon).

Several conclusions can be drawn based on Figures 6–8. For System 1, where only renewable energy is used, the results of the CML 2016 method show a significant increase in acidification potential, reaching 95%. At the same time, greenhouse gases also contribute significantly to emissions, resulting in a Global Warming Potential value of 3.4%. In this case, the geothermal heat pump utilizes 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 result in increased levels of acidification and greenhouse gas emissions. This leads to increased AP and GWP quotients. The results of the CML 2016 method yield very similar outcomes for systems 2 and 3 in terms of various environmental impact categories. The ADP values are 61.18% in System 2 and 62.15% in System 3.

Meanwhile, the GWP is 6.2% in System 2 and 5.91% in System 3. The HTP values range from 4.31% to 4.4%, and the POCP values range from 3.3% to 3.5% for both systems. In general, gas boiler and absorption heat pump systems have 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 is a significant discrepancy to be noted in one crucial category, namely the potential for acidification. In System 2, the value is 1.7%, whereas in System 3, it is 14%. The high ratio is 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 is primarily determined by the emission of nitrogen oxides into the environment, as mentioned previously. **Table 7** summarizes the quantities of material and energy resources, as well as the corresponding emission values, in kilograms.

Table 7. Resources and emissions regarding the thermal systems in kilograms. .

Resources and Emissions	System 1	System 2	System 3
Energy resources	0.0142	11.3	5.93
Material resources	173	1240	183
Emissions to air	153	29.5	28.5
Emissions to fresh water	17.9	1500	145

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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 has a higher resource load and emissions compared to heat pump systems, except for emissions into the air.

4. Discussion

This study aims to determine the environmental effects and primary energy requirements of both renewable and conventional heating systems. It does so by describing two newly developed models that can be used during the design phase of buildings. The developed empirical model for environmental reliability utilizes life cycle assessment calculations. The theoretical complex decision-support model also integrates the environmental LCA with the energetic and economic aspects.

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, it is essential to emphasize the importance of buildings with nearly zero energy requirements and to review and interpret the literature related to the energy efficiency of building thermal systems.

With the aim of achieving nearly zero energy buildings, the industry is striving to reduce environmental impact and improve energy efficiency in the future [42,43]. The design technology of various facilities is currently a research and development area in the construction industry. However, each building and thermal engineering system requires a unique assessment to identify opportunities for optimizing environmental loads, improving energy efficiency, and reducing costs. A regularly conducted life cycle assessment of a building's thermal system can provide essential information and be a fundamental element of its sustainability. The life cycle assessment results enable the optimization of various impact parameters during the operational stage of the life cycle. This optimization aims to achieve ideal energy efficiency and optimal costs when using buildings while minimizing environmental impacts [44,45]. Building companies need transparent and auditable guidelines to ensure accurate, consistent, and relevant environmental reporting. Integrating life cycle assessment results into the environmental-social-governance strategy helps representatives of the construction industry make informed decisions on how to enhance their sustainability performance [46].

During the research, the different life cycle results for the three scenarios can be compared separately by considering the ecological effects and primary energies of both renewable and conventional heating systems. The applied software database was continuously updated, which helped to determine the potential environmental impacts. Research results show that the environmental impact of gas boiler heating systems is higher than that of geothermal systems. This is because the assessment considers the energy inputs and associated loads. Comparing the three heating systems, the significant differences in results regarding total impact quantities are based on the ReCiPe LCIA approach. In the case of the CML method, the differences are higher for the abiotic depletion of fossil fuels, particularly when using a gas boiler, and the impact of acidification when applying an electric heat pump. The difference in primary energy demand between renewable and non-renewable resources is also significant. The primary energy values from renewable resources for the geothermal heating system (examined in System 1) were 6-10 times higher. The previously mentioned research study [19] also examined the comparison between electric heat pumps, absorption heat pumps, and gas boilers, similar to our own research. The study's results are consistent with ours, which indicates that the environmental impact of the absorption heat pump is smaller than that of the electric heat pump. Additionally, gas boilers impose a significant ecological burden.

The proposed models are built based on Figures 4 and 5, as well as Table 3. These are essential for improving energy efficiency and reducing environmental burdens through building design. When the environmental reliability model and the complex decision-support model accurately predict the parameters, it becomes possible to reduce the environmental loads of buildings. It reduces the cost of the operational phase by adjusting optimal operating parameters. The life cycle assessment results in Figures 6–8 show that fossil-abiotic depletion, global warming, and acidification have a higher environmental impact. The main factors influencing emissions are natural gas and electricity.

However, it should be noted here that the survey was conducted for Hungarian natural gas and the electricity mix of the European Union. The use of different natural gas sources, electricity mixes, and varying geographical locations can impact the validity of the research [47,48].

5. Conclusions

This study integrates environmental impacts and energy resources through the use of 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. The model described represents a possible integration of environmental, energy, and economic factors, offering reliability and comprehensive decision-support in an environmental context. In conclusion, it can be said that gas boiler and absorption heat pump systems have higher rates of environmental impact in various categories. 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.

A regularly conducted life cycle assessment of a building's thermal system can provide us with the necessary information and is a fundamental component of the building's sustainability certification. However, it is recommended to implement strategies aimed at reducing and optimizing the energy requirements, environmental impacts, and costs of thermal systems. Additionally, it is advisable to utilize developed models that are based on LCA. With the help of research findings, the energy efficiency of heating systems can be improved, resulting in a reduced environmental impact. The research work provides new information about renewable and non-renewable thermal systems. Research results can be beneficial in the construction industry by facilitating the integration of building information modelling and life cycle assessment.

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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	Groubd Source Heat Pump
GWP	Global Warming Potential
HTP	Human Toxicity Potential

HVAC	Heating, Ventilation and Air Condition
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MAETP	Marine Aquatic Ecotoxicity Potential
POCP	Photochemical Ozone Creation Potential
SDGs	Sustainable Development Goals
TETP	Terrestric Ecotoxicity Potential
WSHP	Water Source Heat Pump

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