

Article

Cradle-to-Grave LCA and Cost Assessment of Next-Generation Low-Temperature District Heating Networks

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Abstract

This study presents a cradle-to-grave Life Cycle Assessment (LCA) and cost analysis of next-generation low-temperature district heating networks based on water-condensed electric booster heat pumps. The research, conducted within the ENEA Portici Research Center framework, evaluates multiple case studies to assess environmental and economic sustainability. The system boundaries include heat generators (geothermal heat pump, solar thermal, and photovoltaic–thermal hybrid), network configurations (tree vs. ring), supply temperatures (25 °C vs. 45 °C), and renewable electricity shares (0–100%). Environmental impacts were quantified using the Environmental Footprint 3.1 method, focusing on key indicators such as climate change, resource use, and human toxicity. The results show that supply temperature is a critical factor: 45 °C scenarios lead to notably higher impacts, while network configuration has only marginal effects. Among generation technologies, the photovoltaic–thermal system proved the most sustainable, despite higher investment costs, whereas the solar thermal system displayed the largest environmental burden but lower costs. Geothermal systems showed intermediate performance, with notable impacts from mineral resource use. Renewable electricity integration consistently improved environmental outcomes, reducing climate change impacts by up to 10%. Storage system comparison revealed lithium iron phosphate (LFP) batteries as the most advantageous solution for electrical storage, and phase-change materials (PCM), particularly Rubitherm15, as the most environmentally favorable option for thermal storage, although traditional water tanks remain more cost-effective. Overall, the study highlights the crucial role of renewable integration and temperature optimization in enhancing the eco-efficiency of low-temperature district heating networks, providing guidelines for future sustainable design and deployment.

Keywords: district heating; life cycle assessment; carbon footprint; sustainable heating system



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1. Introduction

The energy sector is one of the largest contributors to global greenhouse gas emissions. Between 2020 and 2025, total emissions are estimated to range between 34 and 37 Gt CO₂ annually, with the European Union accounting for approximately 2.4–3 Gt CO₂ per year [1]. Within this context, the residential sector plays a particularly important role, representing

around 15% of global energy consumption [2]. In Europe, this share rose to 26.2% of final energy consumption in 2023 [3]. In Italy, the residential sector accounted for about 12.9% of total CO₂ emissions in 2022, corresponding to roughly 39.9 Mt CO₂ annually [4].

Despite its growing importance, the decarbonization potential of the residential sector remains largely underexploited. Among the different strategies available to reduce its emissions, district heating has emerged as a proven and effective solution [5]. At present, only 10% of residential demand in Europe is covered by renewable energy sources, while an additional 10% is met through district heating network (DHN) systems [6]. Globally, in 2022, district heating supplied around 9% of the total heating demand in buildings and industry, with no significant variation compared to 2021. Nevertheless, its potential contribution to emissions reduction remains far from being fully realized [6].

A major advantage of district heating lies in its ability to integrate low-carbon energy sources. This technology enables the use of a wide range of renewable and low-emission heat inputs, such as industrial waste heat, geothermal energy, and solar thermal energy [7]. Moreover, DHN systems improve the overall efficiency of the energy system, reducing distribution losses. On the demand side, the integration with heat pumps supports greater electrification of the heating sector, thereby facilitating the transition towards a more sustainable system less dependent on fossil fuels [7].

Over the past two decades, the scientific interest in DHN has increased substantially. As reported by Tien et al. (2025) [8], the number of publications on this topic grew considerably between 2007 and 2024, exceeding 7000 articles per year by 2024. Nevertheless, this rapid expansion has not been mirrored in the field of Life Cycle Assessment (LCA), where research remains limited. By 2023, only three dedicated studies had been published [8]. In the last two years, however, the literature has shown some progress, with the appearance of new case studies and critical reviews. With regard to LCA applications on DHN, several recent contributions stand out. Boussaid et al. (2025) [9] performed a comparative LCA of a district heating system, analyzing different energy portfolios typically used in DHN, including natural gas, biomass, and waste incineration. Marroquin et al. (2025) [10] assessed the global warming potential of a future geothermal-based district heating system in Oklahoma, which would repurpose inactive oil and gas wells. In parallel, Famiglietti et al. (2025) [11] conducted a critical review of LCA studies on large-scale heat pumps, identifying around ten relevant contributions. Although highly relevant for DHN applications, these studies primarily focused on the heat pump technology itself rather than on the district heating system as a whole. Furthermore, Gjoka et al. (2024) [12] carried out an LCA of a combined district heating and cooling network in the Australian context, thereby addressing both a geographical and methodological gap in the existing literature. In the Italian context, the number of LCA-oriented studies on DHN is still limited. For instance, Villa et al. (2025) [13] applied a Life Cycle Costing (LCC) approach to a 5th generation district heating system, without considering environmental impacts. Famiglietti et al. (2023) [14] analyzed the energy profile and climate benefits of a social housing district in Milan, in the framework of achieving net-zero carbon emissions. Additionally, Bartolozzi et al. (2023) [15] investigated a district heating project in Tuscany, highlighting both its environmental and socio-economic strengths and weaknesses.

In addition, many other studies use a simplified approach for calculating CO₂ emissions, as they are often estimated using a simple conversion factor between energy consumed and emissions, without adopting a full life cycle approach. Gustafsson et al. (2016) [16] analyze how energy efficiency measures in a multi-dwelling building in Gävle affect the marginal production of the district heating system, converting energy consumption into CO₂ eq using an emission factor. Zhang et al. (2022) [17] examine the spatio-temporal effects of socioeconomic and meteorological factors on CO₂ emissions from district heat-

ing systems in northern China, employing an equation-based approach that calculates emissions from energy consumption using a CO₂/kWh characterization factor. Wei et al. (2024) [18] propose an integrated dynamic model to predict urban district heating emissions in Heilongjiang Province (China, 2020–2060), applying conversion factors based on CO₂/kWh or coal and natural gas consumption. Finally, Pylsy et al. (2020) [19] develop a multimode district energy system model, including heating, cooling, CHP, heat pumps, and national electricity generation. They assess the impact of building energy efficiency measures through a conversion factor between energy and CO₂ eq. As highlighted by Autelitano et al. (2024) [20], there is a clear and important need to adopt standardized LCA methodologies that allow the assessment not only of CO₂ emissions but also of other environmental impacts using a “from cradle to grave” approach.

The review of the existing literature clearly shows that the application of LCA to DHN remains very limited, thus underlining the need for more case studies to advance the understanding of such systems. This imbalance highlights not only the limited amount of research adopting a LCA perspective, but also the scarcity of consistent and transparent Life Cycle Inventory (LCI) datasets. The lack of available and well-documented LCIs means that analysts and researchers aiming to perform LCA studies on such systems often face significant challenges. In particular, the absence of shared, standardized inventories, linked to well-established databases such as Ecoinvent or GaBi, makes the modeling process highly time-consuming and hinders the reproducibility and comparability of results across studies.

This imbalance highlights not only the scarcity of LCA-based research but also the lack of consistent datasets and life cycle inventories, which are crucial for a robust evaluation of the environmental performance of DHN. Furthermore, most of the available studies adopt a narrow technological perspective, focusing on individual components, such as heat pumps, rather than considering the DHN as an integrated system. This results in a shortage of system-level assessments that would encompass network infrastructure, energy mix composition, and opportunities for multi-technology integration. A further research gap lies in the absence of comparative analyses across different heat generation options within the same DHN configuration. To date, very few studies have systematically assessed the performance of alternative generation portfolios, thereby limiting the ability to identify optimal strategies for the decarbonization of district heating.

This work aims to partially address the gaps identified in the literature by presenting a cradle-to-grave LCA of a low-temperature (LT) DHN. This LT-DHN's supply temperature is approximately 25–45 °C; moreover, the end users are equipped with reversible heat pumps for both heating and cooling. This configuration falls within the category of fifth-generation district heating and cooling (5GDHC) or ambient loop systems, which are increasingly recognized in the literature as key enablers for the decarbonization of the thermal sector. Unlike conventional high-temperature district heating systems (supply temperature above 70 °C), which are predominantly based on fossil-fuel heat sources, this architecture allows for enhanced integration of renewable energy and waste heat recovery. These aspects are specifically addressed in this work through the analysis of multiple renewable energy integration strategies.

The analysis explores multiple dimensions, including the evaluation of different heat generation technologies, alternative network configurations, and various operational schemes. The study is applied to a real case in Portici, Campania (Italy), providing context-specific insights into the environmental performance of such systems. In addition to the environmental assessment, the work also incorporates an economic analysis, complemented by dedicated investigations on the role of both electrical and thermal storage systems.

2. Methodology

The system under investigation is a low-temperature thermal network installed at the ENEA research center in Portici (Italy), designed to simulate a district heating network. It supplies low-temperature heat to eight residential buildings that represent the end-users, each equipped with a water-to-water heat exchanger (9.8 kW), and a water-to-water heat pump (12.3 kW) including a 100-litre water buffer tank. The network also includes a central water-to-water heat pump (105 kW) equipped with a 1000-litre water buffer tank, which is used to experimentally simulate different types of central heat generator, and a distribution pipeline network connecting the central heat pump to the end-users. The analysis is based on the results of a thermodynamic model that assesses the sizing and performance of the DHN, providing estimates of energy consumption and system dimensions derived from previous projects [21,22].

The study focuses on scenario analysis based on life cycle inventories compiled using both primary data and secondary data from the literature. After identifying the most environmentally advantageous network configuration, the eco-efficiency of different heat generation technologies was assessed, with particular attention to the role of renewable energy sources in influencing the overall environmental impact.

Additionally, the investment cost of the various systems was evaluated. A comparative assessment of the environmental and economic performance of thermal and electrical storage solutions was carried out to determine the most efficient option for the analyzed system.

The LCA was conducted in accordance with ISO 14040 and ISO 14044 [23,24].

LCA framework consists of four main stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The goal and scope outline the purpose and boundaries of the study. During the LCI phase, data on inputs and outputs (such as energy and material use) are collected. In the LCIA phase, these data are translated into potential environmental impacts using specific indicators. Finally, the interpretation phase analyzes and contextualizes the results, suggesting possible improvements to minimize impacts. This article discusses the first two LCA steps in detail in Section 2.2 (Goal & Scope and System Boundary) and Section 2.3 (Life Cycle Inventory), while Section 3 (Results) presents the LCIA outcomes and their interpretation.

For LCIA phase, the Environmental Footprint (EF) 3.1 method was applied, which includes 16 environmental impact categories:

- Acidification (Ac), expressed in mol H⁺ eq;
- Climate Change (CC), expressed in kg CO₂ eq;
- Ecotoxicity: freshwater (Ecf), expressed in CTUe;
- Energy resources: non-renewable (Er), expressed in MJ;
- Eutrophication: freshwater (Euf), expressed in kg P eq;
- Eutrophication: marine (Eum), expressed in kg N eq;
- Eutrophication: terrestrial (Eut), expressed in kg N eq;
- Human toxicity: carcinogenic (Htc), expressed in CTUh;
- Human toxicity: non-carcinogenic (Htnc), expressed in CTUh;
- Ionising radiation: human health (Irh), expressed in kBq U²³⁵ eq;
- Land use (LU), expressed as a dimensionless indicator;
- Material resources: metals/minerals (Mr), expressed in kg Sb eq;
- Ozone depletion (OD), expressed in kg CFC-11 eq;
- Particulate matter formation (Pmf), expressed in disease incidence;
- Photochemical oxidant formation: human health (PO), expressed in kg NMVOC eq;
- Water use (WU), expressed in m³ world eq deprived.

The EF 3.1 methodology was selected to align with the most recent recommendations of the European Commission, as it represents the latest version released in 2022 [25]. Although the ReCiPe method is also widely applied in the scientific literature, its most recent version dates back to 2016 [26]. The analyses were carried out using the OpenLCA software v2.4.

The results were subsequently normalized and weighted in order to identify the most relevant impact categories. Detailed analysis was therefore focused on Climate Change, Ecotoxicity freshwater, Energy resources, Human toxicity carcinogenic, Human toxicity non-carcinogenic, Mineral resources, and Water Use, with particular emphasis on Climate Change, which emerged as the most critical category in terms of environmental impact and was also characterized by lower uncertainty and higher reliability of the results in Section 3.1.

2.1. Definition of the Case Studies

The case studies were developed by analyzing four interconnected aspects, covering both the distribution network and the final users. The first aspect concerns the type of heat generator adopted in the system. Three alternative technologies were considered: the geothermal water-to-water heat pump (GEO); the solar thermal system (ST), based on thermal collectors for heat production; the hybrid photovoltaic–thermal system (PVT), capable of producing both electricity and heat, thereby increasing overall efficiency.

The second aspect relates to the configuration of the distribution network supplying end users. Two different layouts were analyzed: tree configuration: a radial pipeline structure with a total length of 401 m; ring configuration: a circular pipeline structure with a total length of 538 m.

The third aspect is the operating temperature of the heat transfer fluid used to supply the users. Two levels were examined: 25 °C: representative of a low-temperature system that maximizes generator efficiency and minimizes thermal losses in the network; 45 °C: representative of a more traditional operating temperature, compatible with various building heating systems.

Finally, the fourth aspect refers to the share of renewable electricity employed to power the system. Four distinct scenarios were defined, corresponding to renewable contributions of 0%, 25%, 50%, and 100% of the total electricity demand. A summary is reported in Table 1 and a schematic figure of the system configurations is reported in Figure 1.

Table 1. Summary of Scenarios.

Level	Scenarios
Heat Generator	GEO (geothermal) ST (Solar Thermal) PVT (Hybrid PV-Thermal)
Network Configuration	TR RI
Operating Temperature [°C]	25 °C 45 °C
Renewable Electricity Share	0% 25% 50% 100%

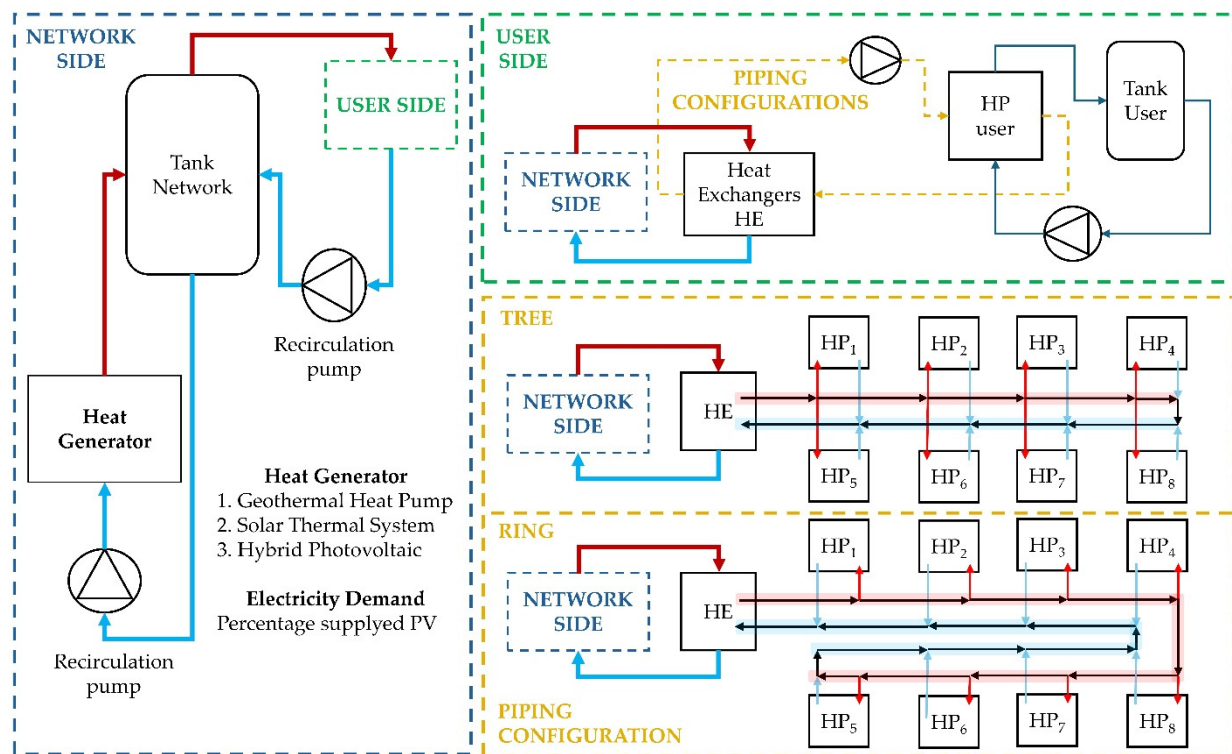


Figure 1. Schematic system configurations.

2.2. Goal & Scope and System Boundary

The specific objective of the analysis is to evaluate the environmental impacts of the district heating network described in the previous sections, with the aim of identifying the most promising operational scenario. The functional unit selected for comparison is 1 kWh of thermal energy delivered to end users. The system boundaries include all components required to perform a detailed assessment of the configurations under study. Three main macro-elements were considered:

1. Heat generator of the network;
2. Distribution network;
3. Energy transfer station devices.

Each of these elements varies according to the scenario analyzed, as defined in Section 2.1 (Definition of Case Study). The heat generator encompasses all infrastructures required by the specific technology under consideration (GEO, ST, or PVT). In all three cases, the generator is coupled with a heat exchanger and a thermal storage tank. The only exception is the GEO configuration, which also requires a geothermal well as an additional infrastructure component. For the distribution network, the materials used are identical across all configurations; however, pipe diameters and total lengths vary depending on the layout considered. All components that constitute the distribution system are included in the analysis, such as pipe supports, insulation materials, and the pumping and valve systems. Excavation works for buried pipelines are not considered due to the lack of reliable data. In addition, doubled streams are considered, taking into account both the supply and return lines. The energy transfer station devices corresponds to the heating system installed at the user's premises, represented by a heat pump. The analysis accounts for all functional components of the heat pump (evaporator, compressor, condenser, pipelines, and valve systems), as well as a storage tank for domestic hot water production. All other components not mentioned, such as air treatment units and humidity control devices, are not considered in the analysis.

Several elements are excluded from the system boundaries:

- Building-related interventions aimed at improving energy efficiency;
- Structural components of the buildings themselves;
- The transportation of components and materials during installation and construction phases.

Another important aspect is that the electricity grid infrastructure is not included within the system boundaries. Nevertheless, the analysis considers the environmental impacts associated with electricity consumption, whether sourced from the national grid or from renewable energy, as specified in Section 2.1 (Definition of Case Study). Finally, the adopted approach follows a cradle-to-grave perspective, covering all life cycle phases: construction, operation, maintenance, and end-of-life disposal. Figure 2 provides a schematic representation of the system boundaries.

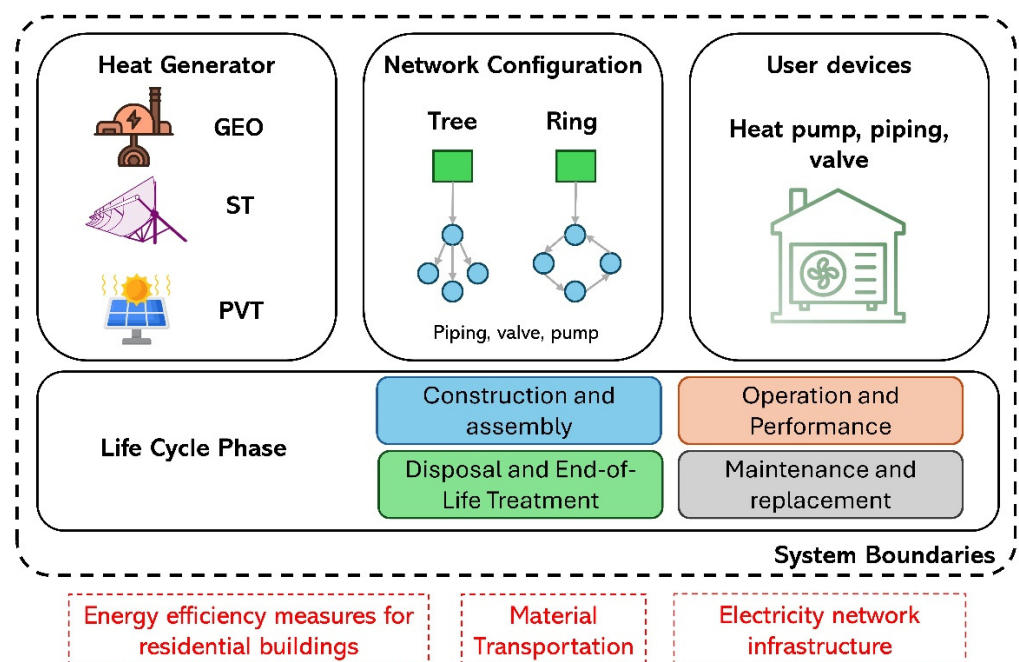


Figure 2. System Boundaries.

2.3. Life Cycle Inventory

The following data were used to build the LCI. It should be noted that the quantities reported in the tables below are absolute values, i.e., they are not normalized per functional unit. These data are representative of each process considered in the analysis.

The LCI is structured as follows:

- User-side construction phase (C-UT);
- Network-side construction phase (C-NETWORK);
- User-side operation phase (O-UT);
- Network-side operation phase (O-NETWORK);
- User-side maintenance (M-UT);
- Network-side maintenance (M-NETWORK);
- End-of-life/disposal phase (EoL).

The C-UT phase consists of several mechanical components: a heat exchanger (9–82 kW), a heat pump (12.3 kW), a 100 L storage tank, and a 20 W pump. The piping system is also included, composed of 5 m of pipes with 2 inch inner diameter and 20 m of pipes with 1 inch inner diameter. In addition, 15 kg of electronic control devices

are considered, representing valves, flow meters, and gate valves, as well as the water contained within the distribution system.

The providers used for the components are reported in Table 2.

Table 2. User Construction Phase.

Input	Amount	Unit	Provider
Electronic devices	15	kg	market for electronics, for control units electronics, for control units Cutoff, S-GLO
Heat exchanger	9.82	kW	HE_alfalaval
Heat pump	1.23	Item (s)	market for heat pump, brine-water, 10 kW heat pump, brine-water, 10 kW Cutoff, S-GLO
Tank	0.16667	Item (s)	market for hot water tank, 600l hot water tank, 600l Cutoff, S-GLO
Piping 2 inch	5	m	Piping_2"
Piping 1 inch	20	m	Piping_1"
Pump	20	W	market for pump, 40 W pump, 40 W Cutoff, S-GLO
Water	121.6	kg	market for tap water tap water Cutoff, S-Europe without Switzerland
Output			
C-UT	1	items	

Most of the providers used in the LCI are sourced from the Ecoinvent 3.10 database, with the exception of two components: HE_AlfaLaval and the piping system.

The HE_AlfaLaval model represents a heat exchanger supplied by Alfa Laval. This component was modeled according to the material specifications provided in the technical catalog of the model. The component is made entirely of stainless steel (Ecoinvent provider: *market for steel, chromium steel 18/8*) with a total weight of 21.2 kg.

The piping system consists primarily of low-alloy steel, stainless steel, and stone wool. The Ecoinvent processes used for these materials are:

- Market for steel, chromium steel 18/8;
- Market for steel, low-alloyed, hot rolled;
- Market for stone wool.

The network-side construction phase (C-NETWORK) has a structure similar to C-UT, but with different dimensions, resulting in variations in material quantities. Table 3 reports all the processes considered, including:

- Heat generator (105 kW);
- Storage tank (25 m³);
- Distribution pump, with power varying according to the scenario: approximately 22–23 kW for the 25 °C scenario, and 8–9 kW for the 45 °C scenario.

The pipes follow the same LCI processes as described previously; however, their lengths vary by scenario. The 1" pipes have a fixed length of 291 m, while the 2" pipes differ depending on the network configuration: 247 m for the ring layout and 110 m for the tree layout. These elements are doubled so that they consider both the supply side and the return side.

The network and user-side operation phases (O-NETWORK and O-UT) account exclusively for the electricity consumption of the distribution network and of the eight end users, respectively. These consumptions vary notably depending on the selected supply temperature. Specifically, the network is estimated to consume approximately 9900 kWh/year in the 25 °C scenario and 18,700 kWh/year in the 45 °C scenario. For the end users, the average consumption per building is 1700 kWh/year at 25 °C and

1550 kWh/year at 45 °C. This inversion in consumption patterns between network and users is attributable to the different pumping and heat transfer requirements under the two operating conditions. These values, derived from a model developed and validated within another project in ENEA, are reported in Table 4 and fully documented in the corresponding report [21,22].

Table 3. Network Construction Phase.

Input	Amount	Unit	Provider
Electronic devices	150	kg	market for electronics, for control units electronics, for control units Cutoff, S-GLO
Heat exchanger	105	kW	Heat Generator
Tank	12.5	Item (s)	market for heat storage, 2000l heat storage, 2000l Cutoff, S-GLO
Piping 1"	291	m	Piping_1"
Piping 2"	247 110	m	Piping_2"
Pump	23 9	kW	Pump Grid
Water	121.6	kg	market for tap water tap water Cutoff, S-Europe without Switzerland
Output C-Grid	1	items	

Table 4. User and Networks Operation Phases.

Electricity Consumption [kWh]	Operation Temperature 25 °C	Operation Temperature 45 °C
Grid	9900	18,700
User	1700	1550

The maintenance contributions (M-NETWORK and M-UT) refer to the annual replacement of materials used in the construction phases (C-NETWORK and C-UT), estimated at 2% per year, implying that approximately 60% of materials will be replaced over the system's lifetime. This estimation considers planned maintenance and the replacement of worn components. The end-of-life (EoL) phase is modeled by accounting for treatment, recycling, and disposal of materials, using processes consistent with those of the materials in the inventory and considering the recycling and disposal rates provided in the database.

A comparison between electrical and thermal storage systems was also carried out, with a parallel analysis of each system. The results section presents a comparison of both storage types.

For electrical storage, the functional unit is 1 kWh of storage capacity, comparing four types of lithium-ion batteries:

- Li-ion, LFP;
- Li-ion, LiMn₂O₄;
- Li-ion, NCA;
- Li-ion, NMC111.

Each battery type has a specific energy capacity as follows:

- LFP cells: 0.159 kWh/kg;
- LiMn₂O₄ cells: 0.114 kWh/kg;
- NCA cells: 0.224 kWh/kg;
- NMC111 cells: 0.197 kWh/kg.

For thermal storage, the functional unit is 1 kWh of thermal storage, comparing standard water-based systems (boilers) with innovative systems using phase change materials (PCM), specifically, Rubitemp15 and Puretemp15.

3. Results

3.1. Life Cycle Impact Assessment

The initial comparison presented in the analysis aims to highlight the differences between the scenarios considered in terms of network configuration (Tree vs. Ring) and the supply temperature of the heat transfer fluid (25 °C vs. 45 °C). For this reason, the following discussion focuses exclusively on the GEO system.

The results, reported in Figure 3, show the contribution of the different life cycle phases to various environmental indicators: construction (C), operation (O), maintenance (M), and EoL.

The first observation concerns the comparison between the two network configurations. Differences between the Tree and Ring layouts are generally marginal. The Tree network exhibits a slightly lower environmental impact, with an average reduction of about 1% compared to the Ring configuration across all analyzed indicators. This difference is primarily due to the shorter total pipeline length; as noted in Section 2.3 (“Life Cycle Inventory”), the Ring configuration includes approximately 137 additional meters of piping. At the system scale, this increase does not result in substantial changes in the overall environmental indicators.

Analyzing the impact contributions from the C-NETWORK phase, an important weight is observed only for specific indicators—ecotoxicity freshwater, human toxicity carcinogenic, and mineral resources—which account for 22%, 32%, and 20%, respectively. Within these percentages, the share attributable solely to the distribution network is about 1% of total impact, with the dominant contribution coming from the heat generator. This explains the low sensitivity of the comparison between Tree and Ring configurations when evaluated at the system level.

In contrast, the comparison between the two supply temperature levels shows substantial differences. The 45 °C scenario is less favorable than the 25 °C scenario, due to the higher electricity consumption required to achieve the elevated temperature. This effect is particularly evident in the Climate Change and Energy resources indicators, where electricity consumption accounts for over 70% of the total impact. In these cases, the 45 °C scenario results in an increase of approximately 20% for Climate Change and 30% for Energy resources compared to the 25 °C scenario.

For other indicators, where construction and maintenance phases play a more important role, such as human toxicity c, mineral resources, human toxicity non-carcinogenic, and ecotoxicity freshwater, the impact increase is smaller but still notable: 7–8% for human toxicity carcinogenic and mineral resources and 10–12% for human toxicity non-carcinogenic and ecotoxicity freshwater. In these cases, the main contributions come from metal components, particularly steel, which represent a substantial share of impacts in the construction and maintenance phases.

Finally, the EoL phase has a negligible effect on all analyzed indicators, highlighting that the overall environmental balance of the system is dominated by construction, operation, and maintenance phases.

Based on the results obtained, the subsequent graphs focus exclusively on the Tree network configuration, which, although only slightly, represents the least environmentally impactful solution overall. Figure 4 presents the comparison among the different heat generation technologies for the network. The indicators are expressed as percentages to allow a clearer and more effective comparison across the analyzed scenarios.

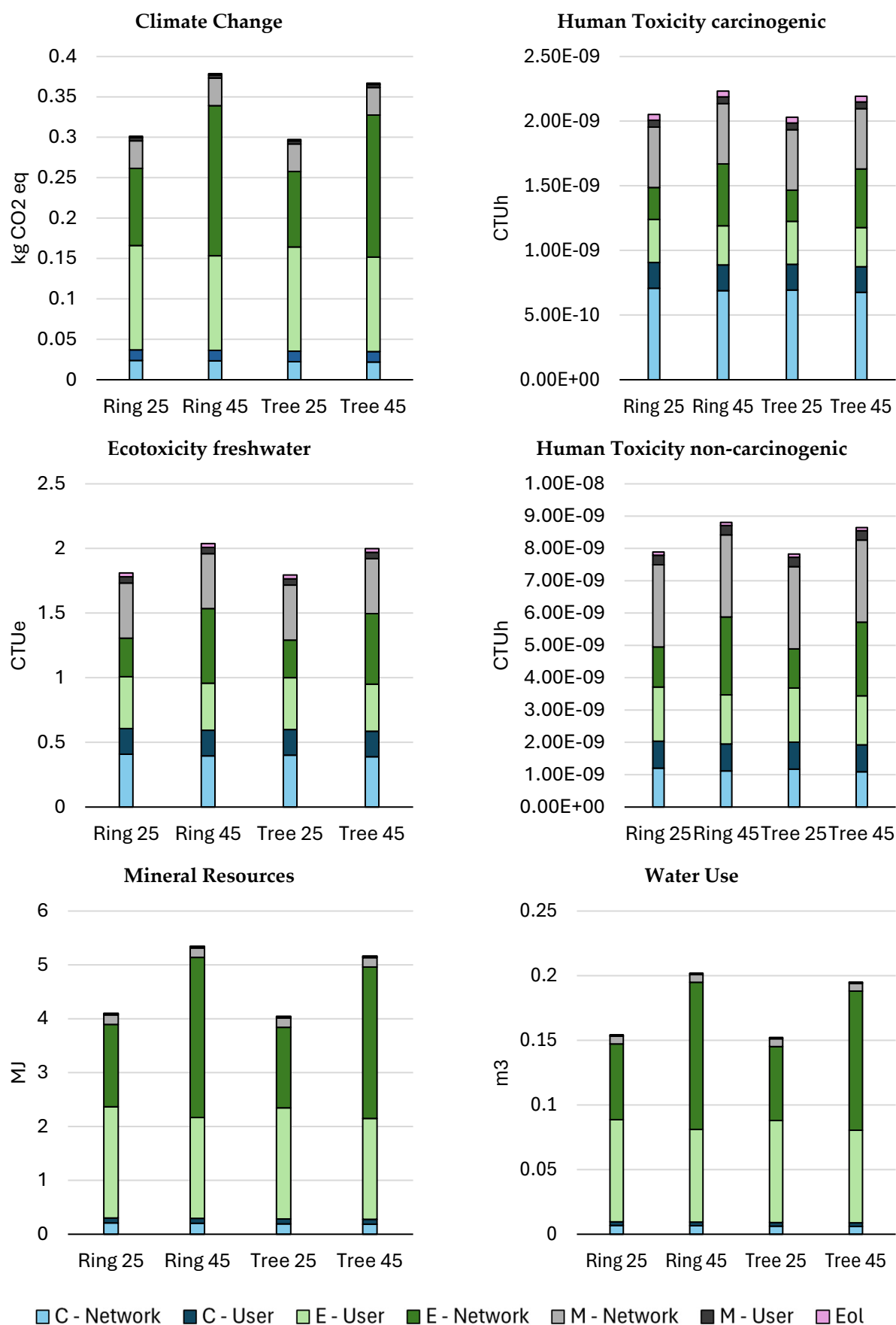


Figure 3. Environmental Impact Analysis of the Geothermal System under Tree/Ring Network Configurations and 25 °C/45 °C Supply Temperatures.

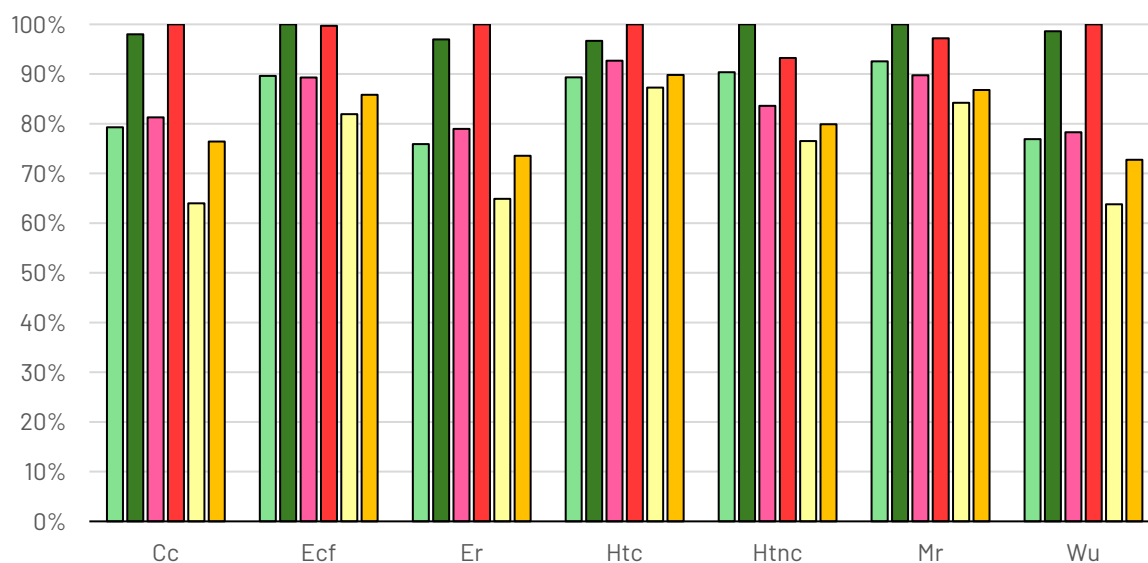


Figure 4. Environmental Impact Assessment of Different Heat Generation Technologies (GEO, ST, and PVT).

Significant differences between the technologies are evident, with particularly notable effects in some specific scenarios. The PVT hybrid system clearly stands out due to its ability to reduce environmental impacts associated with electricity consumption in the network, thanks to the direct production of a portion of electricity through integrated photovoltaic panels. This feature notably mitigates the contribution associated with the operation phase, with impact reductions reaching up to 25% in the climate change, energy resources, and water use indicators compared to the other technologies.

The comparative analysis of the indicators highlights substantial differences among the technologies. Specifically, ST emerges as the most impactful solution for the climate change, energy resources, human toxicity carcinogenic, and water use indicators, demonstrating that the materials and production processes associated with this technology notably affect the overall environmental balance. For the ecotoxicity freshwater indicator, the difference between ST and GEO is negligible, approximately 0.5%. Conversely, for the human toxicity non-carcinogenic and mineral resources indicators, GEO exhibits higher impacts than ST, primarily due to the use of high-impact materials, such as specific steels employed in the construction of the geothermal heat pump and extraction well.

The final comparison among the three heat generation technologies was conducted using the climate change environmental impact indicator as a reference, analyzed across different levels of renewable energy (RE) penetration and considering two supply temperature scenarios for end users: 25 °C and 45 °C. This is shown in Figure 5.

A baseline scenario was assumed, represented by a district heating network fed by a conventional boiler (Boiler + DH), which serves as a reference for evaluating the performance of the other solutions. As shown in Figure 5, all three considered technologies exhibit lower environmental impacts compared to the Boiler + DH scenario, confirming the role of the analyzed solutions in enhancing the sustainability of district heating systems.

However, in the 45 °C scenario without renewable energy penetration, the benefits are limited: impact reductions are approximately 6% for ST and 14% for GEO.

The integration of renewable energy, on the other hand, produces a substantial reduction in environmental impacts for all technologies examined. With a 25% renewable energy share, the average impact reduction is 10.24% in the 25 °C scenario and 9.53% in the 45 °C scenario.

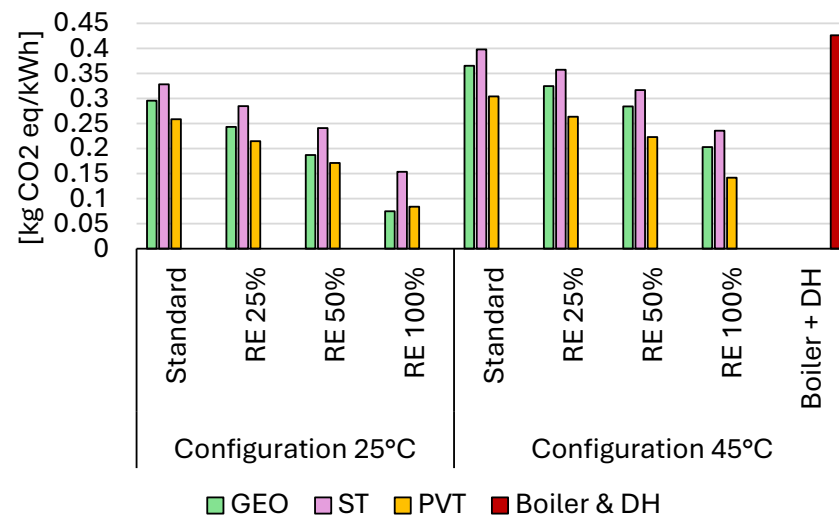


Figure 5. Comparison of Scenarios with Different Renewable Energy Penetration (Climate Change Environmental Indicator).

These results underscore the strategic importance of renewable energy deployment for optimizing environmental performance, regardless of the heat generation technology employed.

3.2. Economic Investment

In the economic analysis, the investment cost of the systems with the three different types of heat generators was evaluated, considering both Ring and Tree network configurations. It is important to note that the 25 °C and 45 °C supply temperature scenarios do not affect the investment cost. Due to the lack of data, the system equipment was assumed to operate at 25 °C, equivalent to its performance at 45 °C. It is acknowledged, however, that a realistic application at 45 °C would likely result in a slight increase in costs.

Figure 6 shows that, unlike the results obtained for environmental aspects, the PVT system exhibits the highest investment cost. This is solely due to the cost of the technology itself, as both the GEO and ST systems have lower costs compared to PVT, by approximately 11.5% and 16.2%, respectively. Regarding other costs, such as those related to end users, piping, and storage, no visible differences are observed among the different systems. However, a notable difference is found in the cost of piping between the Ring and Tree configurations, with the Tree configuration showing a 25% lower cost compared to the Ring configuration.

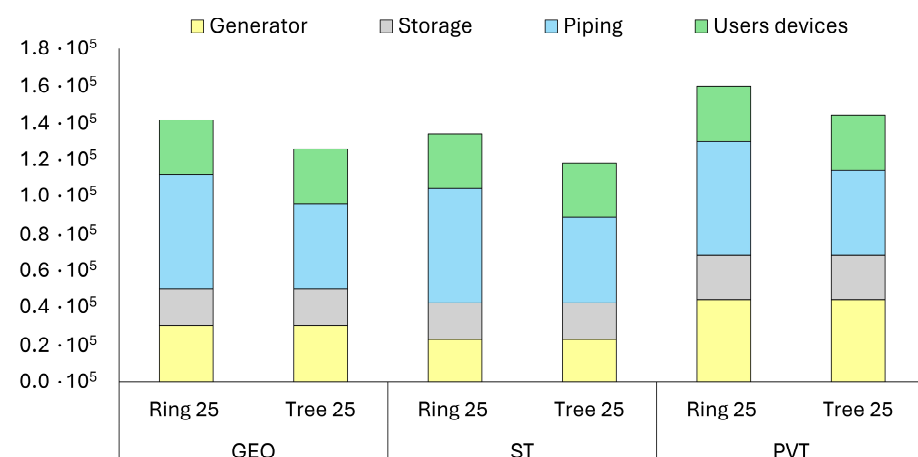
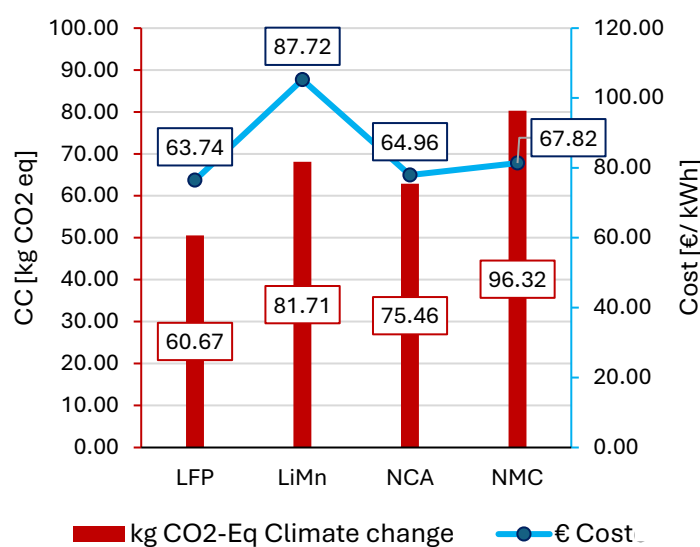


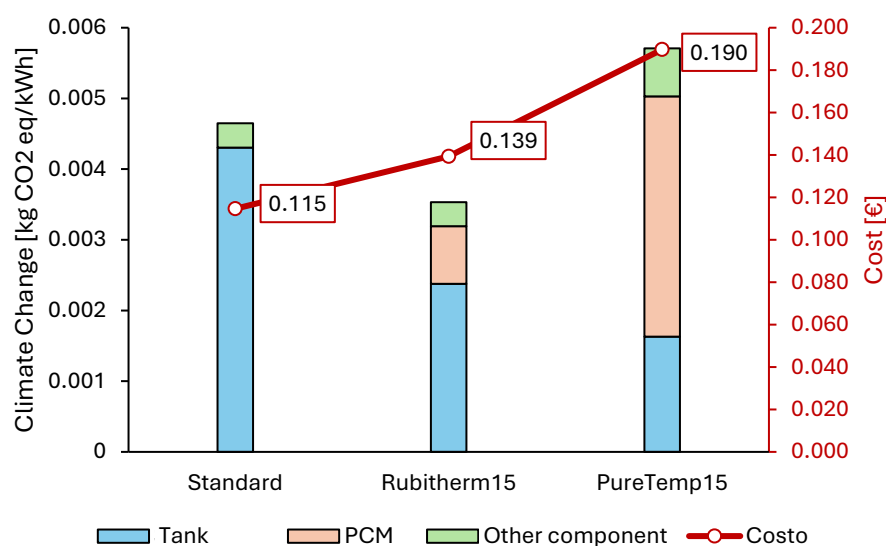
Figure 6. Investment Cost for Various District Heating Network Scenarios.

3.3. Electrical and Thermal Storage System Comparison

The analysis of electrical storage focused on the climate change environmental impact indicator and the cost per unit of capacity (1 kWh). The results (Figure 7A) indicate that LFP batteries have the lowest environmental impact, with a value of 60.67 kg CO₂ eq per kWh installed. In comparison, NCA, LiMn, and NMC batteries show respective increases in impact of 24.37%, 34.68%, and 58.76% relative to LFP. Regarding cost, LFP, NCA, and NMC batteries range between €64 and €68/kWh, while LiMn batteries are notably more expensive, with an additional cost of approximately €15/kWh. These data highlight that LFP batteries are the most advantageous from both an environmental and economic perspective. LFP cells, using abundant and low-cost materials such as iron and phosphate, provide environmental and economic benefits but have a lower energy density compared to NMC and NCA, making them heavier and bulkier for the same capacity.



(A)



(B)

Figure 7. Environmental and Economic Comparison of Electrical (A) and Thermal (B) Storage Systems.

The comparison of thermal storage systems for the network focuses on the climate change indicator and the economic cost per kWh of storage. The three systems examined include a standard water tank and two PCM-based systems: Rubitherm15 and PureTemp15.

The PCM systems are composed of the phase-change material and necessary components such as valves and meters.

Figure 7B shows that the environmental impact associated with tank construction varies depending on the tank size, which must be adapted to accommodate water or PCM. Additionally, the choice of PCM notably affects environmental impacts, with Rubitherm15 having an impact of 0.8 g CO₂ eq/kWh and PureTemp15 3.4 g CO₂ eq/kWh. Overall, the Rubitherm15 PCM system is the least environmentally impactful, with a value of 3.5 g CO₂ eq/kWh, compared to 4.6 g CO₂ eq/kWh for the standard system and 5.7 g CO₂ eq/kWh for the PureTemp15 system. Regarding economic cost, the standard system is the most affordable, at 11.5 c€/kWh, while the Rubitherm15 and PureTemp15 systems have costs of 13.9 c€/kWh and 19.0 c€/kWh, respectively. This highlights that, from an economic perspective, the standard water tank system is the most advantageous. In summary, the comparison demonstrates that cost-effectiveness, both environmental and economic, can vary notably depending on the type of PCM used. While PCMs may offer environmental benefits, the higher economic cost could limit their competitiveness relative to traditional water-based storage systems.

4. Discussion

In this section, the results are compared with existing literature and interpreted in light of their implications for policymakers and engineers working in the field.

The first key aspect concerns the importance of assessing DHNs from an environmental perspective in their entirety. As highlighted by Autelitano et al. (2024) [20], a life-cycle-based approach is essential, encompassing multiple environmental indicators. This represents a significant distinction from a large portion of the literature, which focuses exclusively on CO₂-equivalent emissions derived from energy consumption [16–19].

The results of this study demonstrate that several environmental impact categories (such as human toxicity carcinogenic and non-carcinogenic, Ecotoxicity) are largely driven by the use of metallic materials and components within the DHN infrastructure. The importance of broadening the analysis to include a wider range of indicators is further reinforced by literature, where many LCA studies limit their scope to the climate change indicator only [27,28], or to just two or three relevant categories [29,30]. Only a few studies provide a comprehensive evaluation covering a broad spectrum of environmental indicators [31,32].

Such an extended approach is crucial to avoid burden shifting, namely the reduction in impact in one category at the expense of an increase in another. Nevertheless, comparison with other studies remains largely limited to the climate change indicator for two main reasons. The first is political, as the goals of the Paris Agreement prioritize CO₂ emission reduction. The second is methodological: the climate change indicator is calculated using the IPCC model [33], which is consistently adopted across all major LCIA methodologies, including Environmental Footprint 3.1, ReCiPe 2016, CML, and ILCD. Conversely, these methodologies do not share common scientific models for other environmental categories, making direct comparison difficult. Consequently, climate change remains the only universally comparable indicator across literature. However, it remains essential to evaluate all environmental indicators through a cradle-to-grave approach, to define meaningful ranges of environmental sustainability.

Finally, this section discusses the main limitations of the present analysis, which also outline the directions for future research. These limitations include the absence of an uncertainty assessment for the input data used in the environmental model, the adoption of an energy-based functional unit that does not account for the quality of the heat supplied to end users, and an economic evaluation limited solely to investment costs. Future

developments of this work should therefore address these aspects to provide a more comprehensive and robust assessment.

5. Conclusions

This study has investigated the environmental and economic performance of a low-temperature DHN installed at the ENEA research center in Portici (Italy). The system, designed to replicate the operation of a real DHN, integrates multiple components, including a central heat generator, distributed storage units, and end-user substations, whose performance was evaluated through a dedicated thermodynamic model. Building upon this framework, a cradle-to-grave LCA was conducted to analyze the impacts of different heat generation technologies, alternative network configurations, and operational strategies. The assessment was complemented by an economic analysis and specific investigations on the role of both electrical and thermal storage systems. Collectively, the results provide a comprehensive picture of the trade-offs between environmental sustainability, energy efficiency, and cost-effectiveness in the deployment of low-temperature district heating solutions.

The results of the analysis indicate that, from an environmental perspective, the main factor influencing all scenarios is the overall energy contribution. This highlights the critical importance of reducing electricity consumption in order to maximize the performance of thermal systems. Moreover, visible environmental benefits are achieved through a higher integration of renewable energy sources. By contrast, the configuration of the DHN exhibits only a marginal impact on environmental indicators (approximately 1%), while having a more substantial effect on economic costs, with differences of around 25%.

A decisive parameter in the assessment is the supply temperature level: energy consumption, and consequently environmental impacts, increase considerably when operating at 45 °C. However, this variation is closely dependent on system design and the specific requirements of end-users.

Regarding the type of heat generator, the most environmentally sustainable option is the hybrid PVT system, albeit associated with the highest costs. Conversely, the ST system, while being the least sustainable in terms of several environmental indicators, proves to be the most cost-effective solution. An intermediate option is represented by the GEO system, which entails costs approximately 30% higher than the ST configuration but demonstrates reduced impacts in selected categories such as climate change, energy resources, human toxicity carcinogenic, and water use.

As for storage technologies, LFP batteries emerge as the most sustainable option for electrical storage, while PCM-based solutions, such as Rubitherm15, demonstrate the best environmental performance in thermal storage applications. Nevertheless, in terms of economic feasibility, conventional storage tanks remain the most advantageous option for thermal storage systems.

As a possible future development of this work, there is the investigation of heat quality as a functional unit and as a system output, by integrating an exergy-based approach and analyzing the differences in heat quality delivered to the end user. Another aspect to be addressed in future work is the incorporation of data uncertainty and the quantification of prediction errors in the assessment of environmental impacts. This would also enable the application of a Monte Carlo analysis on the final results, providing a more robust and statistically grounded evaluation.

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