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Life Cycle Assessment of District Heating Infrastructures: A Comparison of Pipe Typologies in France

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Abstract: Identifying decarbonization strategies at the district level is increasingly necessary to align the development of urban projects with European climate neutrality objectives. It is well known that district heating and cooling networks are an attractive energy system solution because they permit the integration of renewable energies and local excess of hot or cold sources. The detailed design and optimization of network infrastructures are essential to achieve the full potential of this energy system. The authors conducted an attributional life cycle assessment to compare the environmental profile of five distribution network infrastructures (i.e., pipes, heat carrier fluid, trenches, heat exchangers, valves, and water pumps) based on a study case in Marseille, France. The work aims to put into perspective the environmental profile of subsystems comprising a district heating infrastructure, and compare pipe typologies that can be used to guide decision-making in eco-design processing. Rigid and flexible piping systems were compared separately. The results show that the main impact source is the pipe subsystem, followed by the trench works for most impact categories. The authors underlined the importance of pipe typology choice, which can reduce emissions by up to 80% and 77% for rigid and flexible systems, respectively.

Keywords: district heating network; life cycle assessment; environmental impact; greenhouse gas emissions; pre-insulated pipes

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1. Introduction

Even though cities occupy only 2% of the continent's land areas, they represent 60% of global energy consumption, 70% of Greenhouse Gas (GHG) emissions, and 70% of global waste [1]. The scientific community repeatedly stresses the urgency of drastically reducing the impacts of cities. To address this issue, the European Commission (EC) has set a demanding objective, through its European Climate Law and Green Deal, to achieve at least 55% of GHG reduction by 2030 and reach a climate neutrality target by 2050. Legally binding since June 2021, the revised renewable energy directive [2] ensures the uptake of renewables in the transport sector, as well as in heating and cooling. To this end, District Heating and Cooling Networks (DHCNs) are identified as one of the main infrastructures allowing efficient integration of local renewable energies and valorizing excess heat or cold sources [3]. A District Cooling Network (DCN) is a cooling system with centralized production using cooling sources. The chilled water is transported through a pipe network and then transferred to the users' buildings through heat exchangers. A District Heating Network (DHN) is a centralized heat distribution system for multiple users' space heating and hot water generation. It comprises four functional parts: heat generation, the primary network, sub-stations, and the secondary network. The mutualization of heat production at the district level takes advantage of the density and proximity of inhabitants, i.e., the end users of heat. The coexistence in the city of different types of users of heat (offices, residential buildings, etc.) also allows the system to act as a heat storage and exchanger between buildings, increasing the efficiency of district heating, and responding to the high targets set for the building sector.

An extensive assessment of environmental impacts, beyond merely reporting GHG emissions, is increasingly required to reach these decarbonization goals. The Life Cycle Assessment (LCA) method is the internationally recognized quantitative method to address this need. It is considered the most reliable way to evaluate energy systems with complex components, such as DHCN [4,5]. To this end, the French environmental regulation "Réglementation Environnementale (RE) 2020" has set the LCA as a mandatory step for new buildings in France to integrate other relevant metrics, including energy use [6]. This indicator is highly relevant in the residential sector, which represents 22% of global energy use [7].

A literature review on LCA applied to DHNs identifies several articles and studies of interest. The LCA approach applied at DHCs enabled the drafting of considerations and recommendations useful in system design and management [8,9].

LCA studies on DHN were mainly provided to test and compare the efficiency of generators, considering their environmental profiles [10,11]. LCA analyses applied to DHNs also allowed the evaluation of different scenarios for integrating renewable sources [12]. In particular, the scenarios considered the use of low-temperature systems. Moreover, in these cases, the approach taken allowed the assessment of the environmental profile during the use phase of the systems [13]. Centralized solar heating plants with storage, including significative applicative case studies, were also analyzed. Rehman et al. (2018) adopted a life cycle approach to compare the performance between centralized or semi-centralized solar district heating systems for Finnish scenarios [14]. In some cases, the LCA approach was integrated with machine learning to study the optimal integration of solar-assisted district heating in different urban-sized communities [15].

Neirotti et al. (2019) compared heat distributed using a district heating network with individual appliances (natural gas boilers). The results highlight that the comparison heavily depends on the allocation method used for combined heat and power plant production [16]. A similar study with LCA was also applied to test the efficiency of existing district heating networks through applying a Phase Change Materials (PCMs) accumulator to the power plant [17,18]. This technology is designed for return temperature control in the network shared between multiple utilities [19,20].

Oliver-Solà et al. (2009) performed an LCA to determine the environmental impacts of a district heating infrastructure in an urban area. This study identified the subsystems that were the main contributors to the overall impact of the infrastructure, namely the dwellings and the power plant for their study case, followed by the service pipes [21]. Fröling et al. (2004) analyzed the different subsystems of the distribution subsystem of a DHN. When focusing on the service pipes of different Nominal Diameters (NDs), the results showed that the most important contributor to the environmental impact was material extraction and production of the steel pipes [22]. The excavation work mainly contributed to the network construction subsystem, especially the trench works [23]. Unlike previous papers, the authors of this article extended the evaluation of district heating networks by comparing different types of pipes and their influence on the overall infrastructure results, as well as analyzing the factors contributing to the environmental profile [11–17]. The novelty of the work was traced to the environmental outcomes obtained related to a district heating infrastructure. Thus, this work aims to provide a holistic viewpoint regarding the environmental burden of each DHN component, and answer the research question regarding which components should be evaluated more consistently or neglected by LCA practitioners. Moreover, it shows the environmental profiles of the five types of infrastructure considered.

The environmental performance of DHNs is highly dependent on their characteristics and the choice of distribution components, and can be divided into rigid and flexible piping systems. The rigid infrastructure consists of steel service pipes. These systems are designed for high temperatures and operating pressures, and serve as main pipelines in large district heating networks. These pipes are supplied in bars, and the service pipes must be welded on-site. Flexible piping systems usually consist of polymeric service pipes. Maximum operating temperatures and pressures are reduced. However, they have the advantage that long lengths can be laid in one piece because this type of pipe can be produced coiled as a loop and delivered to the construction site. Lengths of several hundred meters are common. This method greatly reduces the cost of splicing technology.

This variability in the choice of infrastructure is illustrated through the comparison of five different typologies of network pipes, among the most used in France. Of these five pre-insulated piping products, two are rigid systems with a black steel heat carrier pipe, insulated using either rock wool or PolyUrethane (PU) foam, and an external layer of stainless steel and PolyEthylene High Density (PEHD). The other three products are flexible systems with a heat carrier pipe in various polymers, namely PolyEthylene (PE) and PolyPropylene (PP), insulated with either PE of PU foams and an external layer of PEHD or PolyVinyl Chloride (PVC). To conduct this study, a model developed in the scope of this research was applied to a study case in Marseille, fixing all the input parameters to present sound results. The tool mentioned and the hypotheses followed are a valid model for virtually any district in France, but are not the scope of this article. Finally, a sensitivity analysis was conducted on the trench work subsystem to validate the action levers to prioritize.

The intended application of the model developed is integration into the LCA evaluation software UrbanPrint [24]. This software was developed by the research and development institute Efficacity, and aims to evaluate the environmental performance of any urban development project in France. The developed parametric LCA model would, therefore, guide decision makers through the design of either a new DHN (at the district scale) or the extension of an existing network (close to the district). The model used an attributional modeling approach, following the methodology of standards ISO 14040-44, EN 15978, and EN 15804 [25–29]. It was conducted using the ecoinvent 3.8 cut-off database [30].

2. Material and Methods

This section introduces the methodology used to assess the environmental profile of the DHN infrastructure and its variability when applying different typologies of pipes within the time boundaries of the study. Hereafter, the reported product systems are system boundaries, the functional unit, and the characterization method considered to conduct the study.

2.1. Product Systems

The product systems were defined considering the "cradle-to-grave" approach, following the European Normatives, EN 15978, which states the LCA methodology for construction products and services, and EN 15804+A1, which outlines the principles that define an Environmental Product Declaration (EPD)—in turn, quantifies the environmental impacts of a product according to a specific list of impact categories. The life cycle phases were organized from Module A to D. As this study aimed to focus on the DHN infrastructure, the use phase (module B) was excluded, except for Module B4 (replacement stage). Therefore, the modules considered were: (i) Module A—production (A1–3) and construction phase (A4–5), (ii) Module B4—replacement in the use stage, (iii) Module C—end-of-life stage (C1–4), and (iv) Module D—reuse, recovery, and recycling potential.

For each Module, the following components of a DHN were studied:

- the primary network was modeled, considering service pipes, trench works, and heat carrier fluid—in this case, water and water pumps;
- the substations were modeled, considering a heat exchanger and regulating valves—more precisely, a motorized regulating valve and a differential pressure regulator valve per substation. This type of valve was chosen by designers for reasons related to internal pressure management of the entire system [31].

Elbows, bends, fittings, and valve vaults were not considered in the study because not relevant for the comparison.

Figure 1 presents the product systems studied and the components of the infrastructures evaluated, hereafter designated as subsystems.

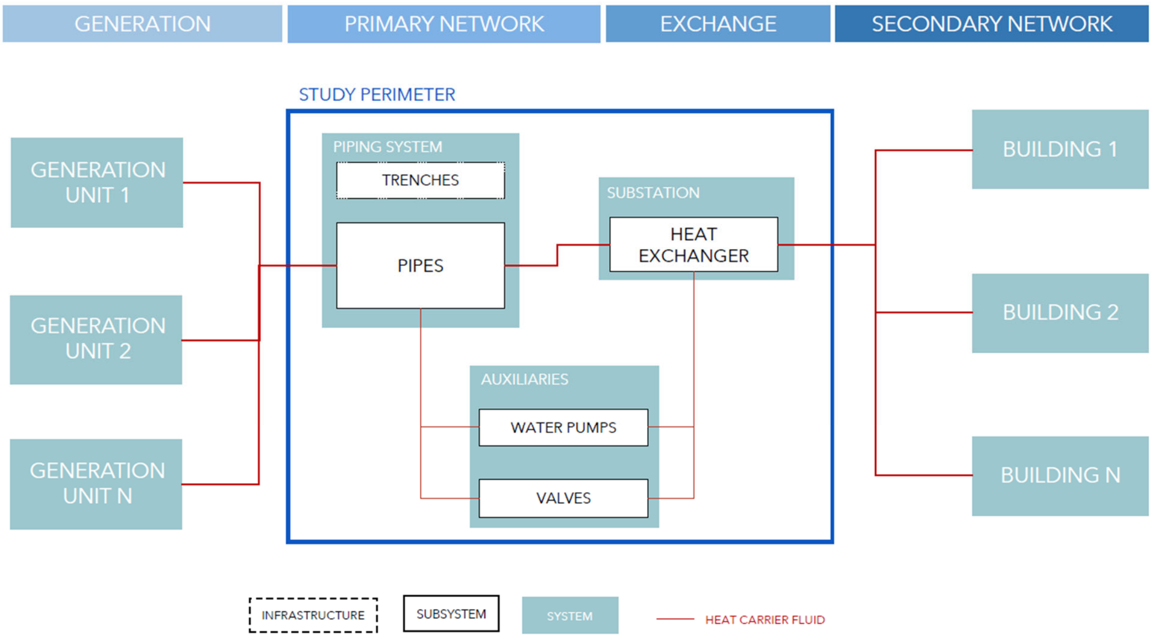

Figure 1. Product system composition.

The distribution pipes in the primary network were usually composed of three layers. From inside to outside, the layers were: (i) the fluid carrier pipe, which must resist water pressure or corrosion; (ii) the insulation layer, which avoids important thermal losses; and (iii) the external layer, which protects the insulation from external conditions. The study covers only single pipes, where one pipe is used for the supply part and another one for the return. Twin pipes are used when the supply and return heat carrier pipes are combined into the same insulation pipe. In this case, one larger pipe controls the supply and return of the water. Figure 2 represents the different layers of a single pipe.

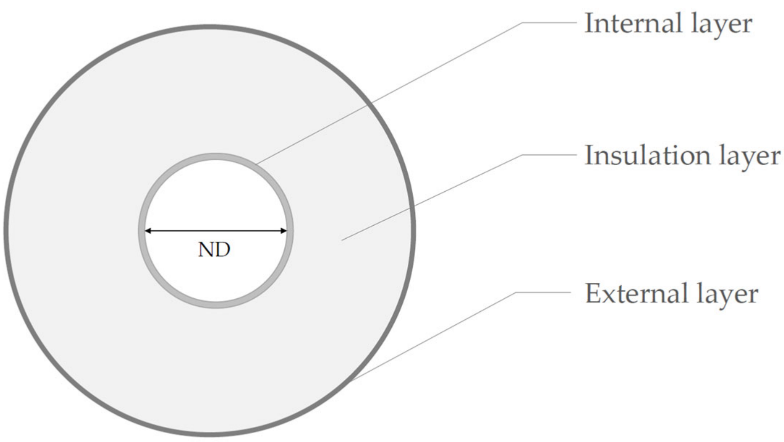

Figure 2. Single pipe composition.

Civil construction works were not considered in the substation component since one substation per building was designed [32]; it was located in the technical room of each building and, therefore, out of scope.

The packaging of these components was evaluated for heat exchangers, valves, and pumps. The packaging was excluded from the analysis for the other components considered irrelevant, as explained in the study conducted by ADEME, Solinnen, Crigen, and Tractebel (2020) on the environmental impact of renewable DHN for high power in France [32].

2.2. System Boundaries

Multifunctionalities were assessed following the ecoinvent library cut-off method [30]. Particularly for Module D, as defined via the standard EN 15804, potential benefits beyond the system boundaries were allocated as a 50–50 breakdown: 50% to the producer and 50% to the consumer. This partition is not described in the EN standard; however, it is indicated by the European Commission via the Circular Footprint Formula used in the Environmental Footprint Program. The decision to use allocation stems from the French Quartier Energie Carbone method [33]. The cut-off criteria were set at 1% of the mass and primary energy demand and emissions for inputs and outputs, respectively, as specified in EN 15804.

The time boundaries of this study had three different timeframes: (i) Reference Study Period (RSP), (ii) Required Service Life (ReqSL), and (iii) Estimated Service Life (ESL). The RSP was the temporal boundary in which the product system was assessed. The ReqSL was the timeframe in which the district heating network was required to provide its service without fail. To the best of the authors' knowledge, in France, and in Europe more generally, cases of dismantling the DHN system are difficult to find [3,21]. Therefore, RSP and ReqSL were assumed to be equal to 50 years. The ESL considered the lifespan of each component, and was used to evaluate the Number of Replacements (NR) needed for Module B4, based on Equation (1).

$$NR_{(i)} = rounded\ up\left(\frac{ReqSL}{ESL_{(i)}} - 1\right) \quad (1)$$

where:

- $NR_{(i)}$ is the number of replacements of the product, component, or element (i);
- $ReqSL$ is the required service life of the product, component, or element;
- $ESL_{(i)}$ is the estimated service life of the component (i).

Table 1 includes the ESL for the components studied and the reference.

Table 1. Number of replacements for each component.

Component	ESL [Years]	NR	Source
Pipes	30	1	CEN 2019 [34]
Water	30	1	CEN 2019 [34]
Trench	50	0	ADEME et al., 2020 [32]
Pumps	10	4	ADEME et al., 2020 [32]
Valves	15	4	Bartolozzi et al., 2017 [8]

2.3. Functional Unit

The Functional Unit (FU) of the analysis was set for (i) rigid (steel) infrastructures and (ii) flexible (polymer) infrastructures, considering a length of 100 m (including both flow and return pipe), one substation per building (considering in total 63 building within the district and approximately 1.42 substations each 100 m), and an RSP of 50 years, in compliance with previous studies (Fröling et al., Bartolozzi et al., and Oliver-Solà et al.) and indication provided by both Klöpffer and Grahl (2014) and Hauschild et al. (2018) [35,36]. Due to the different mechanical properties and applications (functions) of the two infrastructure typologies, other specifications were added to the definition of the FU for the product systems analyzed in this article:

- rigid infrastructures providing a supply temperature above 80–100 °C (not exceeding 140 °C) and thermal performance (U-value) of 0.331 W/(m^{2}K), with a ND of 450 mm. Generally used for third-generation DHN;

- flexible infrastructure providing a supply temperature up to 50–70 °C (not exceeding 80 °C) and thermal performance (U-value) of 0.267 W/(m^2K), with a ND of 500 mm. Generally used for fourth-generation DHN (though not for fifth-generation DHNs because they do not have thermal insulation around the pipes).

The NDs discussed above resulted from an economic analysis of the installation costs (considering three first-order influencing factors: pipe costs, assembly, and trench works) and operation costs (with, as a first-order factor, the cost of energy required to guarantee the flow of the heat carrier fluid), as better described in Section 3.2.

The thermal transmittance was calculated based on the material and thickness of each layer, as reported in the inventory presented in Section 3.3. The decision to maintain different thermal transmittances for each functional unit originated from the ambition of maintaining pipe products close to their initial layer thicknesses and, therefore, their real manufacture thermal transmittance.

2.4. Life Cycle Impacts Assessment Method

EN 15804+A1 presented the different impact categories required to conduct a complete and relevant LCA study, which are the mandatory parameters to conduct an Environmental Product Declaration (EPD). In France, the national normative XP P01-064/CN demands that EPDs of construction products be completed with two additional parameters: air pollution and water pollution [37]. The recent RE2020 excluded these two indicators; however, they are still presented in this work. Table 2 recaps the indicators used to conduct the LCA study.

Table 2. Impact categories list.

Types of Parameters	Impact Category	Acronyms	Unit	Source
Parameters describing environmental impacts	Global warming potential	GWP	kg CO_2 eq	EN 15804+A1
	Ozone depletion	OD	kg CFC-11 eq	
	Acidification for soil and water	A	kg SO_2 eq	
	Eutrophication	E	kg $PO_4{}^-$ eq	
	Photochemical ozone creation	POC	kg C_2H_4 eq	
	Depletion of abiotic resources -elements	DARe	kg Sb eq	
	Depletion of abiotic resources -fossil	DARf	MJ, High Heating Value (HHV)	
Additional national parameters	Water pollution	WP	m^3	XP P01-064/CN
	Air pollution	AP	m^3	
Parameters describing resource use	Renewable primary energy excl. raw materials (RM)	RPE	MJ, HHV	EN 15804+A1
	Renewable primary energy used as RM	RPERM	MJ, HHV	
	Total renewable primary energy	TRPE	MJ, HHV	
	Non-renewable primary energy excl. RM	NRPE	MJ, HHV	
	Non-renewable primary energy used as RM	NRPERM	MJ, HHV	
	Total non-renewable primary energy	TNRPE	MJ, HHV	
	Use of secondary material	USM	kg	
	Use of renewable secondary fuels	URSF	MJ, HHV	
	Use of non-renewable secondary fuels	UNRSF	MJ, HHV	
	Net use of fresh water	UFW	m^3	
Environmental information describing waste categories	Hazardous waste disposed	HW	kg	EN 15804+A1
	Non-hazardous waste disposed	NHW	kg	
	Radioactive waste disposed	RW	kg	
Environmental information describing output flows	Components for re-use	CRU	kg	EN 15804+A1
	Materials for recycling	MR	kg	
	Materials for energy recovery	MER	kg	
	Exported energy—electricity	EE_{elec}	MJ	
	Exported energy—thermal	EE_{th}	MJ	
	Exported energy—gas	EE_g	MJ	

3. Life Cycle Inventory Analysis—Case Study

The authors sized the different components according to a real case study, and gave a direct application of the results as a first scope of verification. The case study is located in the Port of Marseille, climatic zone H3—Mediterranean area, with a reference

1596 Heating Degree Day (HDD) characterized through RE2020 [6]. The district heating network was an extension (under construction) of the Massileo network, and will supply a new neighborhood called Les Fabriques [38].

3.1. Network Modeling and Sizing

The Les Fabriques project aims to use the Massileo district network extension for Space Heating (SH) and Domestic Hot Water (DHW). The total available floor area, estimated at 248,000 m^2 (i.e., the total area of the buildings, excluding the roof area, surface occupied by external walls, uncovered parts, stairwells, and common hallways), was linked to a maximum peak power (at substation level) evaluated at 12,663 kW_{th}—which stands for thermal kW—for the entire district [39].

The authors modeled the substation by considering plate heat exchangers, as recommended by ADEME [32]. To determine ratios of mass–capacity in kg/kW_{th}, the authors conducted a statistical analysis of brazed and gasketed heat exchangers, using the datasheet from the manufacturer Alfa Laval [40]. The distribution of ratios for mass–capacity was studied per cluster of capacities. The sensitivity analysis on gasketed plate heat exchangers derived from the sample of ratios concluded that the ratios ranged from 0.157 kg/kW_{th} to 0.281 kg/kW_{th}—in the case of capacities smaller than 550 kW_{th}, this range led to a variation lower than 1% for every impact category indicator. Therefore, the mean value at 0.211 kg/kW_{th} was considered for this study. Motorized regulation valves and differential pressure regulators, considered for every substation, were assumed from the technical datasheet of Danfoss and Caleffi, respectively [41,42].

The Massileo network extension includes the installation of 9000 m of pipes and three additional thermal generators, which will determine the number of water pumps (two for each additional production plant and six in total). The useful power of the pumps was determined from the flow rate and prevalence via the Darcy Weisbach formula [43]. The mass of the pumps was then assumed from the technical datasheets of Grundfos [44]. The trench works included (for a pre-existing urban area): the destruction of the existing bitumen pavement, excavation of the ground soil, on-site production and transport of sand and gravel to fill the trenches after placement of the pipes, and, finally, laying a new bitumen pavement [45].

3.2. Optimal Nominal Diameter

The Nominal Diameters (NDs) of the two infrastructures analyzed were fixed as equal to 450 mm (for the rigid) and 500 mm (for the flexible). The choice of Nominal Diameter for a district network is usually driven by economic reasons. The optimized capital cost must be found, considering the two main parameters affected by the ND: (i) the cost of pipes, including the installation, replacement, and maintenance, which increase with the ND; and (ii) the cost of electricity for water pumps, which depends on the water velocity (fixing the water flow rate). Since electricity consumption for pumping is the main source of cost, according to the firm A2A SpA, it is good practice to set the velocity of water for this type of network at approximately 2 m/s, in this case assuming a constant flow rate over the year of 302.5 L/s [46].

3.3. Pipe Typologies

After a benchmark analysis of various pipes in the main manufacturers operating in the French market (i.e., Wannitube [47], Inpal [48], Uponor [49], REHAU [50], ELPAST+ [51], and Interplast [52]), five representative products were selected: (i) two were are rigid pre-insulated systems (products A and B) with an internal layer of steel, and (ii) three were flexible pre-insulated systems in polymer materials (products C, D, and E). Table 3 and Figure 3 show the compositions of the five pipes analyzed and compared in this article.

Table 3. Pipe products compositions.

Characteristics	Steel (Rigid Systems) Product A	Product B	Polymer (Flexible Systems) Product C	Product D	Product E
Internal radius [m]	0.225	0.225	0.2204	0.2203	0.220
Heat carrier layer	Black steel	Black steel	Polyethylene (PE)	PE	PP
Thickness [mm]	5	4	29.6	29.7	30
Insulation	Rock wool	PU foam	PE foam	PU foam	PU foam
Thickness [mm]	70	82	110.5	97.1	93
Air layer	Yes	No	No	No	No
Thickness [mm]	25	0	0	0	0
External layer	Stainless steel	PEHD	PEHD	PEHD	PVC
Thickness [mm]	2	4	8	7.9	9.5
External radius [m]	0.352	0.340	0.3685	0.355	0.3525
U_{total} [W/(m^{2}K)]	0.331	0.331	0.267	0.267	0.267

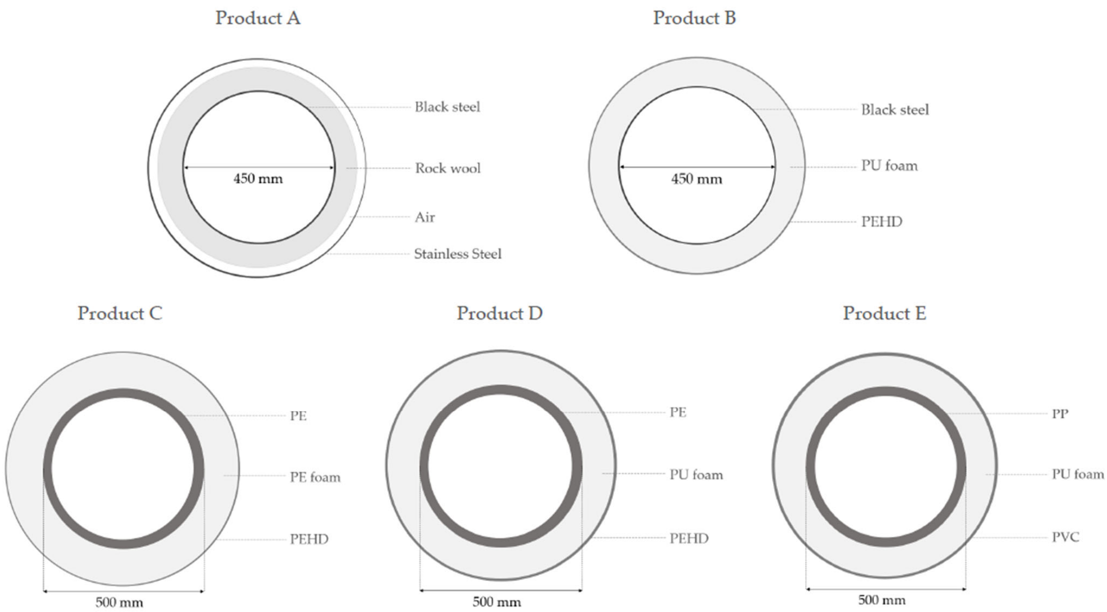

Figure 3. Products' composition: Products A and B (DN 450) and Products C, D, and E (DN 500).

3.4. Life Cycle Inventory Analysis

This section shows the life cycle inventory data used for the comparison. As explained above, the inventory originates from manufacturer technical data.

The inventory tables described the materials and weights of each component of the district heating infrastructures used for the study case (Tables 4 and 5), therefore, for the extension of 100 m (functional unit).

Table 4. Life cycle inventory for steel pipes (DN 450) with respect to FU.

Component	Element	Material	Amount	Unit
Product A Distribution pipe	Internal layer	Steel, low alloyed, hot rolled sheet	1.10×10^4	kg
	Isolation	Rock wool	1.74×10^3	kg
	External layer	Chromium steel	6.43×10^3	kg
Product B Distribution pipe	Internal layer	Steel, low alloyed, hot rolled sheet	8.83×10^3	kg
	Isolation	PU, rigid foam	1.54×10^3	kg
	External layer	PEHD, granulate	1.51×10^3	kg
Heat carrier fluid	Water supply and return (leakages included equal to 8%)	Tap water, underground	3.43×10^4	kg

Table 4. *Cont.*

Component	Element	Material	Amount	Unit
Trenches for product A	Destruction of existing pavement	-	2.21×10^2	m^2
	Excavation and refilling	Excavation, skid-steer loader	6.53×10^2	m^3
	Refilling material	Gravel, crushed	1.92×10^5	kg
		Sand	3.66×10^5	kg
	Installation of new road	Bitumen pavement production	2.21×10^2	m^2
Trenches for product B	Destruction of existing pavement	-	2.16×10^2	m^2
	Excavation and refilling	Excavation, skid-steer loader	6.30×10^2	m^3
	Refilling material	Gravel, crushed	1.85×10^5	kg
		Sand	3.53×10^5	kg
	Installation of new road	Bitumen pavement production	2.16×10^2	m^2
Substation	Water pumps	Chromium steel	1.19×10^2	kg
	Valves	Brass	4.71×10^1	kg
	Gasketed plate heat exchanger	Chromium steel	2.97×10^1	kg

Table 5. Life cycle inventory for steel pipes (DN 500) with respect to FU.

Component	Element	Material	Amount	Unit
Product C Distribution pipe	Internal layer	PEHD, granulate	8.13×10^3	kg
	Isolation	PE linear low density	1.08×10^3	kg
	External layer	PEHD, granulate	3.50×10^3	kg
	Heat carrier fluid supply and return (leakages included equal to 8%)	Tap water, underground	3.30×10^4	kg
Product D Distribution pipe	Internal layer	PEHD, granulate	8.16×10^3	kg
	Isolation	PU, rigid foam	2.01×10^3	kg
	External layer	PEHD, granulate	3.33×10^3	kg
	Heat carrier fluid supply and return (leakages included equal to 8%)	Tap water, underground	3.29×10^4	kg
Product E Distribution pipe	Internal layer	PP, granulate	7.80×10^3	kg
	Isolation	PU, rigid foam	1.92×10^3	kg
	External layer	PVC, suspension polymerized	6.18×10^3	kg
	Heat carrier fluid supply and return (leakages included equal to 8%)	Tap water, underground	3.28×10^4	kg
Trenches for product C	Destruction of existing pavement	-	2.37×10^2	m^2
	Excavation and refilling	Excavation, skid-steer loader	7.35×10^2	m^3
	Refilling material	Gravel, crushed	2.18×10^5	kg
		Sand	4.15×10^5	kg
	Installation of new road	Bitumen pavement production	2.37×10^2	m^2
Trenches for product D	Destruction of existing pavement	-	2.32×10^2	m^2
	Excavation and refilling	Excavation, skid-steer loader	7.07×10^2	m^3
	Refilling material	Gravel, crushed	2.09×10^5	kg
		Sand	3.98×10^5	kg
	Installation of new road	Bitumen pavement production	2.32×10^2	m^2
Trenches for product E	Destruction of existing pavement	-	2.31×10^2	m^2
	Excavation and refilling	Excavation, skid-steer loader	7.02×10^2	m^3
	Refilling material	Gravel, crushed	2.08×10^5	kg
		Sand	3.95×10^5	kg
	Installation of new road	Bitumen pavement production	2.31×10^2	m^2
Substation	Water pumps	Chromium steel	1.19×10^2	kg
	Valves	Brass	4.71×10^1	kg
	Gasketed plate heat exchanger	Chromium steel	2.97×10^1	kg

Distances and trucks used for the distribution of components from the manufacturing plants to the construction site are listed in Table 6. The scenarios for end of life and valorization (Modules C3, C4, and D) are provided in Table A4 (Appendix C).

Table 6. Transportation hypothesis.

Stage	Transport Mode	Distance [km]
Valves	Train	3000
	Truck EURO 6, lorry 16–32 metric ton	100
Heat exchangers	Truck EURO 6, lorry 16–32 metric ton	1000
Network pipes	Container ship, freight	10,000
	Truck EURO 6, lorry 16–32 metric ton	100
Others	Truck EURO 6, lorry 16–32 metric ton	100
End of life	Truck EURO 6, lorry 16–32 metric ton	100

4. Results

In this section, the authors present the steel and polymer infrastructure results. The impact category indicators listed in the following subsections are those with a variability greater than 20%; this minimum variability was selected to avoid the presentation of excessively redundant results. The outcomes obtained for the other indicators are shown in the Supplementary Material. Results for rigid infrastructure (steel) and flexible infrastructure (polymer) are presented separately; however, discussions might be the same for the two comparisons.

4.1. Rigid Infrastructure Comparison

As shown in Table A1, the most important life cycle phases are Modules A1–3 (production stage) and Module B4 (replacement). Overall, they represented more than 91% of the total impact. The Modules considering the materials' production are more impactful than the other stages (Modules A1–3 and B4 precisely). Module A4–5 never exceeded 9.1% (measured for Air Pollution), and Module C never exceeded 0.21%, except for net Use of Fresh Water (UFW), which reached −1.97% (negative due to the recovery of freshwater during the treatment).

Figure 4 shows the contribution of each subsystem evaluated (i.e., pipes, water, tranches, heat exchangers, pumps, and valves) for products A and B (steel infrastructures), considering the impact categories with variability higher than 20% and comparing the two products (as already stated). In all cases, the pipes were by far the main contributor, followed by the trench works or valves. Water and pumps are relatively less significant, as they never represent more than 2% and 13%, respectively. Heat exchanger contributor is irrelevant in comparison; for every impact, this contributor does not exceed 1% of the total. The impact category Depletion of Abiotic Resources—Elements (DARe) defines valves as the main contributor for product B due to casting brass consumption. The figure shows that Product B had a better environmental performance for all impact categories: its impact was reduced up to 80% for Hazardous Waste disposed (HW) compared to Product A. This result was due to the material difference of the external layer, as steel is more impactful.

To the best of the authors' knowledge, very few LCA studies present the breakdown in the infrastructures of a district heating system per component (i.e., pipes, trench, etc.). Fröling et al. (2004), Fröling et al. (2005), and Oliver-Solà (2009) give impacts for trenches and pipes using a pipe typology comparable to Product B (an internal steel layer, insulated with PU Foam, and an external layer of PEHD). For this product, the results obtained were aligned with the order of magnitude gathered in these previous studies. Oliver-Solà estimated an impact related to the main grid pipes (for the same length of 100 m, but an ND of 100 mm) equal to 3.00×10^4 kg CO_2eq [21]. This experiment's result was approximately three times lower than the outcome of this study (9.01×10^4 kg CO_2eq). The differences were related to the ND (100 vs. 450 mm) and the visualization of the contributions. Oliver-Solà allocated the burden of the excavation and refilling linked to the replacement of pipes to the trench; the authors of this article attributed these factors to the pipe subsystem. For the same reason, the results related to the trenches were much higher for Oliver-Solà (1.20×10^5 vs. 1.32×10^4 kg CO_2eq/FU). This important difference was also related to the production, destruction, and replacement of a rigid base layer in cement considered by Oliver-Solà. Regarding the trench, the result of 1.32×10^4 kg CO_2eq was coherent with the results presented by Fröling et al. (2005), which estimated the trench impacts at 1.1×10^4 kg CO_2eq for an ND 500 [23]. Regarding the pipe impacts, Fröling et al. (2004) studied the production of a pipe of ND 500 with a typology similar to Product B for 16 m. By rescaling the results to 100 m and doubling the values to simulate the replacement, the result was approximately 1×10^5, which is coherent with this study (9.1×10^4 kg CO_2eq/FU) [22]. Due to a lack of data, the impacts for other subsystems, such as the valves, water, pumps, or heat exchanger, were not compared.

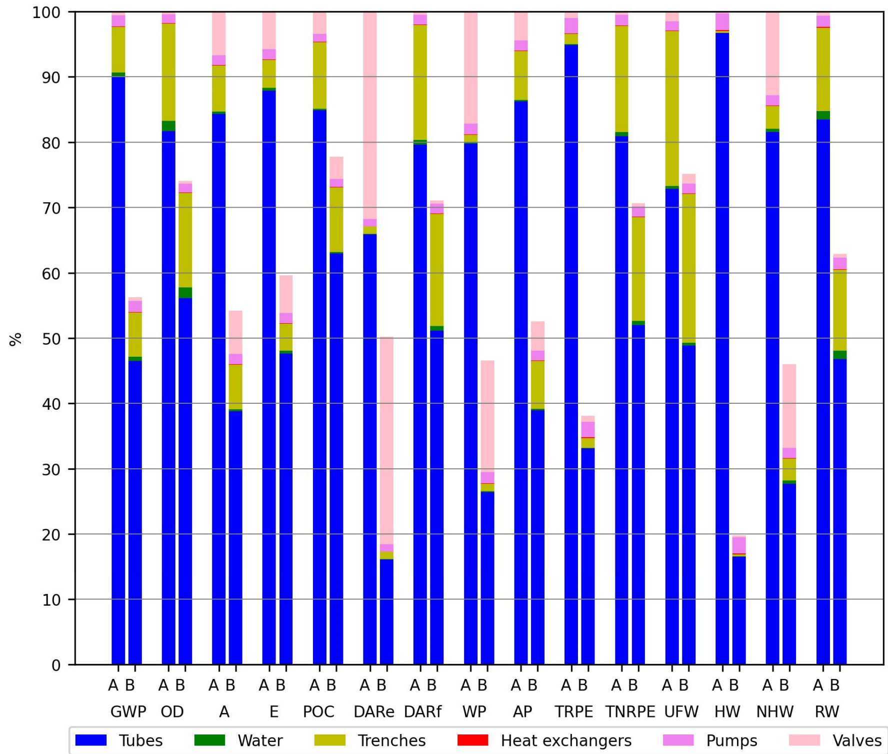

Figure 4. Relative comparison of products A and B per impact category and rigid infrastructures.

4.2. Flexible Infrastructure Comparison

As shown in Table A2, in this case, the most important life cycle phases were Modules A1–3 (production stage) and Module B4 (replacement). They represented at least 81% of the overall impact, followed by A4–5 (higher score of 19.5% for Air Pollution). Module C did not exceed 1% for the most impact categories, except for Net Use of Fresh Water (UFW), which reached negative values due to the recovery of freshwater during the treatment.

The relative breakdown per subsystem for polymer infrastructures gave a similar but not identical conclusion to steel infrastructures: the pipe subsystem was the main contributor in most impact categories (except for Ozone Depletion for product C, where the trench works were the majority contributor). It was followed by either the trench works (for Global Warming Potential, Ozone Depletion, Photochemical Ozone Creation, Air Pollution, Net Use of Fresh Water, and Radioactive Waste disposed) or the valves (for Eutrophication and Air Pollution). In the case of Total Renewable Primary Energy, the second contributor was the pumps. The heat exchangers also did not significantly contribute to the total impact. The pumps were more significant for polymer than steel infrastructures: they represented up to 10% for Renewable Primary Energy excluding RM; however, for Hazardous Waste

Disposed, it was estimated at 55% for product C. Similarly, the water contributed more than steel infrastructures, representing up to 4% for Ozone Depletion.

Comparing the products on the eight impact categories shown in Figure 5, we can see that four have Product D as the maximum (Global Warming Potential, Photochemical Ozone Creation, Air Pollution, and Net Use of Fresh Water), while five have Product E as the maximum (Ozone Depletion, Eutrophication, Renewable Primary Energy excluding RM, Total Renewable Primary Energy excluding Raw Materials, and Radioactive Waste Disposed). However, for all categories, Product C has the best environmental performance. This performance ranges from 23% (Ozone Depletion) to 78% (Global Warming Potential).

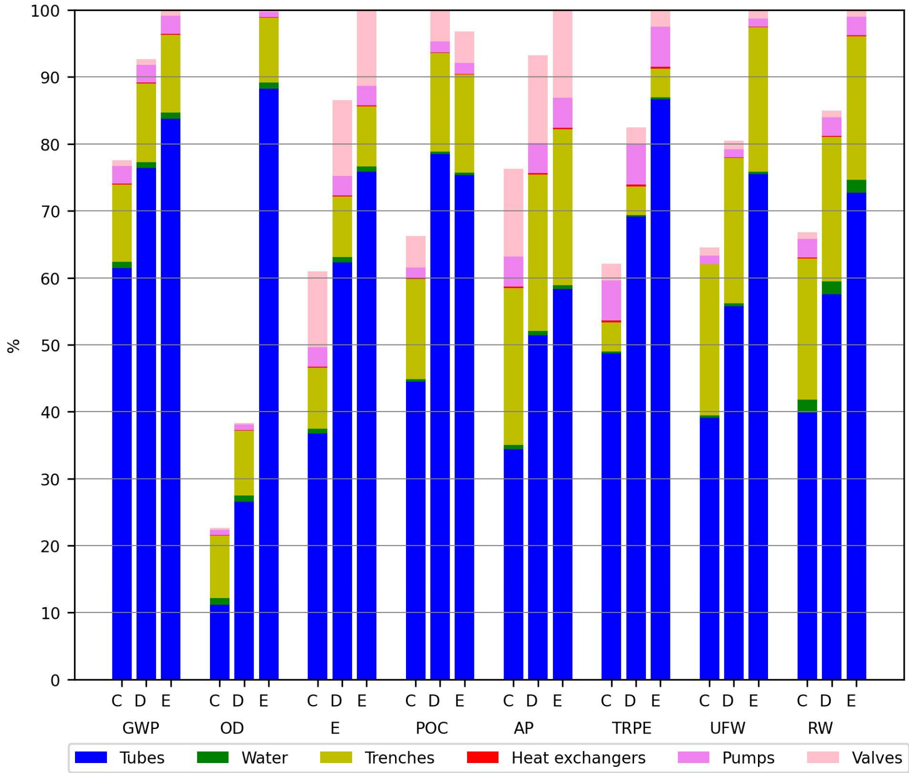

Figure 5. Relative comparison of products C, D, and E per impact category for flexible infrastructures.

In Table 7, the authors present the breakdown of the impacts of four different components: (i) the internal layer, (ii) the insulation, (iii) the external layer, and (iv) information related to the assembly or replacement works induced via the overall pipe (named "other" in the table). Since the pipe subsystem was the largest contributor to most impact categories, the table represents its absolute contribution. Results show that the "other" component was less significant for all impact indicators than the pipe layers; this outcome did not change significantly between both products.

The breakdown for product B proposed in this table is coherent with the GWP results of a comparable pipe typology studied by Fröling et al. (2004) and Oliver-Solà (2009), where the internal layers assessed were responsible for 66% and 67%, respectively.

The main reduction from product A to B stems from the external layer: galvanized steel for product A and PEHD for product B. The impact related to the external layer of product B was reduced by up to 99.8% for Hazardous Waste disposed compared to product A. However, the insulation layer of product B (PU foam) was more impactful for every impact category than that of product A (rock wool); this greater significance ranged from 1.5 (for Non-Hazardous Waste disposed) to 15 (for Net Use of Fresh Water).

For polymeric infrastructure, the most significant contributors were:

- for products D and E, the insulation represented the most significant contributor for all the impact categories shown in the table;

- for product C, the most important contributor was the external layer (except for Air Pollution).

Comparing the results between products, product C returned a better score for all impact categories due to the choice of insulation (PE foam). Indeed, products D and E had the same insulation material (PU foam); therefore, the related impacts were similar. However, for product E, the choice of PP as the internal layer (in PVC) caused a notable reduction when compared to the PEHD layer used for the other two products.

Table 7. Pipe components breakdown.

Impact Category	**Unit**	**Pipe Component**	**Rigid Infrastructure**		**Flexible Infrastructure**		
			A	**B**	**C**	**D**	**E**
Global Warming	kg CO_2 eq	Internal layer	7.42×10^4	5.93×10^4	4.66×10^4	4.68×10^4	4.37×10^4
		Insulation	4.82×10^3	2.07×10^4	7.67×10^3	2.70×10^4	2.58×10^4
		External layer	9.39×10^4	8.63×10^3	2.01×10^4	1.91×10^4	3.26×10^4
		Other	1.54×10^3	1.50×10^3	1.60×10^3	1.56×10^3	1.55×10^3
Ozone Depletion	kg CFC-11 eq	Internal layer	5.05×10^{-3}	4.03×10^{-3}	1.20×10^{-3}	1.20×10^{-3}	9.50×10^{-4}
		Insulation	3.10×10^{-4}	2.84×10^{-3}	3.61×10^{-4}	3.69×10^{-3}	3.52×10^{-3}
		External layer	5.08×10^{-3}	2.22×10^{-4}	5.15×10^{-4}	4.90×10^{-4}	1.41×10^{-2}
		Other	2.92×10^{-4}	2.85×10^{-4}	3.14×10^{-4}	3.06×10^{-4}	3.04×10^{-4}
Acidification for soil and water	kg SO_2 eq	Internal layer	3.13×10^2	2.50×10^2	-	-	-
		Insulation	4.20×10^1	1.01×10^2	-	-	-
		External layer	4.80×10^2	2.91×10^1	-	-	-
		Other	7.90×10^0	7.70×10^0	-	-	-
Eutrophication	kg PO_4^- eq	Internal layer	1.43×10^2	1.14×10^2	3.88×10^1	3.89×10^1	3.48×10^1
		Insulation	7.49×10^0	4.17×10^1	8.08×10^0	5.43×10^1	5.18×10^1
		External layer	1.52×10^2	7.18×10^0	1.67×10^1	1.59×10^1	4.65×10^1
		Other	1.64×10^0	1.60×10^0	1.64×10^0	1.59×10^0	1.58×10^0
Photochemical ozone creation	kg C_2H_4 eq	Internal layer	3.42×10^1	2.73×10^1	1.42×10^1	1.43×10^1	1.03×10^1
		Insulation	2.64×10^0	1.73×10^1	2.06×10^0	2.25×10^1	2.15×10^1
		External layer	2.81×10^1	2.63×10^0	6.11×10^0	5.81×10^0	8.94×10^0
		Other	3.74×10^0	3.66×10^0	4.00×10^0	3.91×10^0	3.89×10^0
Depletion of abiotic resources -elements	kg Sb eq	Internal layer	1.05×10^0	8.41×10^{-1}	-	-	-
		Insulation	5.74×10^{-2}	2.61×10^{-1}	-	-	-
		External layer	3.68×100	5.13×10^{-2}	-	-	-
		Other	2.46×10^{-2}	2.41×10^{-2}	-	-	-
Depletion of abiotic resources -fossil	MJ, HHV	Internal layer	8.12×10^5	6.49×10^5	-	-	-
		Insulation	5.58×10^4	3.45×10^5	-	-	-
		External layer	1.02×10^6	2.10×10^5	-	-	-
		Other	2.48×10^4	2.42×10^4	-	-	-
Water pollution	m^3	Internal layer	2.88×10^5	2.30×10^5	-	-	-
		Insulation	9.60×10^3	5.42×10^4	-	-	-
		External layer	5.97×10^5	1.16×10^4	-	-	-
		Other	8.89×10^2	8.74×10^2	-	-	-
Air pollution	m^3	Internal layer	1.77×10^7	1.41×10^7	2.19×10^6	2.19×10^6	2.04×10^6
		Insulation	7.48×10^5	2.55×10^6	4.01×10^5	3.32×10^6	3.17×10^6
		External layer	2.18×10^7	4.05×10^5	9.40×10^5	8.94×10^5	2.36×10^6
		Other	2.08×10^6	2.03×10^6	2.21×10^6	2.16×10^6	2.15×10^6
Total renewable primary energy	MJ, HHV	Internal layer	1.03×10^5	8.25×10^4	4.21×10^4	4.22×10^4	3.81×10^4
		Insulation	2.66×10^3	2.97×10^4	8.88×10^3	3.87×10^4	3.69×10^4
		External layer	2.39×10^5	7.78×10^3	1.81×10^4	1.72×10^4	4.81×10^4
		Other	3.51×10^2	3.45×10^2	1.96×10^2	1.91×10^2	1.90×10^2
Total non-renewable primary energy	MJ, HHV	Internal layer	9.54×10^5	7.63×10^5	-	-	-
		Insulation	5.68×10^4	4.09×10^5	-	-	-
		External layer	1.18×10^6	2.26×10^5	-	-	-
		Other	2.53×10^4	2.47×10^4	-	-	-
Net use of fresh water	m^3	Internal layer	5.99×10^2	4.78×10^2	4.21×10^4	4.22×10^4	3.81×10^4
		Insulation	2.81×10^1	4.28×10^2	8.88×10^3	3.87×10^4	3.69×10^4
		External layer	8.86×10^2	1.06×10^2	1.81×10^4	1.72×10^4	4.81×10^4
		Other	3.89×10^0	3.83×10^0	2.57×10^2	2.51×10^2	2.50×10^2

Table 7. *Cont.*

Impact Category	Unit	Pipe Component	Rigid Infrastructure A	B	Flexible Infrastructure C	D	E
Hazardous waste disposed	kg	Internal layer	1.93×10^4	1.54×10^4	-	-	-
		Insulation	1.10×10^2	7.10×10^2	-	-	-
		External layer	7.58×10^4	1.47×10^2	-	-	-
		Other	3.30×10^1	3.26×10^1	-	-	-
Non-hazardous waste disposed	kg	Internal layer	5.56×10^4	4.45×10^4	-	-	-
		Insulation	5.45×10^3	8.12×10^3	-	-	-
		External layer	1.01×10^5	1.81×10^3	-	-	-
		Other	1.22×10^3	1.19×10^3	-	-	-
Radioactive waste disposed	kg	Internal layer	3.65×10^0	2.91×10^0	5.74×10^2	5.76×10^2	5.08×10^2
		Insulation	9.24×10^{-2}	1.08×10^0	1.36×10^2	5.57×10^2	5.31×10^2
		External layer	3.95×10^0	2.40×10^{-1}	2.47×10^2	2.35×10^2	8.11×10^2
		Other	1.66×10^{-1}	1.62×10^{-1}	2.80×10^0	2.74×10^0	2.72×10^0

4.3. One at a Time Sensitivity Analysis

As underlined in the precedent section, the trench work often constituted the second most important contributor to a DHN infrastructure's environmental impacts. An additional step was, therefore, required to identify possible strategies to reduce the trench work impacts. Firstly, a breakdown of the contributor was conducted, and a sensitivity analysis was then performed on one of the most important identified factors. These tests were conducted on the functional unit, with Product A (selected as the reference product) and using a One-at-a-time Sensitivity Analysis (OAT-SA), which was performed through changing the value of uncertain factors one-at-a-time while keeping the others constant [53]. The main contributors of trench works were summarized as:

- excavation and refilling of the soil with the use of diesel work engines, which was designated as 'excavation';
- extraction and transport of filler material (e.g., sand and gravel) to fill the trenches after the pipes were installed, which was designated as 'filler material';
- destruction and relaying of a bitumen pavement if the network is in a district area with a pre-existing pavement, which was designated 'pavement replacement'.

A detailed breakdown of the results achieved for trench work subsystem impacts using these three components can be found in Table A3 (Appendix B). The outcomes show that pavement replacement and filler material were major contributors, whereas excavation was only represented up to 4%. These results led to the conclusion that eco-design strategies must be prioritized for importing filler material and replacing the existing pavement. Since new streets must be constructed in the case study, the strategies to avoid producing a new pavement are limited, while the study focuses on the reuse of filler material. Therefore, the OAT-SA was used to understand the influence on the overall infrastructure impacts if filler material originates from reuse.

Filler material was modeled by comparing the following two scenarios:

- scenario 1 (baseline)—trenches are filled using a layer of filler material imported from off-site locations.
- scenario 2—in total, 50% of trenches are built via reusing the excavated soil mass, while the rest are constructed using imported filler material.

Table 8 presents the outcomes obtained, in which the variation in percentages is assessed as:

$$\frac{Scenario\ 1 - Scenario\ 2}{Scenario\ 1} * 100 \quad (2)$$

The results showed that the strategy tested significantly influenced the trenches subsystem: the variation increases to 47% (for net Use of Fresh Water). However, the variation in the total infrastructure never exceeds 11% (always for Use of Fresh Water). Reducing environmental impacts through reuse of 50% of excavated soil can potentially reduce the trenches' contribution. This metric could have had a greater influence if more than 50% of the mass had been reused. This rate has been chosen arbitrarily to meet existing structural requirements that filler material brings to the road above the pipes. Nonetheless, this rate depends on the type of road constructed afterward and the type of soil located in the project location.

Table 8. Sensitivity Analysis results on filler material import in trench subsystem.

Impact Category	Unit	Total Variation	Trench Variation
Global warming	kg CO_2 eq	1.5%	22%
Ozone depletion	kg CFC-11 eq	2.8%	19%
Acidification for soil and water	kg SO_2 eq	1.7%	24%
Eutrophication	kg PO_4^- eq	1.3%	31%
Photochemical ozone creation	kg C_2H_4 eq	1.6%	16%
Depletion of abiotic resources—elements	kg Sb eq	0.3%	30%
Depletion of abiotic resources—fossil	MJ, HHV	1.6%	9%
Water pollution	m^3	0.5%	39%
Air pollution	m^3	0.9%	12%
Renewable primary energy excl. RM	MJ, HHV	0.5%	35%
Renewable primary energy used as RM	MJ, HHV	0.0%	0%
Total renewable primary energy	MJ, HHV	0.5%	35%
Non-renewable primary energy excl. RM	MJ, HHV	1.7%	19%
Non-renewable primary energy used as RM	MJ, HHV	0.0%	0%
Total non-renewable primary energy	MJ, HHV	1.5%	10%
Use of secondary material	kg	0.0%	0%
Use of renewable secondary fuels	MJ, HHV	0.0%	0%
Use of non-renewable secondary fuels	MJ, HHV	0.0%	0%
Net use of fresh water	m^3	11.0%	47%
Hazardous waste disposed	kg	0.1%	33%
Non-hazardous waste disposed	kg	1.0%	30%
Radioactive waste disposed	kg	2.6%	20%
Components for re-use	kg	0.0%	0%
Materials for recycling	kg	0.0%	0%
Materials for energy recovery	kg	0.0%	0%
Exported energy—electricity	MJ	0.0%	0%
Exported energy—thermal	MJ	0.0%	0%
Exported energy—gas	MJ	0.0%	0%

5. Discussion

The results for the overall DHN infrastructure were essential to understand which subsystems are important contributors and are, therefore, to be correctly sized and chosen. Figures 4 and 5 show that valves and pumps are relatively important and should not be overlooked in the infrastructure system analysis. Previous studies (Fröling et al., Bartolozzi et al., Oliver-Solà et al., Famiglietti 2021, Famiglietti 2023 [54], ADEME Solinnen Crigen and Tractebel) did not consider this component in the analysis; thus, it can be tracked as a finding of this article. The replacement works performed on the bitumen pavement were also a significant contributor; in most impact categories, replacement works represented the second most important subsystem. Moreover, the results showed that a heat exchanger's environmental impact on the district heating infrastructure was irrelevant. Finally, in most impact categories, the pipes subsystem represented the most critical contributor for the rigid (steel) and flexible (polymer) infrastructure.

The results have shown the importance of optimizing the use of materials and processes corresponding to certain materials in the environmental performance of the products analyzed. The distribution of impacts through life cycle stages is coherent with the findings of Fröling et al. (2004), who identified material production as the contributor of more than 93% of the overall impact [22]. The step to prioritize in an eco-design approach would be the choice of less impactful pipe materials. When choosing a piping system/manufacturer, the choice of material comprising the product is a primary influencer on the overall environmental impact on the district heating infrastructure. If the network's technical characteristics allow it, avoiding a steel layer can drastically cut the overall impact for rigid systems. Indeed, replacing the external steel layer with polymer can cut up to 80% of the impact. In flexible systems, the choice of insulation was seen to be a determinant: a PE foam is preferable to a PU foam (in the case study analyzed). Rockwool insulation can also induce a reduction in the impact. Regarding the choice of polymers for the internal or external layers, PEHD and PP have shown better environmental performance than PVC.

This comparison is especially relevant for DHN designers when choosing between different piping products in the design phase. As with comparable prices for the two steel and three polymer products, their environmental costs are shown to be clearly distinct, and induce a very different impact on the overall district infrastructure because the pipes are the main contributors.

6. Conclusions

In this work, the environmental performances of five district heating infrastructures were compared through the attributional life cycle approach, using ecoinvent 3.8 as a background database and EN 15804+A1 plus XP P01-064/CN as a characterization method. In particular, two different infrastructure typologies, with different mechanical properties and applications (functions), were analyzed and then compared separately:

- two rigid infrastructures composed of (i) steel pipes, (ii) rock wool or polyurethane rigid foam as insulation, and (iii) an external layer in steel or high-density polyethylene. To supply temperatures above 80–100 °C (not exceeding 140 °C) and thermal performance, these infrastructures are generally used for third generation district heating networks;
- three flexible infrastructures composed of (i) polymeric pipes in high- or low-density polyethylene, polypropylene, or polyvinyl chloride; (ii) low-density polyethylene linear or polyurethane rigid foam as insulation; and (iii) an external layer in polyethylene high density, low density-polyethylene linear, or polyvinyl chloride. To supply temperature up to 50–70 °C (not exceeding 80 °C), these infrastructures are generally used for fourth generation district heating networks.

The calculation was performed for a new district called Les Fabriques located in Marseille, France, which will be realized in the following year with a total available floor area estimated at 248,000 m^2. The district will have a network of 9 km in length, providing space heating and domestic hot water service. The authors derived the following conclusions:

- the most important life cycle phases are Modules A1–3 (production stage) and Module B4 (replacement) for both infrastructure typologies (rigid and flexible);
- the pipes are the main contributor, followed by the trench works or valves. Water and pumps are relatively less significant. The heat exchanger is an irrelevant contributor in comparison.

Avoiding a steel layer substituting with the polymer can drastically cut the overall impact for rigid systems (up to 80%). In flexible systems, the choice of insulation was seen to be a determinant: polyethylene foam is preferable to polyurethane foam. Regarding the choice of polymers for the internal or external layers, high-density polyethylene had better environmental performance than a polyvinyl chloride layer.

A One-at-a-Time sensitivity analysis was conducted to evaluate the potential benefits of the reuse of filler material during the excavation of trenches (if present). The benefits never exceeded 11% for the entire environmental profile of the infrastructure.

The consistency of the results could be further improved through testing the comparison results through uncertainties analysis (Monte Carlo method and hypothesis test) concerning the method used for the impact assessment and the background processes (from ecoinvent) chosen. The authors highlighted that, to further improve the work, different nominal diameters should be investigated for comparison, as the pipe subsystem is the primary contributor to most impact categories; thus, it could affect the outcomes. The choice of the optimal diameter should also be evaluated in greater detail via implementing a cost analysis concerning capital and operating expenditure, and assessing potential environmental benefits achievable using trenchless digging technology.

Moreover, other aspects beyond the environmental perspective could be included in the investigation. For example, we could add the Life Cycle Cost and the Social-Life Cycle Assessment to the Environmental-Life Cycle Assessment and obtain a Life Cycle Sustainability Analysis.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16093912/s1, File Microsoft Excel: Supporting_materials_Results.xlsx.

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Abbreviations

Nomenclature	
th	Thermal
elec	Electric
g	Gas
Subscripts	
A	Acidification for Soil and Water
AP	Air Pollution
CRU	Components for Re-Use
DARe	Depletion of Abiotic Resources—Elements
DARf	Depletion of Abiotic Resources—Fossils
DHN	District Heating Network
DHCNs	District Heating and Cooling Networks
DHW	Domestic Hot Water
E	Eutrophication
EC	European Commission
EE_{elec}	Exported Energy—Electricity
EE_{th}	Exported Energy—Thermal
EE_g	Exported Energy—Gas
ESL	Estimated Service Life
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDD	Heating Degree Days
HHV	High Heating Value
HW	Hazardous Waste Disposed
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory

MER	Materialsfor Energy Recovery
MR	Materials for Recycling
ND	Nominal Diameter
NHW	Non-Hazardous Waste Disposed
NR	Number of Replacements
NRPE	Non-Renewable Primary Energy excl. Raw Materials
NRPERM	Non-Renewable Primary Energy Used as Raw Materials
OD	Ozone Depletion
OAT-SA	One-at-a-Time Sensitivity Analysis
PCM	Phase Change Material
PE	PolyEthylene
PEHD	PolyEthylene High Density
POC	Photochemical Ozone Creation
PP	PolyPropylene
PU	Polyurethane
PVC	PolyVinyl Chloride
RE	Réglementation Environnementale
RPE	Renewable Primary Energy excl. Raw Materials
RPERM	Renewable Primary Energy used as Raw Materials
RW	Radioactive Waste disposed
ReqSL	Required Service Life
RSP	Reference Study Period
SH	Space Heating
TNRPE	Total Non-Renewable Primary Energy
TRPE	Total Renewable Primary Energy
UFW	Net Use of Fresh Water
UNRSF	Use of Non Renewable Secondary Fuels
URSF	Use of Renewable Secondary Fuels
USM	Use of Secondary Material
WP	Water Pollution

Appendix A

Tables A1 and A2 present the results per Module as required according to the standard EN 15978 for rigid (steel pipes) and flexible (polymer pipes) infrastructure, respectively.

Table A1. Result breakdown for rigid infrastructure (steel pipes) per Module.

Impact Category	Product	Unit	TOTAL	A1–3	A4–5	B4	C	D
GWP	A	kg CO_2 eq	1.94×10^5	53.4%	2.5%	44.2%	0.01%	−0.1%
	B		1.09×10^5	51.7%	3.7%	44.9%	0.02%	−0.2%
OD	A	kg CFC-11 eq	1.31×10^{-2}	51.4%	6.6%	42.0%	0.01%	−0.1%
	B		9.73×10^{-3}	51.6%	7.5%	41.0%	0.02%	−0.1%
A	A	kg SO_2 eq	9.99×10^2	47.5%	6.0%	46.6%	0.01%	−0.1%
	B		5.42×10^2	46.5%	7.6%	46.2%	0.03%	−0.2%
E	A	kg PO_4^- eq	3.46×10^2	51.4%	2.2%	46.4%	0.12%	−0.1%
	B		2.06×10^2	48.9%	2.6%	48.4%	0.21%	−0.2%
POC	A	kg C_2H_4 eq	8.09×10^1	48.5%	7.7%	43.9%	0.01%	−0.1%
	B		6.29×10^1	46.6%	8.4%	45.2%	0.01%	−0.1%
DARe	A	kg Sb eq	7.30×10^0	43.6%	0.4%	56.1%	0.00%	−0.1%
	B		3.67×10^0	35.5%	0.8%	63.9%	0.01%	−0.2%
DARf	A	MJ, HHV	2.40×10^6	57.5%	3.0%	39.6%	0.01%	−0.1%
	B		1.71×10^6	59.3%	3.5%	37.4%	0.01%	−0.2%
WP	A	m^3	1.12×10^6	48.2%	0.2%	51.8%	0.02%	−0.2%
	B		5.23×10^5	42.7%	0.4%	57.2%	0.04%	−0.3%

Table A1. *Cont.*

Impact Category	Product	Unit	TOTAL	A1–3	A4–5	B4	C	D
AP	A B	m^3	4.90×10^7 2.58×10^7	49.6% 45.5%	5.1% 9.1%	45.4% 45.7%	0.01% 0.01%	−0.1% −0.3%
RPE	A B	MJ, HHV	3.64×10^5 1.39×10^5	51.8% 52.2%	0.2% 0.4%	48.2% 47.8%	0.01% 0.02%	−0.2% −0.5%
TRPE	A B	MJ, HHV	3.64×10^5 1.39×10^5	51.8% 52.2%	0.2% 0.5%	48.2% 47.8%	0.01% 0.02%	−0.2% −0.5%
NRPE	A B	MJ, HHV	2.52×10^6 1.72×10^6	53.3% 53.6%	2.9% 3.6%	43.9% 43.0%	0.01% 0.01%	−0.1% −0.2%
TNRPE	A B	MJ, HHV	2.74×10^6 1.93×10^6	57.0% 58.7%	2.7% 3.2%	40.4% 38.3%	0.01% 0.01%	−0.1% −0.2%
UFW	A B	m^3	2.08×10^3 1.56×10^3	64.2% 67.0%	0.4% 0.4%	37.1% 34.7%	−1.48% −1.97%	−0.1% −0.1%
HW	A B	kg	9.84×10^4 1.95×10^4	52.2% 54.3%	0.1% 0.2%	48.0% 46.8%	0.00% 0.01%	−0.3% −1.3%
NHW	A B	kg	2.01×10^5 9.24×10^4	48.7% 44.9%	1.3% 2.7%	50.0% 52.6%	0.04% 0.10%	−0.1% −0.3%
RW	A B	kg	9.40×10^0 5.92×10^0	51.0% 51.7%	5.3% 7.0%	43.8% 41.4%	0.01% 0.02%	−0.1% −0.1%

Table A2. Result breakdown for flexible infrastructure (polymer pipes) per Module.

Impact Category	Product	Unit	TOTAL	A1–A3	A4–5	B4	C1–4	D
GWP	C D E	kg CO_2 eq	9.59×10^4 1.15×10^5 1.24×10^5	43.6% 43.3% 43.8%	3.8% 3.8% 3.7%	52.9% 53.1% 52.7%	0.02% 0.02% 0.02%	−0.3% −0.2% −0.2%
OD	C D E	kg CFC-11 eq	4.86×10^{-3} 8.22×10^{-3} 2.14×10^{-2}	52.6% 50.3% 50.9%	13.6% 9.6% 3.9%	34.0% 40.2% 45.2%	0.04% 0.02% 0.01%	−0.2% −0.1% −0.1%
E	C D E	kg PO_4^- eq	1.08×10^2 1.54×10^2 1.78×10^2	45.6% 44.0% 44.4%	5.0% 3.9% 3.7%	49.5% 52.1% 51.8%	0.38% 0.27% 0.23%	−0.4% −0.3% −0.2%
POC	C D E	kg C_2H_4 eq	3.93×10^1 5.92×10^1 5.73×10^1	40.0% 43.0% 41.9%	14.3% 9.7% 10.5%	45.9% 47.4% 47.7%	0.02% 0.01% 0.01%	−0.2% −0.1% −0.1%
AP	C D E	m^3	1.27×10^7 1.55×10^7 1.66×10^7	31.7% 34.7% 35.3%	19.5% 16.3% 15.4%	49.3% 49.4% 49.8%	0.03% 0.02% 0.02%	−0.6% −0.5% −0.4%
RPE	C D E	MJ. HHV	8.82×10^4 1.17×10^5 1.42×10^5	50.8% 50.4% 50.2%	0.6% 0.6% 0.5%	49.4% 49.6% 49.8%	0.02% 0.02% 0.01%	−0.8% −0.6% −0.5%
TRPE	C D E	MJ. HHV	8.83×10^4 1.17×10^5 1.42×10^5	50.7% 50.3% 50.2%	0.7% 0.6% 0.5%	49.4% 49.6% 49.8%	0.02% 0.02% 0.01%	−0.8% −0.6% −0.5%
UFW	C D E	m^3	1.59×10^3 1.98×10^3 2.46×10^3	68.6% 64.2% 56.4%	0.3% 0.4% 0.3%	33.1% 37.1% 44.6%	−1.86% −1.49% −1.20%	−0.1% −0.1% −0.1%
RW	C D E	kg	3.96×10^0 5.04×10^0 5.93×10^0	54.8% 52.5% 51.6%	9.5% 8.9% 7.9%	35.9% 38.8% 40.6%	0.03% 0.02% 0.02%	−0.2% −0.2% −0.1%

Appendix B

This appendix shows the relative breakdown of the trench work subsystem in its three components, i.e., excavation, filler material, and pavement replacement (Table A3).

Table A3. Trench subsystem result breakdown per component (product A).

Impact Category	Unit	Total	Excavation	Filler Material	Pavement Replacement
GWP	kg CO_2 eq	1.35×10^4	2%	44%	54%
OD	kg CFC-11 eq	1.95×10^{-3}	3%	38%	59%
A	kg SO_2 eq	7.06×10^1	3%	48%	49%
E	kg $PO_4{}^-$ eq	1.49×10^1	4%	63%	33%
POC	kg C_2H_4 eq	8.22×10^0	2%	32%	66%
DARe	kg Sb eq	8.23×10^{-2}	0%	61%	39%
DARf	MJ. HHV	4.23×10^5	1%	19%	80%
WP	m^3	1.35×10^4	1%	78%	21%
AP	m^3	3.67×10^6	1%	24%	75%
RPE	MJ. HHV	5.60×10^3	0%	71%	29%
RPERM	MJ. HHV	5.71×10^1	0%	0%	100%
TRPE	MJ. HHV	5.66×10^3	0%	70%	29%
NRPE	MJ. HHV	2.28×10^5	2%	38%	60%
NRPERM	MJ. HHV	2.17×10^5	0%	0%	100%
TNRPE	MJ. HHV	4.44×10^5	1%	19%	80%
USM	kg	1.19×10^4	0%	0%	100%
URSF	MJ. HHV	0.00×10^0	0%	0%	0%
UNRSF	MJ. HHV	0.00×10^0	0%	0%	0%
UFW	m^3	4.92×10^2	0%	94%	6%
HW	kg	2.98×10^2	1%	67%	31%
NHW	kg	6.95×10^3	0%	61%	40%
RW	kg	1.20×10^0	2%	41%	56%
CRU	kg	0.00×10^0	0%	0%	0%
MR	kg	4.00×10^1	0%	0%	100%
MER	kg	0.00×10^0	0%	0%	0%
EE_{elec}	MJ	0.00×10^0	0%	0%	0%
EE_{th}	MJ	0.00×10^0	0%	0%	0%
EE_g	MJ	0.00×10^0	0%	0%	0%

Appendix C

Table A4 summarizes the scenarios adopted to model Modules C3 (waste processing), C4 (disposal), and D (benefits and loads beyond the system boundaries). In the third column, the table shows the rates of the three end-of-life (EoL) scenarios—recycling, incineration, and landfill disposal. In the case of incineration, the combustion of solid waste allows it to valorize into either electricity or heat. The amount of energy produced is reported in the fourth column. The values are obtained as a result of the multiplication of the lower heating value (LHV) percentages of each material and the efficiency of the incineration process (for both heat and electricity). In the case of recycling, the valorization of recycled materials is accounted for in Module D, while their efficiency can be found in the fourth column [32]. The fifth column reports the substitution ratios, describing the quality of the outgoing material with respect to the substitute. The last column describes the substituted production (average suppliers, attributional modeling) thanks to recycling and incineration with energy recovery activity. The recycling percentages were assumed from ADEME [32]. The incineration rates are from the circular footprint formula data, except for the polymer given by ADEME [55]. Finally, the landfill disposal rate is calculated as the rest of the percentage when subtracting the other two rates.

Table A4. EoL scenarios, benefits, and loads.

Material	EoL Scenario	Values (%)	Recycling and Specific Energy from Incineration	Substitution Ratio	Avoided Burdens
Steel	Recycling Incineration Landfill	90.0% 0.0% 10.0%	81.45% for steel	1:1 steel	Primary production of low-alloyed steel.
Stainless steel	Recycling Incineration Landfill	90.0% 0.0% 10.0%	81.45% for steel	1:1 steel	Primary production of chromium steel.
Brass	Recycling Incineration Landfill	0.0% 0.0% 100.0%	-	1:1 brass	-
Cast iron	Recycling Incineration Landfill	90.0% 0.0% 10.0%	81.45% for iron	1:1 iron	Primary production of cast iron.
PVC	Recycling Incineration Landfill	32.0% 43.0% 25.0%	55.71% for PVC 2.28 for electricity [kWh/kg] 4.66 for heat [kWh/kg]	1:1 polymer	Primary production of PVC granules. Electricity from the national grid and heat production from a natural gas boiler.
PP	Recycling Incineration Landfill	27.0% 43.0% 30.0%	55.71% for PP 3.47 for electricity [kWh/kg] 5.55 for heat [kWh/kg]	1:1 polymer	Primary production of PP granules. Electricity from the national grid and heat production from a natural gas boiler.
PEHD	Recycling Incineration Landfill	22.5% 43.0% 34.5%	55.71% for PEHD 3.47 for electricity [kWh/kg] 5.55 for heat [kWh/kg]	1:1 polymer	Primary production of PEHD granules. Electricity from the national grid and heat production from a natural gas boiler.
PE foam	Recycling Incineration Landfill	0.0% 43.0% 57.0%	55.71% for PE foam 3.47 for electricity [kWh/kg] 5.55 for heat [kWh/kg]	1:1 polymer foam	Primary production of PELD granules. Electricity from the national grid and heat production from a natural gas boiler.
PU foam	Recycling Incineration Landfill	0.0% 64.0% 36.0%	55.71% for PU foam 7.69 for electricity [kWh/kg] 3.95 for heat [kWh/kg]	1:1 polymer foam	Primary production of PU rigid foam. Electricity from the national grid and heat production from a natural gas boiler.
Rock wool	Recycling Incineration Landfill	25.0% 0.0% 36.0%	25.00% for rock wool 2.85 for electricity [kWh/kg] 1.39 for heat [kWh/kg]	1:1 mineral foam	Primary production of stone wool. Electricity from the national grid and heat production from a natural gas boiler.
Glass wool	Recycling Incineration Landfill	0.0% 64.0% 36.0%	2.85 for electricity [kWh/kg] 1.39 for heat [kWh/kg]	1:1 mineral foam	Electricity from the national grid and heat production from a natural gas boiler.
Foam glass	Recycling Incineration Landfill	0.0% 64.0% 36.0%	2.85 for electricity [kWh/kg] 1.39 for heat [kWh/kg]	1:1 mineral foam	Electricity from the national grid and heat production from a natural gas boiler.
Packaging cardboard	Recycling Incineration Landfill	0.0% 64.0% 36.0%	86.11%% for cardboard 7.69 for electricity [kWh/kg] 3.95 for heat [kWh/kg]	1:1 cardboard	Primary production of corrugated board. Electricity from the national grid and heat production from a natural gas boiler.

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