



# Carbon footprint analysis of the district heating supply chain: From heat production to infrastructure

Xenia Malcher <sup>a,b,\*</sup>, Helena Przystacki <sup>a,b</sup>, Joachim Seifert <sup>a,c</sup>, Matthias Finkbeiner <sup>a</sup>

<sup>a</sup> Technical University of Berlin, Germany

<sup>b</sup> Berliner Energie und Wärme GmbH, Germany

<sup>c</sup> Technical University of Dresden, Germany

## ARTICLE INFO

### Keywords:

Carbon footprint analysis  
Civil engineering  
Decarbonization strategies  
District heating network  
Infrastructure emissions

## ABSTRACT

District heating is pivotal in urban decarbonization. As cities strive for climate neutrality, understanding emissions across the district heating supply chain is essential. Yet most studies focus on heat generation and fuel supply, while impacts of distribution infrastructure receive far less attention. This study closes that gap by delivering the first system-wide, bottom-up carbon footprint assessment of a metropolitan district heating network using real operational data from Berlin. Results show fuel combustion accounts for about 87% of total emissions, plant construction for 2%, and the distribution network for roughly 11%. Around 70% of network-related emissions stem from civil engineering activities such as excavation and backfilling. When comparing plastic casing pipes and ducted steel pipes, distinct embodied emission profiles emerge. However, civil engineering impacts remain the dominant factor. In addition, road restoration proves critical, as asphalt reinstatement generates nearly twice the emissions of natural stone pavement. Building on this, a scenario analysis indicates that bundling house-connection works can cut emissions by 12.8% by avoiding repeated excavation and transport processes. Looking ahead, as heat generation becomes increasingly decarbonized, the relative importance of infrastructure emissions will rise, making low-carbon construction and planning strategies indispensable. This approach calls for integrating carbon-footprint accounting into heating plans and regulations, prioritizing low-emission materials, and coordinating construction processes. The study offers a system-wide evidence base to help policymakers and utilities design infrastructure strategies aligned with climate-neutral district heating.

## 1. Introduction

Transforming urban energy systems towards climate neutrality is a central objective of the energy transition. District heating (DH) plays a key role in this process, particularly in densely populated areas, where technical implementation is often complex. (Energie-Agentur, 2023). As a collective supply system, district heating enables the integration of renewable heat sources and industrial waste heat. It also allows for

centralized management of efficiency measures (Maab et al., 2021).

However, the district heating supply chain, from heat generation to distribution and delivery to end users, generates various emissions, that must be considered to accurately assess their climate impact (Fritsche and Rausch, 2008; Moser et al., 2025).

Life-cycle assessment (LCA) has become a common approach to evaluate the environmental performance of district heating systems

(Jeandaux et al., 2021). Typically, three central stages of the supply chain are considered: (1) the construction and infrastructure of generation facilities, (2) the combustion or utilization of energy carriers for heat production, and (3) the district heating network itself, which transports the generated heat to consumers (Fritsche and Rausch, 2008).

Each Section is linked to specific CO<sub>2</sub> emissions, both direct (eg, from the combustion of fossil fuels) and indirect (eg, from material production, construction processes, or network energy losses) (Malcher et al., 2025a).

There is extensive LCA literature on district heating systems, particularly in the Nordic countries such as Denmark, Sweden, and Finland. Recent studies have increasingly applied life-cycle assessment approaches to evaluate environmental impacts of district heating systems and infrastructures. For example, Soldal and Modahl (2021a)

assessed the climate impacts of district heating infrastructure using an

\* Corresponding author. Technical University of Berlin, Germany.

E-mail address: [xenia.malcher@campus.tu-berlin.de](mailto:xenia.malcher@campus.tu-berlin.de) (X. Malcher).

<https://doi.org/10.1016/j.cesys.2026.100423>

Received December 8, 2025; Received in revised form March 6, 2026; Accepted 10 March 2026 Available online 11 March 2026

2666-7894/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

LCA-based approach and illustrated the relevance of infrastructure-related emissions based on example facilities. Similarly, Famiglietti et al. (2021) performed a life-cycle assessment of a district heating network and compared its environmental performance with alternative heating systems such as electric heat pumps. Tien et al. (2025) did not assess one specific district heating system empirically, but proposed a systematic review and multi-level framework for applying LCA to district heating systems. Most studies focus on heat generation and fuel chains, while the distribution infrastructure is often treated only in a simplified or aggregated manner. System-level assessments consistently show that heat generation and fuel supply dominate total greenhouse gas emissions, whereas infrastructure-related emissions typically contribute only a low single-digit percentage share, with increasing relative importance as renewable and waste-based heat sources expand (Malcher et al., 2025a, 2025b; Parajuli, 2014).

With the progressive decarbonization of heat generation and the increasing deployment of renewable and waste-based heat sources, infrastructure-related emissions are gaining relative importance in the overall life-cycle balance of district heating systems.

Several recent studies have explicitly applied LCA to district heating infrastructures, however, they differ substantially in scope, system boundary and spatial resolution. In addition to environmental assessments, modeling approaches have also been developed to analyze the technical performance of district heating networks. For example, Tzouganakis et al. (2025) developed an algorithm for district heating system analysis and design optimization that calculates flow velocities, pressure drops and heat losses in pipe networks and supports optimization of insulation materials and network configurations. Vauchez et al. (2023) focused on the comparison of individual infrastructure components (eg, pipe typologies and trenches) but did not assess an entire metropolitan network. Their results demonstrate large variations between rigid and flexible piping systems but do not provide a system-wide assessment of the full district heating supply chain. Jeandaux et al. (2021) performed system-level assessments across several European countries, yet treated distribution infrastructure in an aggregated manner without spatial disaggregation. Earlier studies by Persson et al. (2006) examined the environmental impacts of district heating distribution systems and identified network construction as a relevant contributor, but these assessments relied on simplified network representations and limited spatial coverage.

To better position the contribution of this study within the existing literature, Table 1 summarizes key characteristics of previous studies that assessed environmental impacts of district heating systems and infrastructures.

Overall, existing research either (i) focuses on heat generation and fuel supply chains without detailed and spatially resolved infrastructure coverage, or (ii) analyzes isolated infrastructure components without

embedding them into the full district heating supply chain. As illustrated in Table 1, previous studies differ substantially in scope and methodological approach, but none provide a comprehensive and spatially resolved assessment of distribution infrastructure embedded in the full

district heating supply chain of a metropolitan network. Consequently, despite extensive research on district heating systems, there is still no comprehensive, empirically grounded and spatially resolved carbon footprint assessment of distribution infrastructure embedded in the full supply chain of a large metropolitan network. This study addresses this research gap by providing a network-wide, bottom-up carbon footprint assessment of district heating distribution infrastructure based on real operational data from Berlin. Unlike previous studies, this work integrates civil engineering, material production, installation, operation, maintenance, and end-of-life processes and embeds infrastructure emissions consistently within the full district heating supply chain. This enables a quantitative comparison between infrastructure-related emissions and total system emissions at the scale of a large metropolitan district heating network.

The analysis presented in this paper relies on publicly available data from *Berliner Energie und Wärme* (BEW) (BEW Berliner Energie und Wärme, 2025). As the largest district heating provider in the capital, BEW operates one of the most extensive networks in Germany (AGFW, 2023). Berlin's district heating system is particularly suitable for this study because it represents a large, diverse, and complex urban network (Enegelmann et al., 2021). It combines multiple heat sources, varying pipe ages and diameters, and a wide range of installation environments typical for Central European metropolitan DH systems (Malcher and Gonzalez-Salazar, 2024). It thus provides a valuable dataset for examining infrastructure-related emissions in the urban context.

This study aims to quantify the CO<sub>2</sub> emissions associated with the construction and operation of district heating distribution infrastructure and evaluate their relevance within the total carbon footprint of a modern urban DH system. The guiding research question is: How significant are infrastructure-related emissions in the overall emission profile of a large metropolitan district heating network?

The novelty of this study lies in providing the first system wide empirical carbon footprint assessment of district heating distribution infrastructure based on real operational data from Berlin. In doing so, we assess all major stages of the district heating supply chain, including the construction of generation plants, the combustion of energy sources, and the construction and operation of the distribution network, and integrate these components into a unified life cycle framework.

## 2. Method: carbon footprint assessment and integration into the district heating supply chain

This Section describes the methodological foundation of the carbon

**Table 1**  
Comparison of previous studies of district heating systems.

Study	Scope of analysis	Infrastructure details	Spatial scale	Method	Key limitation
Famiglietti et al. (2021)	Environmental performance of district heating networks	Moderate	Case study district LCA		Focus on system comparison rather than detailed infrastructure processes
Jeandaux et al. (2021)	European DH systems	Low	Multi-country	LCA	Infrastructure treated in aggregated form, not spatially resolved
Persson et al. (2006)	DH distribution system	Moderate	Model-based	LCA	Simplified network representation and limited spatial coverage
Soldal and Modahl, 2021a	DH infrastructure	Moderate	Example facilities	LCA	Based on example facilities, limited transferability and spatial resolution
Tien et al. (2025)	Sustainability of DHS	Low	Review/not case-specific	LCA	Methodological review rather than original empirical infrastructure assessment
Tzouganakis et al. (2025)	DHS modeling and design optimization	High (network modeling)	Case study network	Hydraulic modelling/ optimization	Focus on technical network analysis rather than life-cycle emissions
Vauchez et al. (2023)	Pipe typologies in district heating networks	High (component level)	Component scale	LCA	No integration into full supply chain
<b>This study</b>	Full DH supply chain including infrastructure	High	Metropolitan network	Carbon Footprint Assessment	System-wide infrastructure analysis based on real operational data

footprint assessment and its integration into evaluating the district heating supply chain. The goal is to quantify CO<sub>2</sub> emissions associated with the construction, operation, and decommissioning of the distribution infrastructure for district heating. By adopting a carbon footprint approach, we can assess environmental impacts at all stages of the infrastructure. This provides a basis for classifying individual emission sources within the supply chain (Zhang et al., 2024).

The assessment followed ISO 14067, using a component-based, attributional bottom-up approach. (I. 1, 2018). To ensure consistency and comparability with other studies, all emission data were normalized to a standard reference unit described in Section 2.1 (Soldal, 2021).

### 2.1. Objective, system boundaries, and functional unit

The carbon footprint assessment in this study aimed to quantify the greenhouse gas (GHG) emissions associated with the construction, operation, and end-of-life of district heating distribution infrastructure.

The analysis adheres to ISO 14067 and applies a bottom-up, attributional approach (MindLogistik; I. 1, 2018).

The functional unit is defined as 1 MJ (MJ) of useful heat delivered to end users via the district heating network. This reference unit facilitates comparability with other heating technologies and carbon footprint studies (Soldal and Modahl, 2021b). We use MJ as an SI-based, technology-neutral energy unit that does not imply system-specific scales or accounting conventions associated with kWh or MWh. Results can be directly converted to other common units (eg, kWh or MWh) for comparison.

Heat losses in the distribution network are not included in the functional unit itself, as the functional unit refers exclusively to the useful heat that reaches the end user. Instead, heat losses are explicitly modeled as part of the use phase of the distribution infrastructure.

Thermal losses were quantified using literature-based and project-specific heat loss coefficients for the respective pipe systems and insulation standards. These losses were treated as additional energy demand that increases the required input heat upstream of the network. Consequently, all upstream and operational processes were scaled to the useful heat output of 1 MJ, while the additional heat required to compensate for network losses was accounted for as part of the operational emissions of the distribution system. This approach ensures full consistency with ISO 14067 and with established LCA practice for district heating systems and facilitates comparability with alternative heating technologies (Soldal and Modahl, 2021b).

The system boundaries encompass the full carbon footprint of the distribution infrastructure (UIC/IFEU (International Union of Railway-s/Institut für Energie-und Umweltforschung Heidelberg GmbH), 2021).

They are structured as follows. Emissions from heat generation are allocated within Section 3, so they are excluded from the infrastructure carbon footprint (CF) (Ustinovichius et al., 2020).

- I. Upstream (pre-construction): This phase includes raw material extraction, production of construction materials (eg, steel, polyethylene, insulation), and transportation to the construction site.
- II. Construction phase: This involves civil engineering works (excavation, backfilling, surface restoration), pipe laying, machinery use, and energy consumption on-site.
- III. Use phase: This includes maintenance, repair, operational losses (eg, thermal losses through insulation), and auxiliary energy use (eg, for pumps and control systems).
- IV. End-of-life: This phase covers dismantling, transport, recycling, and disposal of materials (International Organization for Standardization, 2006).

The carbon footprint assessment includes both direct emissions (eg, diesel used in excavation) and indirect emissions (eg, embodied carbon in materials) (European Investment Bank, 2023).

A process flow diagram of the methodology (see Fig. 1) illustrates the step-by-step procedure, from goal definition and data collection to impact assessment and interpretation.

### 2.2. Data sources and modeling approach

The carbon footprint assessment is based on both primary and secondary data:

- Primary data were obtained from real-world infrastructure projects in Berlin, including detailed information on pipe types, material quantities, trench cross-sections, and surface types (eg, asphalt, cobblestone, concrete).
- Secondary data were collected from established carbon footprint assessment databases such as ecoinvent (v3.8), which provide emission factors for materials, transport, and energy inputs.
- Literature data were used to supplement assumptions on service life (50 years for pre-insulated pipes), maintenance intervals, thermal losses, and dismantling procedures (Kagi and Zschokke, 2021).

The extrapolation from the Sprengelkiez case study to the entire Berlin district heating network is based on the representativeness of its structural characteristics. The Sprengelkiez reflects typical urban installation conditions found across large parts of Berlin, including comparable building densities, trench geometries, surface types (asphalt, paving stones, concrete slabs), and commonly used pipe diameters for secondary distribution networks. According to BEW's internal network statistics, these characteristics fall well within the modal ranges of the citywide distribution infrastructure.

To ensure methodological robustness, the extrapolation does not rely solely on Sprengelkiez-specific data. Instead, pipe diameters, surface compositions, and construction profiles were cross-checked against network-wide distributions provided by BEW. Weighted averages were applied where necessary to reflect the actual composition of the Berlin network. Furthermore, sensitivity analyzes were conducted to evaluate the influence of deviations in surface types, pipe dimensions, and installation environments on infrastructure-related emissions. This approach ensures that the final carbon footprint results represent not only the Sprengelkiez area but the broader characteristics of the Berlin district heating system.

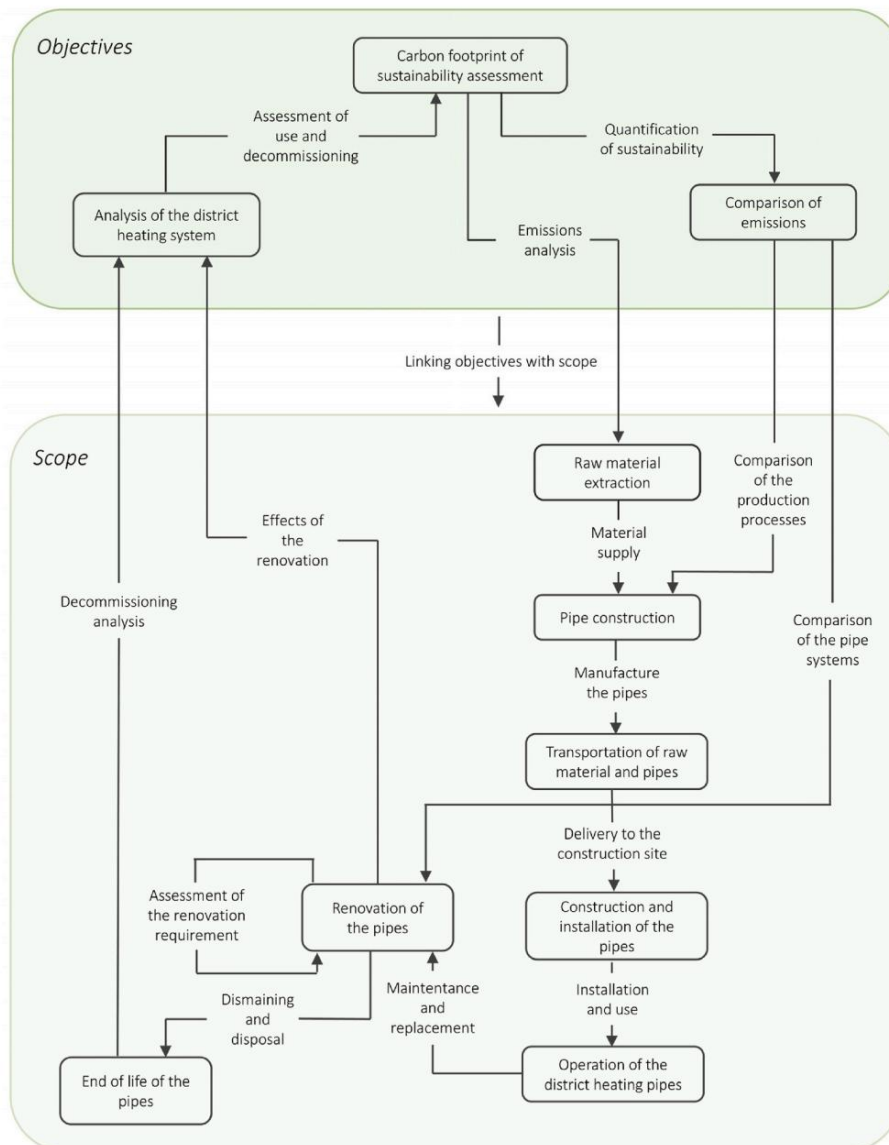
The modeling followed a component-based structure: individual elements (eg, pipe, insulation, sand bedding, surface layers) were modeled separately. These were then aggregated to represent typical network segments (Lokesh et al., 2022). Several scenarios were analyzed, including:

- Pipe systems: Pre-insulated plastic casing pipes vs. steel pipes in concrete ducts
- Surface types: Asphalt, paving stones, concrete slabs

The process scaled all emission results to the functional unit and expressed them in kg CO<sub>2</sub>/MJ of delivered heat. Emissions were calculated per meter of network length (kg CO<sub>2</sub>/m) to enable infrastructure-specific comparisons. Scenario analyzes address uncertainty by varying parameters such as service life, insulation quality, and emission factors for surface materials. Studies with incompatible system boundaries or incomplete methodological transparency were excluded.

To ensure methodological transparency, data quality and representativeness were carefully assessed throughout the study. Primary data from Berlin infrastructure projects (2018–2023) provide strong temporal and geographical relevance, as they reflect real construction practices and urban conditions in a major Central European district heating network. Complementing this, secondary data from ecoinvent 3.8 were selected for technological similarity and European system boundaries, in line with ISO recommendations.

Data quality was evaluated based on reliability, completeness, and



**Fig. 1.** System boundaries and carbon footprint assessment of district heating pipes, from raw material extraction to end-of-life processes.

methodological consistency. Where uncertainties in emission factors occurred, upper and lower bounds were tested through sensitivity analyses. Additionally, scenario analyzes varied key parameters, such as pipe lifetime, insulation performance, material emission factors, and main-tenance intensity, to assess the robustness of results and identify the most influential drivers of the infrastructure carbon footprint.

The analysis was structured in two consecutive steps. The first step was a case study of the Sprengelkiez model district (see Section 4.1), which aimed to determine specific emission factors for district heating pipe installation in realistic urban conditions. The second step complemented these results with a component-level analysis of individual pipe systems and construction processes (including materials, excavation, and surface restoration), allowing a differentiated interpretation of the overall carbon footprint.

To ensure a comprehensive supply-chain perspective of district heating infrastructure, the following methodological framework was defined (see Fig. 2). The approach distinguishes between infrastructure-related emissions and plant construction, specifying the functional unit and system boundaries used in this study (Soukka et al., 2018).

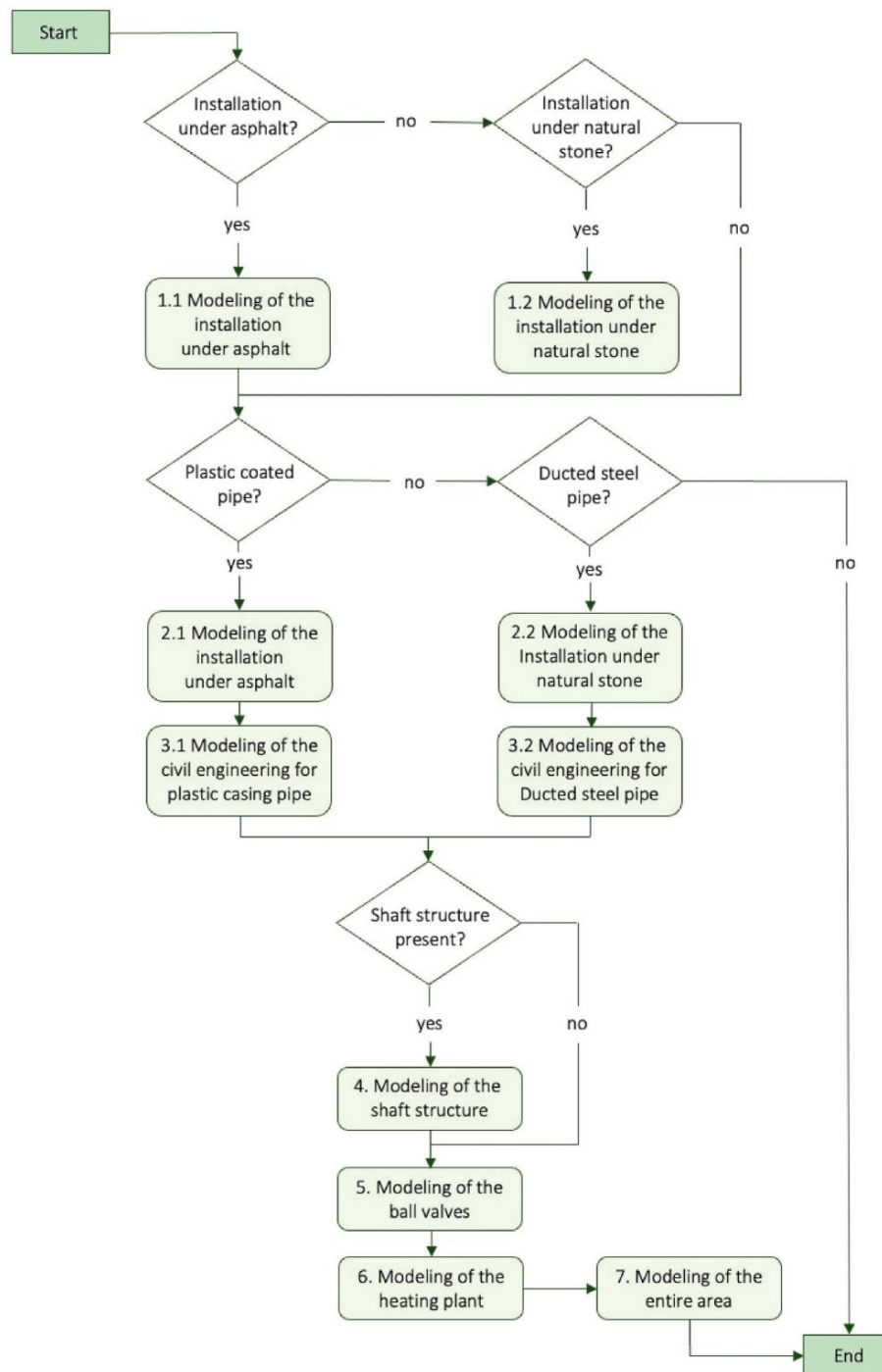
Having established the methodological foundation, Section 3 integrates these elements into the entire district heating supply chain. It

quantifies the relative contributions of power plant construction, fuel combustion, and network infrastructure to the overall carbon footprint, placing infrastructure emissions within the total system balance.

### 3. Classification of district heating networks in the district heating supply chain

It is necessary to classify the entire district heating supply chain to embed the methodological framework and system boundaries defined in Section 2 into a broader context. The emissions from constructing and operating the distribution network represent only one part of the total carbon footprint. For a comprehensive assessment, these emissions must be considered alongside those generated from building generation facilities and from the combustion of fuels.

The district heating supply chain comprises several successive stages: construction of power plants and related infrastructure; heat generation from fossil or renewable sources; and heat distribution through the network to end consumers. This Section examines how these stages differ in terms of CO<sub>2</sub> emissions per megajoule of useful heat and what relative share they contribute to the overall balance. This analysis positions network-related emissions in relation to other supply chains



**Fig. 2.** Flowchart of the modeling process for different pipe installation types and associated infrastructure components in district heating systems.

components, laying the groundwork for the more detailed process-level analyses, such as pipe laying, presented in later Sections.

### 3.1. Emissions from power plants and plant construction

A significant proportion of emissions along the district heating supply chain are generated in the upstream phase of constructing and manufacturing the technical infrastructure, not during ongoing operation. These so-called "gray emissions" encompass various processes, including the manufacture and installation of components such as steel, concrete, boilers, and turbines, as well as drilling and construction activities. Although these emissions are integral to the overall balance

sheet, they are often insufficiently considered in many studies.

Since reliable and differentiated data on heat generation are only available to a limited extent in the literature, many sources, such as [Lacirignola et al. \(2014\)](#), focus exclusively on electricity generation. In this study, the emission share of power plants and plant construction was determined based on a targeted literature search. The aim was to provide an estimate of the emissions per megajoule of heat generated as realistically as possible.

The research covers five typical types of plants that play a role in Berlin's district heating landscape: combined cycle power plants (CCPP), waste-to-energy plants, geothermal plants, biomass CHP plants, and large heat pumps or power-to-heat plants. The study assessed and

evaluated the CO<sub>2</sub> emissions from the construction phase for each type, considering their system boundaries and whether they included only technical components or buildings.

The literature shows that CCGT construction results in 0.002 kg CO<sub>2</sub>/ MJ heat (Kaczmarczyk et al., 2024), while waste-to-energy plants average about 0.0035 kg CO<sub>2</sub>/ MJ (Brogaard and Christensen, 2013).

Geothermal plants show the highest values at 0.005 kg CO<sub>2</sub>/MJ, because of borehole drilling (Kaczmarczyk et al., 2024). Biomass CHP falls into the mid-range at around 0.003 kg CO<sub>2</sub>/MJ (Guest et al., 2011), whereas large heat pumps and power-to-heat plants have the lowest values at only 0.001–0.002 kg CO<sub>2</sub>/MJ (Soldal and Modahl, 2021a). Based on the compiled data (see Table 2), an average emission factor of 0.001775 kg CO<sub>2</sub>/MJ is assumed for plant construction.

For estimating emissions from plant construction, an average value across different heat generation technologies was applied, as specific data on the Berlin district heating system's portfolio are not available.

Therefore, a representative mean factor of 0.001775 kg CO<sub>2</sub>/MJ useful heat was used (*Q<sub>heat</sub>*). This value aligns well with the range reported for comparable district heating systems in the literature and is a realistic approximation of the Berlin context. Therefore, using an annual heat production of about 32 × 10<sup>9</sup> MJ (32,000,000,000 MJ), the total emissions from plant construction can be estimated (*E<sub>plant</sub>*):

$$E_{plant} = Q_{heat} \times EF_{plant} \quad \text{Equation 1}$$

This indicates that the total annual carbon dioxide emissions resulting from the construction of Berlin's district heating system amount to **56,800,000 kg CO<sub>2</sub>** annually.

### 3.2. Emissions from the combustion of the energy source

The combustion of fuels for heat generation is the dominant source of emissions in the district heating supply chain. While infrastructure-related emissions, such as those from the construction of plants and pipelines, occur during the early stages of a system's life cycle, the operational phase of heat production contributes the largest share of total greenhouse gas (GHG) emissions throughout the system's lifetime.

BEW primarily operates combined heat and power (CHP) plants to generate heat in district heating networks. These facilities produce both heat and electricity, resulting in a more efficient use of fuel compared to separate generation systems. However, as long as fossil energy sources such as natural gas, hard coal, and waste fractions containing fossil materials remain part of the fuel mix, significant CO<sub>2</sub> emissions will continue to occur during operation.

Quantifying these emissions is crucial for understanding district heating systems' current carbon intensity and identifying the potential for emission reductions through fuel switching, renewable integration, and waste heat recovery. The data used in this study are based on official reports from the German Environment Agency (Umweltbundesamt (2025), which publishes verified annual emission figures for large

**Table 2**

Overview of CO<sub>2</sub> emissions from the construction phase of a typical heat generation plants (kg CO<sub>2</sub>/MJ) (Kaczmarczyk et al., 2024; Brogaard and Christensen, 2013; Guest et al., 2011; Soldal and Modahl, 2021a).

No. Plant Type	Range [kg CO <sub>2</sub> / [MJ]	Average [kg CO <sub>2</sub> /MJ]	System Boundary	Source
1 Combined Cycle Gas Turbine (CCGT)	0.00075–0.00254	0.001613	Construction phase incl. technical components (boiler, turbines), concrete foundations, and building structure; project-specific LCA	Kaczmarczyk et al. (Kaczmarczyk et al., 2024)
2 Municipal Waste Incineration Plant	0.00058–0.00117	0.000875	Includes boiler, turbine, flue gas treatment, pipelines, steel structures, construction processes, transport and buildings	Brogaard et al. (Brogaard and Christensen, 2013)
3 Geothermal Plant	0.00306	0.00306	Drilling, casing (steel/cement), ORC system, pumps, building; based on hypothetical project design, incl. infrastructure	Kaczmarczyk et al. (Kaczmarczyk et al., 2024)
4 Biomass CHP (Combined Heat and Power)	0.00055–0.0007	0.000625	Plant with boiler and technical systems, including building and installation; considers only the construction phase, excludes fuel supply	Guest et al. (Guest et al., 2011)
5 Large-scale Heat Pump/ Power to Heat	0.0023–0.0031	0.0027	Generation units (heat pumps, electrode boilers), buildings, district heating network, substations, and heat exchangers	Soldal et al. (Soldal and Modahl, 2021a)
∅ Overall Average (all 5 types)		<b>0.001775</b>	Aggregate of system boundaries from all technologies? average scope of included construction elements	

combustion plants exceeding 100 tons of CO<sub>2</sub> per year. For 2023, these official datasets provide detailed information on BEW major heat generation sites across Berlin. The reported emissions from each site encompass both electricity and heat production, as most of the company's facilities operate in cogeneration mode. Table 3 presents a summary of the data:

This table represents the total direct CO<sub>2</sub> emissions resulting from fuel combustion across BEW's leading generation portfolio. Both combined heat and power (CHP) plants and pure heating plants were included in calculating the emissions generated. The total emissions from CHP plants were allocated to heat and electricity using the energy-based allocation approach (also known as calorific value or energy quantity allocation), ie in proportion to the proper energy quantities generated. Based on previous years, it was assumed that CHP contributes a heat share of 62.5% of the total energy output in Berlin (*heat*).

Therefore, the emissions attributable specifically to district heating can be calculated as follows:

$$E_{comb,heat} = E_{total} \times s_{heat} \quad \text{Equation 2}$$

Hence, the annual combustion-related emissions for heat production in Berlin's district heating system are estimated at **2,623,000,000 kg CO<sub>2</sub>/a**.

### 3.3. Emissions from the district heating network

Besides the emissions from fuel combustion and plant construction, the district heating network generates a distinct share of greenhouse gas emissions. These emissions arise from the construction and installation of distribution pipelines, related civil engineering activities, material production, and transportation processes. Although these emissions occur during the construction phase, they represent a long-term environmental burden throughout the network's lifetime.

The calculation of network-related emissions in this study is based on a detailed carbon footprint analysis conducted for the Sprengelkiez model district in Berlin. This area was selected as a representative case

**Table 3**

Annual CO<sub>2</sub> emissions from BEW generation sites in 2023 (Umweltbundesamt, 2025) (Reported by the German environmental agency).

Lichterfelde	604,000,000 kg CO <sub>2</sub> /year
Charlottenburg	102,000,000 kg CO <sub>2</sub> /year
Klingenberg	407,000,000 kg CO <sub>2</sub> /year
Marzahn	584,000,000 kg CO <sub>2</sub> /year
Middle	696,000,000 kg CO <sub>2</sub> /year
Moabit	258,000,000 kg CO <sub>2</sub> /year
Reuters-West	1,547,000,000 kg CO <sub>2</sub> /year
<b>Total</b>	<b>4,198,000,000 kg CO<sub>2</sub>/year</b>

study due to its typical urban conditions, such as high building density, narrow streets, and mixed building structures, which are common in many parts of Berlin's district heating system. The Sprengelkiez analysis provides site-specific data on material quantities, pipe lengths, and surface restoration types, which were used as the basis for extrapolating the results to the entire network. Section 4 offers a more detailed description of this case study. In the Sprengelkiez area, the construction of a 5,089 km network Section resulted in total emissions of 41,957,000 kg of CO<sub>2</sub>. This corresponds to a specific network-related emission factor per kilometer, which can be calculated as follows:

$$EF_{net,km} = \frac{E_{net,total}}{L_{net}} \quad \text{Equation 3}$$

where  $EF_{net,km}$  is the emission factor per kilometer of network length,  $E_{Net,ges}$  represents the total network-related emissions, and  $L_{net}$  is the installed network length. Scaling this value to the total length of Berlin's district heating network, operated by BEW and measuring 2059 km, yields an estimated total network emission of 16,964,073,029 kg CO<sub>2</sub> over its entire service life ( $E_{net,total}$ ).

According to expert assessments from BEW, the average service life of district heating pipes is 50 years (*tlife*). When these total emissions are distributed across this lifetime, the annualized emissions can be calculated as follows:

$$E_{net,annual} = \frac{E_{net,total}}{tlife} \quad \text{Equation 4}$$

This corresponds to annualized network emissions of 339,281,461 kg CO<sub>2</sub> per year. These values include all relevant processes such as pipe manufacturing, excavation and backfilling, surface restoration under asphalt and natural stone, transport activities, installation of valves and shafts, operational energy use, and end-of-life processes like recycling and disposal.<sup>1</sup>

### 3.4. Total emissions of the district heating supply chain

Based on the preceding analyses, the total carbon footprint of Berlin's district heating supply chain can be quantified by combining the emissions from the three main components: (1) Plant and power station construction, (2) Combustion of the energy source, and (3) Construction and operation of the district heating network. Together, these components represent the full carbon footprint cycle of the district heating system, from producing heat to its distribution within the city. The calculated annual emission values for each component are:

- Plant and power station construction: 56,800,000 kg CO<sub>2</sub> per year
- Combustion of the energy source: 2,623,000,000 kg CO<sub>2</sub> per year
- District heating network (construction and operation): 339,281,461 kg CO<sub>2</sub> per year

Summed together, this results in a total annual emission of **3,019,081,461 kg CO<sub>2</sub>** per year ( $E_{total,a}$ ).

Based on these emissions the distribution across the three components of the district heating supply chain shows that plant and power-plant construction account for **1.88%** of total emissions, while the combustion of energy sources represents by far the largest share at **86.88%**. The construction and operation of the district heating network contribute the remaining **11.24%**. The proportional share of network-related emissions in the total supply chain can be expressed as follows:

$$A_{net} = \frac{E_{net,a}}{E_{total,a}} \quad \text{Equation 5}$$

<sup>1</sup> In addition to embodied emissions, Berlin's district heating network exhibits average thermal losses of approximately 10%, based on utility data.

where  $A_{net}$  is the percentage share of network emissions,  $E_{net,a}$  represents the annual emissions of the district heating network, and  $E_{total,a}$  is the total annual emission of the district heating supply chain.

The results presented in this Section offer a comprehensive overview of the emissions associated with the district heating supply chain. They show that while combustion processes are the primary source of emissions, the construction and maintenance of distribution infrastructure also contribute a relevant share that cannot be neglected.

As illustrated in Fig. 3, the overall annual emissions of Berlin's district heating system amount to approximately  $3.02 \times 10^9$  kg CO<sub>2</sub>. Out of this total, energy sources combustion accounts for 86.88% ( $2.62 \times 10^9$  kg CO<sub>2</sub> per year), the construction and operation of the district heating network accounts for 11.24% ( $339 \times 10^6$  kg CO<sub>2</sub> per year), and the construction of power plants and facilities accounts for 1.88% ( $56.8 \times$

$10^6$  kg CO<sub>2</sub> per year). This proportional distribution shows that although fuel combustion remains the dominant source of greenhouse gas emissions, infrastructure-related processes already account for a substantial share of the total carbon footprint.

After establishing the overall emission balance of the district heating supply chain in Section 3, Section 4 focuses in greater detail on the network infrastructure. Using the Sprengelkiez model district as a case study, it analyzes the carbon footprint of pipeline construction and operation under real urban conditions. This Section reveals the primary sources of emissions and highlights opportunities for reducing embodied carbon in future network expansions.

## 4. Results of the carbon footprint assessment of the network

Section 3 detailed that the entire Berlin district heating system emitted 3,019,081,461 kg of CO<sub>2</sub>. This was extrapolated from the Sprengelkiez model district. Section 4 now turns to the model district itself, presenting the detailed carbon footprint assessment that forms the empirical basis for the network-wide extrapolation. The analysis aims to identify the key emission drivers within the construction and operation of the distribution infrastructure and to highlight potential optimization strategies for reducing the environmental impact of district heating systems.

The following Sections examine the environmental effects of pipeline installation under real urban conditions, considering different surface restoration types, pipe systems, and construction practices. A hotspot analysis further identifies the most emission-intensive processes within civil engineering activities. The results apply to the scale of the entire Berlin network, and a scenario analysis explores the potential of alternative construction strategies to lower emissions.

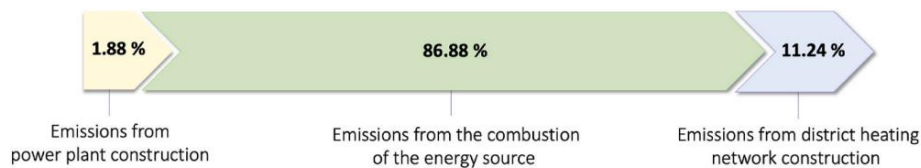
### 4.1. The Sprengelkiez case study

To determine the emissions associated with district heating infrastructure, the Sprengelkiez district in Berlin was selected as a representative case study. This area was chosen because it reflects the typical characteristics of dense urban neighborhoods in Berlin: a high connection density, a mixed building stock, and narrow streets that make pipeline installation and surface restoration emission-intensive.

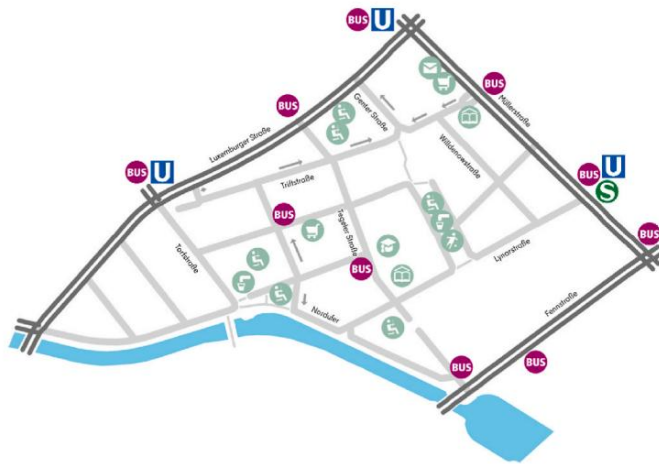
Within the Sprengelkiez area, the local district heating network has a total length of 5,089 km (see Fig. 4). Based on the carbon footprint analysis of all relevant processes, including pipe manufacturing, material production, excavation and backfilling, transport, and road surface restoration, the total emissions for this Section amount to 41,957,000 kg CO<sub>2</sub>.

These results form the empirical foundation for extrapolating emissions to the full Berlin district heating network. Emission factors per kilometer of pipeline were derived using the calculated emissions for the Sprengelkiez area to estimate total infrastructure-related emissions across Berlin.

The resulting emission factors were then used to extrapolate Berlin's



**Fig. 3.** District heating supply chain measured in kg CO<sub>2</sub>, with contributions from power plant construction (1.88%), combustion of the energy source (86.88%), and district heating network construction (11.24%).



**Fig. 4.** Sprengelkiez district on a scale of 1:10,000.

total network emissions. 2059 km of pipelines make up the city's district heating system, transporting about  $32 \times 10^9$  MJ (MJ) of useful heat each year (VWB AG, 2023). Following expert assessments from BEW, the extrapolation considered the installed pipes' assumed service life of 50 years.

The Sprengelkiez case study, therefore, provides the empirical benchmark for quantifying infrastructure-related emissions in Berlin's district heating system and serves as the reference point for the following analysis on pipe systems, surface types, and construction processes. The following Section builds on these findings and compares the specific carbon footprints of different pipe systems and surface restoration types, identifying how material choices and construction methods influence total emissions.

#### 4.2. Carbon footprint of pipe systems

Building on the results of the Sprengelkiez case study, this Section compares the carbon footprint of different pipe systems used in district heating construction. The analysis focuses on two common types of pipeline systems: Pre-insulated plastic casing pipes and steel pipes

installed in concrete ducts. During pipe manufacturing, the comparison considers the total CO<sub>2</sub>-equivalent emissions. Fig. 5 displays the results for different nominal diameters (DN).

The data show that pre-insulated plastic casing pipes produce higher CO<sub>2</sub> emissions during manufacturing than steel pipes laid in ducts. For smaller diameters (eg, DN 50–DN 150), the difference is modest, ranging between 5 and 10 kg CO<sub>2</sub> per meter. However, as the pipe diameter increases, the gap widens. For example, at DN 350, the pre-insulated plastic casing pipe emits 163 kg CO<sub>2</sub>/m, while the corresponding steel pipe emits 95 kg CO<sub>2</sub>/m. This trend continues for larger dimensions: at DN 400, emissions are 202 kg CO<sub>2</sub>/m for the plastic casing pipe and 153 kg CO<sub>2</sub>/m for the steel pipe. At huge diameters (DN 500 and above), only plastic casing pipes are typically used, with emissions reaching 305 kg CO<sub>2</sub>/m for DN 500, 352 kg CO<sub>2</sub>/m for DN 600, and 506 kg CO<sub>2</sub>/m for DN 800.

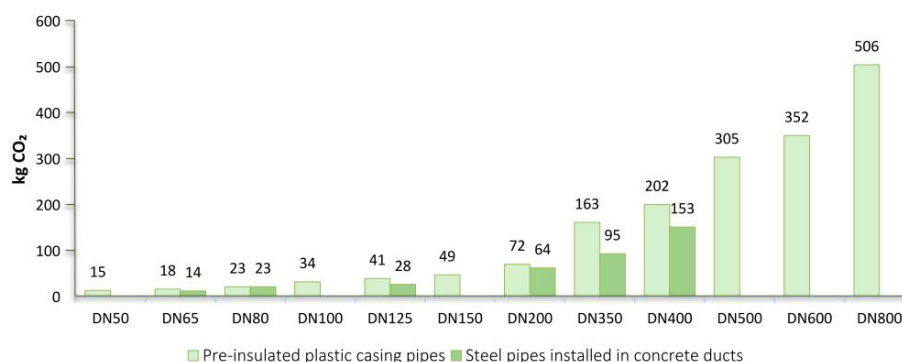
The multi-layer structure of pre-insulated plastic casing pipes (steel carrier pipe, polyurethane foam insulation, and polyethylene casing) and the energy-intensive production of synthetic materials such as plastics and insulation foams contribute to their higher carbon footprint.

In contrast, steel pipes in ducts require more installation effort but involve less embodied carbon during production. While plastic casing pipes have higher manufacturing emissions, they provide better thermal insulation and therefore exhibit lower heat losses during operation. In the overall carbon footprint analysis, this can offset their higher embodied carbon. In contrast, steel pipes laid in ducts may require more maintenance and exhibit higher thermal losses in older networks.

Overall, the results underline that pipe material selection has a measurable, yet modest, impact on total infrastructure emissions. As shown in later Sections, the dominant emission sources are not the pipe materials themselves but the civil engineering activities, such as excavation, backfilling, and surface restoration.

#### 4.3. Influence of road surface pavement

Emissions were recalculated to assess the environmental impact of district heating pipe installation more accurately, based on the restored surface area instead of the material mass. This approach reflects the spatial extent of construction activities and allows for a more realistic comparison of different surface types typically encountered in urban environments.



**Fig. 5.** Comparison of CO<sub>2</sub> emissions from the production of pre-insulated plastic casing pipes and ducted steel pipes (in kg CO<sub>2</sub> per meter of pipe).

The carbon footprint was determined for Berlin's two predominant surface types: asphalt and natural stone. In this case, natural stone surfaces typically consist of granite. The analysis covers all processes related to surface reinstatement after pipe trenching. The results are expressed in kilograms of CO<sub>2</sub> equivalent per square meter of restored surface (kg CO<sub>2</sub>/m<sup>2</sup>). With a typical cross-section, the trench is 1.2 m wide and has a 0.4 m restoration thickness. One square meter of surface area was assumed per meter of pipe.

#### 4.3.1. Results per surface type

The results show that reinstatement under asphalt causes 34.6 kg CO<sub>2</sub>/m<sup>2</sup>, while natural stone paving results in 18.1 kg CO<sub>2</sub>/m<sup>2</sup>. Asphalt surfaces exhibit almost 1.9 times higher emissions than natural stone. The higher values for asphalt are because of the energy-intensive production of bitumen, increased compaction requirements, and the limited recyclability of asphalt layers.

#### 4.3.2. Extrapolation to the Berlin district heating network

The total length of Berlin's district heating network is 2059 km. Assuming an average trench width of 1.2 m, the total restored surface area amounts to 2,470,800 m<sup>2</sup>. The cumulative emissions associated with surface reinstatement can thus be estimated as follows:

- **Asphalt surfaces:** 2,470,800 m<sup>2</sup> × 34.6 kg CO<sub>2</sub>/m<sup>2</sup> = 8.55 × 10<sup>7</sup> kg CO<sub>2</sub>
- **Natural stone surfaces:** 2,470,800 m<sup>2</sup> × 18.1 kg CO<sub>2</sub>/m<sup>2</sup> = 4.47 × 10<sup>7</sup> kg CO<sub>2</sub>

Assuming a service life of 50 years, this corresponds to annualized emissions of 1.71 × 10<sup>6</sup> kg CO<sub>2</sub> per year for asphalt and 0.89 × 10<sup>6</sup> kg CO<sub>2</sub> per year for natural stone. Relative to the total annual network emissions of 3.39 × 10<sup>8</sup> kg CO<sub>2</sub> per year, surface restoration contributes approximately 0.50% for asphalt and 0.26% for natural stone, depending on the proportion of surface types used. Within the civil engineering stage, surface restoration accounts for 38–56% of its emissions for asphalt and around 12% for natural stone configurations.

These findings confirm that the type of surface restoration has a substantial impact on the overall environmental performance of district heating network construction. Asphalt-dominated sections produce twice the emissions per area compared to those with natural stone pavements. The spatial extent and material composition of surface reinstatement are key parameters in determining the carbon footprint emissions of district heating infrastructure.

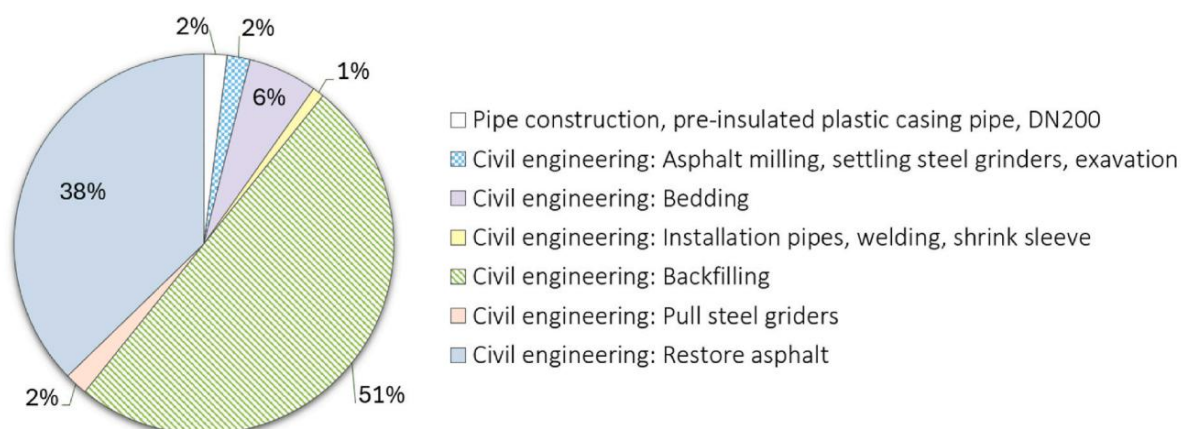


Fig. 6. Emission distribution for pre-insulated plastic casing pipe under asphalt (DN 200): backfilling (51%) and asphalt restoration (38%) dominate the construction emissions.

#### 4.4. Hotspot analysis of the civil engineering

To determine which processes contribute most to the total emissions during district heating pipe installation, a hotspot analysis was carried out. The focus was placed on the civil engineering phase, as it represents the most emission-intensive part of the network construction. The assessment quantifies the relative shares of individual process steps such as excavation, bedding, backfilling, heating-duct construction, pipe installation, surface restoration, and associated transport and machinery use. The analysis focused on four representative construction configurations to reflect typical situations in Berlin's district heating network.

These vary by pipe system and by surface type:

- (1) Pre-insulated plastic casing pipe under asphalt
- (2) Steel pipe in concrete ducts under asphalt
- (3) Pre-insulated plastic casing pipe under natural stone pavement
- (4) Steel pipe in concrete ducts under natural stone pavement

Figs. 6–9 illustrate the resulting emission shares of each process. All values refer to the internal distribution within the civil engineering phase, which accounts for up to 71% of total emissions within the construction stage (sum the material production including upstream raw material extraction, transport, pipe installation and civil engineering) of the network infrastructure in the Sprengelkiez case study.

- 1 Pre-insulated plastic casing pipe under asphalt In this configuration (Fig. 6), the backfilling process shows the highest emission share at 51%. The large mass of material required to refill the trenches and the fuel consumption of heavy machinery mainly caused this. Restoring the asphalt surface follows with 38%, reflecting the high carbon intensity of asphalt production and handling. Other processes, such as bedding, pipe installation, and transport, remain below 5% each and have only a minor influence on the total footprint.
- 2 Steel pipe in ducts under asphalt For the steel pipe under asphalt case (Fig. 7), asphalt restoration becomes the most significant emission source with 54%, followed by heating-duct construction with 25%. The production and placement of reinforced concrete for the duct structure considerably increase embodied emissions. Backfilling contributes 14%, while the remaining categories together make up less than 5%.
- 3 Pre-insulated plastic casing pipe under natural stone pavement When natural stone pavement is involved (Fig. 8), the backfilling operation dominates even more strongly, contributing 72% of total emissions. The heavier excavation, limited mechanization, and higher material turnover in dense city streets are the reasons for this.

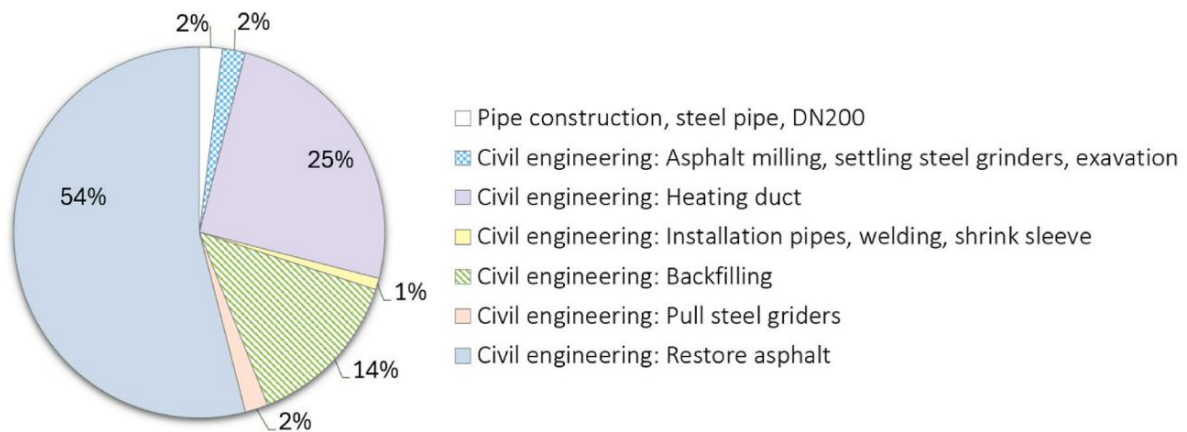


Fig. 7. Emission distribution for steel pipe in concrete duct under asphalt (DN 200): asphalt restoration (54%) and heating-duct construction (25%) are the major contributors.

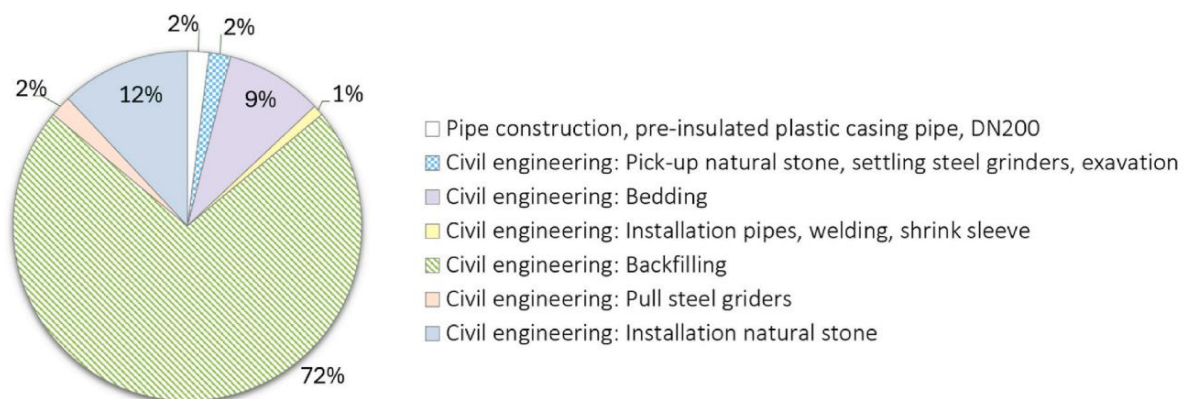


Fig. 8. Emission distribution for pre-insulated plastic casing pipe under natural stone pavement (DN 200): backfilling (72%) represents the largest share, followed by surface restoration (12%) and bedding (9%).

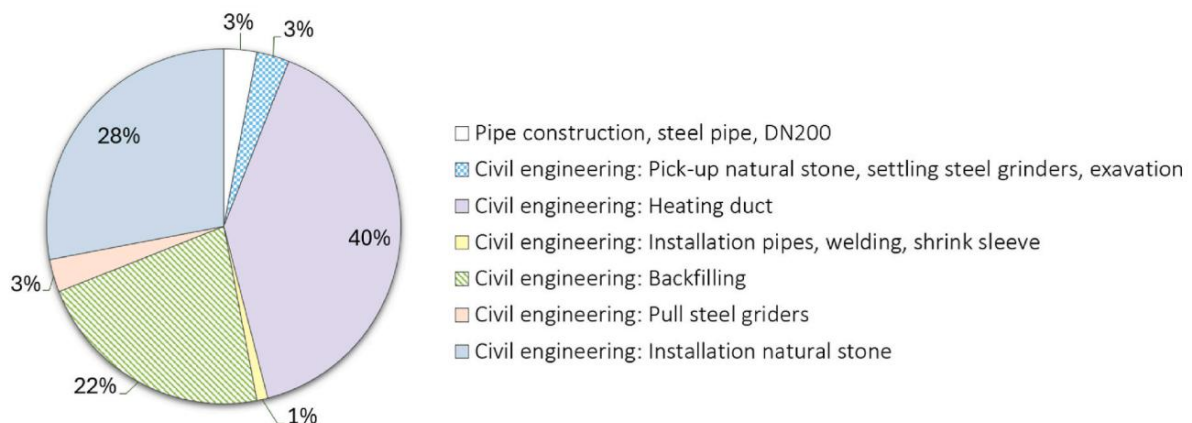


Fig. 9. Emission distribution for steel pipe in concrete duct under natural stone pavement (DN 200): heating-duct construction (40%), surface restoration (28%), and backfilling (22%) constitute the main emission shares.

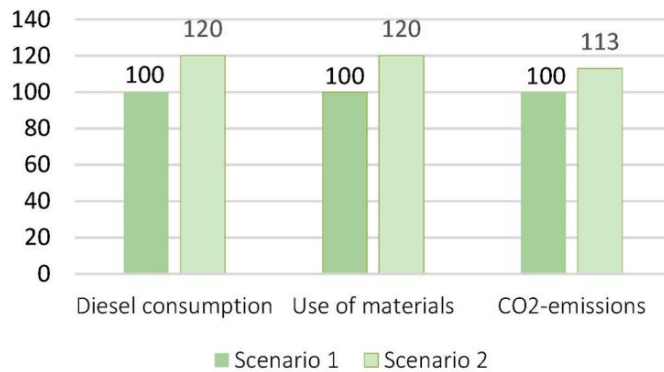
Restoration of natural-stone surfaces accounts for 12% and bedding for 9%. The remaining processes contribute less than 3%.

#### 4 Steel pipe in ducts under natural stone pavement

In the steel-pipe-under-natural-stone scenario (Fig. 9), the distribution is more balanced. Heating-duct construction generates 40% of the emissions, surface restoration 28%, and backfilling 22%. Combining concrete duct manufacturing and labor-intensive surface

reinstatement under natural stone makes this configuration material-intensive.

Overall, the hotspot analysis shows that most construction emissions arise from earthworks and surface restoration, independent of the pipe type. The detailed percentage distributions shown in Figs. 7–10 provide a quantitative basis for assessing where material and process optimization could yield measurable emission reductions in future network



**Fig. 10.** Comparison of total CO<sub>2</sub> emissions between sequential and bundled construction scenarios. Sequential installation results in 12.8% higher emissions due to repeated excavation, material transport, and surface restoration.

expansion projects.

Building on these findings, the following Section examines how construction coordination and process sequencing influence total emissions, comparing sequential and bundled installation approaches.

#### 4.5. Scenario analysis

The analysis covered two typical construction methods: the sequential construction approach, where each house connection is installed in a separate phase, and the bundled construction approach, where several connections are installed together in a coordinated

process.

In the sequential scenario, each connection triggers a separate construction cycle, requiring new excavation, backfilling, and surface restoration for every single project section. This approach currently reflects standard practices, especially when different contractors implement connection requests at other times. In contrast, the bundled scenario represents an optimized, coordinated approach that minimizes redundant construction activities. Several connections are installed

within the same trench during a single construction phase, reducing the number of excavation and restoration steps, as well as material transport and equipment use.

The analysis was based on the process-level carbon footprint in-inventory data from the Sprengelkiez case study. Emission factors for all major civil-engineering activities, excavation, bedding, backfilling, heating-duct construction, and surface restoration, apply to both approaches. The system boundaries included all on-site activities but excluded upstream differences in pipe material, as their contribution was negligible compared to construction-related emissions. All values were normalized per meter of installed connection length to enable comparison between scenarios.

##### 4.5.1. Results

The results show a noticeable difference in the total embodied emissions between the two approaches. The sequential construction method results in 12.8% higher CO<sub>2</sub> emissions than the bundled approach. The repeated execution of identical construction processes such as excavation, backfilling, and asphalt paving drives this increase. Each construction cycle requires mobilizing heavy machinery and repeated material transport, which together raise diesel consumption and material demand. The production and handling of asphalt and aggregates further add to this effect. The bundled construction scenario results in significantly lower emissions because it only requires processes like excavation, backfilling, and surface restoration to be carried out once for several house connections. The shared use of machinery and a single asphalt layer reduces the total volume of material moved and produced. The more efficient logistics also shorten the operation time of

excavators, trucks, and compactors, decreasing fuel use and associated emissions.

When broken down by process category, both scenarios show similar emission structures dominated by backfilling, surface restoration, and heating-duct or bedding construction. However, in the sequential case, surface restoration accounts for a much larger portion of the total footprint because it repeats after each installation. In the bundled case, backfilling remains the largest individual contributor, but overall emissions are lower since the entire trench is completed in one phase.

## 5. Discussion

The previous Sections presented a detailed carbon footprint analysis of the Berlin district heating system, focusing particularly on the embodied emissions arising from the construction and operation of the network infrastructure. The analysis in Section 4 identified the primary emission sources within the civil engineering process, including excavation, backfilling, and surface restoration. It showed the significant influence of construction coordination on total emissions.

Building on these results, the following section discusses the broader implications of these findings for the decarbonization of urban heat supply systems. The discussion addresses the relevance of embodied carbon in district heating infrastructure, evaluates the effectiveness of current construction practices, and explores pathways for improving planning, design, and material use. It also places the results into the broader context of Berlin's climate targets and the long-term transition towards a climate-neutral heat supply.

### 5.1. Discussion of results

The results presented in the previous Sections provide a comprehensive picture of Berlin's district heating supply chain's carbon footprint. The analysis covered both operational emissions from fuel combustion (Section 3) and embodied emissions from infrastructure (Section 4), enabling a carbon footprint perspective on the system's environmental performance.

To assess the plausibility of the methodological approach, the main findings were benchmarked against previous district heating LCA studies, as summarized in Table 4. Famiglietti et al. (2021) reported that

**Table 4**

Validation of the methodological results through comparison with previous studies.

Reference	Verified main finding from literature	Result of this study	Agreement
Famiglietti et al. (2021)	The use phase dominates total impacts in the Milan DH case study (92% in the present scenario, 75% in the future scenario), while component production is secondary.	Fuel combustion dominates total supply-chain emissions (86.88%); infrastructure is smaller but still relevant (11.24%).	Good deal
Jeandaux et al. (2021)	District heating systems should be assessed from a full life-cycle perspective, including production, distribution, installation, use and end-of-life.	This study also applies a full supply-chain perspective and embeds infrastructure emissions within the overall system boundary.	Good deal
Vaucheze et al. (2023)	The pipe subsystem is the main contributor and trench works are the second most important contributor in most impact categories.	Civil engineering dominates network emissions (71%), infrastructure design and construction choices strongly affect results.	Partial agreement

the use phase dominates total impacts in a Milan district heating case study, contributing 92% in the present scenario and 75% in the future scenario, while component production remains secondary. This is consistent with the present study, where fuel combustion accounts for 86.88% of total supply-chain emissions and infrastructure contributes a smaller but still relevant share of 11.24%. [Jeandaux et al. \(2021\)](#) similarly assessed district heating systems from a full life-cycle perspective, including production, distribution, installation, use and end-of-life, supporting the validity of evaluating infrastructure emissions within the broader system boundary. In addition, [Vauchez et al. \(2023\)](#) identified the pipe subsystem as the main contributor and trench works as the second most important contributor in most impact categories, confirming that infrastructure design and construction choices materially affect environmental results. While the exact hotspot ranking differs from the Berlin case, likely due to differences in system boundaries and urban construction conditions, the general order of magnitude and the relevance of infrastructure-related processes are consistent with the literature. These comparisons support the plausibility and robustness of the methodological approach applied in this study.

Against this background, the following discussion further interprets the relative contribution of the different supply-chain stages and the specific hotspots identified for the Berlin case.

Section 3.2 showed that the combustion of energy sources within BEW's power plants remains the dominant emission contributor, which amounts to  $2.62 \times 10^9$  kg ( $2.62 \times 10^9$ ) of CO<sub>2</sub> per year. This corresponds to about 86–87% of the total supply chain emissions of  $3.02 \times 10^9$  kg CO<sub>2</sub> per year. The remaining shares originate from the construction of plants, with  $56.8 \times 10^6$  kg CO<sub>2</sub> (2% of the total supply chain emissions) attributed to plant construction and  $339.3 \times 10^6$  kg CO<sub>2</sub> (11% of the total supply chain emissions) to the district heating network. These results highlight that, while operational decarbonization remains the key short-term priority, embodied infrastructure emissions are already substantial and will become relevant as the fuel mix decarbonizes.

The findings from Sections 4.3 and 4.4 further refined this picture by identifying the primary emission sources within the construction of the district heating network. The study estimated the total network-related emissions for Berlin at  $16.96 \times 10^9$  CO<sub>2</sub> over the system's 50-year service life. This corresponds to an annualized value of approximately  $339 \times 10^6$  kg of CO<sub>2</sub> per year. Within this category, civil engineering processes dominated, accounting for 71% of total network emissions, while pipe production and materials contributed only a minor share. Backfilling, surface restoration, and heating-duct construction emerged as the primary hotspots among these processes. For example, backfilling alone caused up to 72% of emissions in the scenario of pre-insulated plastic casing pipes under natural stone pavement. In comparison, asphalt restoration contributed 56% with ducted steel pipes under asphalt.

The comparison of pipe systems in Section 4.2 also revealed obvious differences in the embodied emissions of various pipe types. Pre-insulated plastic casing pipes exhibited higher production emissions than steel pipes in ducts, especially at larger diameters. At DN 350, the plastic casing pipe reached 163 kg CO<sub>2</sub> per meter, compared to 95 kg CO<sub>2</sub> per meter for the steel pipe; this difference widened to 506 kg CO<sub>2</sub> per meter versus not applicable for DN 800, where only plastic casing pipes are used. However, these differences in pipe manufacturing are relatively small compared to the total emissions from civil works. This confirms that material substitution alone offers only limited mitigation potential unless combined with improvements in construction efficiency.

The scenario analysis in Section 4.5 further emphasized this point by quantifying the effect of construction coordination on total emissions. The analysis showed that sequential installation of house connections results in 12.8% higher CO<sub>2</sub> emissions than a bundled installation approach, because of repeated excavation, backfilling, and asphalt restoration. When extrapolated to the scale of Berlin's district heating network, this organizational difference alone could translate to tens of thousands of tons of additional CO<sub>2</sub> over the system's lifetime. These

results show that better planning coordination and process optimization can achieve emission reductions of a similar magnitude as many technological innovations, with no changes to the physical infrastructure or energy sources.

In addition to construction coordination, material and system choices also involve important trade-offs. While pre-insulated plastic casing pipes exhibit higher embodied carbon during manufacturing due to their multilayer structure, they offer superior thermal insulation and lower operational losses. Ducted steel pipes, on the other hand, involve lower material emissions but require concrete ducts, which significantly increase construction-related emissions. Moreover, ducted systems facilitate easier access for repair and maintenance, whereas direct-buried plastic casing pipes can entail more complex interventions. These trade-offs underline that decisions on pipe systems should consider both initial carbon footprint and long-term performance, including maintenance requirements.

The results of Sections 3 and 4 underline the dual nature of decarbonization challenges in district heating systems. On the one hand, reducing fuel-related emissions through renewable integration, industrial waste heat, and power-to-heat technologies remains the most impactful short-term strategy. On the other hand, the construction and maintenance of the heating network itself represents a long-term carbon lock-in, as each kilometer of new pipeline embodies significant emissions that persist over decades. Ignoring these infrastructure-related emissions would lead to an incomplete picture of the system's climate impact, in the context of Berlin's goal of achieving climate neutrality by 2045.

From a strategic perspective, the findings highlight the need to take a holistic approach to emission reduction. This includes technological improvements and institutional and procedural changes such as early-stage coordination of connection projects, integrated planning of excavation works, and systematic reuse of materials. Reducing the frequency of surface restoration, using recycled aggregates, and improving logistics for material transport could lower embodied emissions.

Finally, the study highlights that the relative importance of these infrastructure emissions will continue to grow as Berlin's energy mix becomes cleaner. The proportion of emissions from infrastructure's embodied carbon will grow as fossil fuel use decreases. Therefore, policies and corporate strategies for decarbonizing district heating should integrate life-cycle-based design principles and carbon accounting for construction processes to ensure that today's network expansions do not compromise tomorrow's climate targets. The following Section translates these technical findings into strategic and policy-oriented implications.

## 5.2. Policy implications

The results show that achieving climate neutrality in district heating requires technological innovation and policy interventions that target embodied emissions in infrastructure development. To support this, the following policy implications are recommended:

- Integrate embodied carbon into heating and cooling plans, subsidy programs, and climate strategies to avoid future carbon lock-in, in line with the revised Energy Efficiency Directive (Directive (EU) 2023/1791) ([Council, 2023](#)) and relevant national heat planning legislation.
- Coordinate infrastructure planning across utilities and municipalities to reduce redundant construction and emissions.
- Enforce life-cycle carbon accounting in public procurement and permitting aligned with existing European regulatory frameworks such as the EU Taxonomy Regulation (Regulation (EU) 2020/852) ([Council, 2020](#)), the Corporate Sustainability Reporting Directive (CSRD, Directive (EU) 2022/2464) ([Council, 2022](#)), and the Corporate Sustainability Due Diligence Directive (CSDDD) ([Council, 2024](#)).

- Prioritize low-carbon construction materials and set CO<sub>2</sub> intensity benchmarks in tenders.
- Establish binding targets for embodied carbon in national and municipal heat planning and infrastructure regulation.
- Require district heating suppliers to include CO<sub>2</sub> reduction criteria and disclose construction emissions in procurement processes.
- Align regulatory instruments, procurement policies, material standards, and inter-operator coordination to embed embodied carbon in future infrastructure policy.

### 5.3. Limitations and future recommendations

Even though this study offers a complete assessment of the embodied emissions of district heating infrastructure, several limitations must be acknowledged. The analysis is based on data from the Sprengelkiez model district, which represents typical urban conditions in Berlin but may not capture the variability of construction methods, soil types, and logistical constraints in other regions. Extrapolating these results to the entire network introduces uncertainties regarding future material developments and changes in construction practices.

An additional limitation concerns the modeling assumption of steel pipes installed in concrete ducts. This configuration reflects the historical and partially still existing installation practice in parts of the Berlin district heating network and was therefore applied in the case study.

However, current state-of-the-art installations typically use directly buried pre-insulated plastic-coating pipes without concrete encasement. The use of concrete ducts increases embodied emissions due to additional material demand and civil engineering processes. Consequently, the results overestimate infrastructure-related emissions compared to modern directly buried systems. Future research should therefore compare alternative pipe installation typologies to assess their relative carbon footprint under varying urban boundary conditions.

A further limitation concerns the assumption that steel pipes are installed in concrete ducts. This reflects the actual installation practice in the existing Berlin network, where all steel-pipe sections are ducted. However, in many modern district heating systems, directly buried pre-insulated steel pipes are now standard.

Another limitation lies in the data availability for specific process emissions, especially regarding upstream supply chains and producing secondary materials. Although emission factors were derived from established databases and industry sources, more granular and site-specific data would improve accuracy. This study focuses on carbon footprint emissions, as CO<sub>2</sub> is the most widely used and policy-relevant metric for evaluating climate effects in infrastructure projects. Other environmental factors, such as water use, land transformation, or particulate matter, were excluded because of limited data availability and comparability across construction scenarios. Consequently, the analysis concentrates on embodied CO<sub>2</sub> emissions. This assessment is therefore not a full life cycle assessment (LCA) but a carbon-footprint-focused analysis. It does not account for additional environmental effects such as particulate matter, noise, or biodiversity loss, which may also influence sustainability assessments of infrastructure projects.

Beyond the system-wide assessment of the carbon footprint conducted in this study, future research should also examine how district heating networks compare to individual heat pumps. Such a comparison is becoming increasingly important, as both technologies are central to European strategies for decarbonizing heat supply. A systematic and context-specific assessment would need to take into account differences in the evolution of the electricity mix, seasonal performance factors, installation conditions, and the emissions embodied in heat pump components. Understanding the urban and technical conditions under which district heating or individual heat pumps achieve a lower carbon footprint would provide valuable insights for heat planning and support the development of hybrid solutions that combine the strengths of both systems.

It is also relevant to acknowledge that the district heating network

analyzed in this study is a typical third-generation system with relatively high supply temperatures and a conventional hydraulic design. The methodological approach used to quantify infrastructure-related emissions can be fully transferred to fourth- and fifth-generation district heating networks because the dominant emission sources, such as excavation, material use, and surface restoration, are independent of the operating temperature. In fourth-generation low-temperature systems, the main difference occurs during the operational phase, where lower temperature gradients reduce emissions related to heat loss. Fifth-generation ambient-temperature networks, which may also provide cooling services, would require an adapted representation of operational energy flows? however, their underlying infrastructure processes would remain comparable. Thus, the framework developed in this study can support assessing future low-temperature and ambient-temperature district heating and cooling systems.

Finally, future work should develop standardized methodologies and KPIs for embodied carbon reporting in district heating systems. Such tools would enable consistent benchmarking across utilities, support transparent communication of climate impacts, and facilitate the integration of infrastructure emissions into strategic decarbonization roadmaps.

## 6. Conclusions

This study presents a comprehensive carbon footprint analysis of Berlin's district heating system, covering plant construction, fuel combustion, and the construction and operation of the district heating network. It examined three research questions: (1) What share of emissions in the district heating supply chain are infrastructure-related?

(2) Which processes and materials drive these emissions? (3) What strategies can effectively reduce these emissions? The analysis revealed that infrastructure accounts for 11.24% of total emissions and that civil engineering processes, such as backfilling and surface restoration, are the main hotspots. Targeted measures, including material optimization, coordinated trenching, and life-cycle carbon accounting, offer substantial mitigation potential.

Beyond these findings, construction logistics and coordination have a substantial impact. The scenario analysis comparing sequential and bundled installation of house connections shows that bundled construction reduces emissions by 12.8%. This improvement results from minimizing redundant excavation, backfilling, and surface restoration steps and reducing fuel use through more efficient machinery deployment. When applied city-wide, such process optimization could avoid tens of thousands of tons of CO<sub>2</sub> over the system's lifetime.

These results underline a paradigm shift in how the decarbonization of district heating systems is understood. While the transition to renewable and waste-heat-based generation remains the most powerful short-term lever, the long-term climate performance of district heating depends on the embodied carbon of its infrastructure. Each kilometer of new pipeline embodies substantial emissions that persist for decades.

The 11.24% share of network-related emissions identified in this study must become a central consideration in planning and policy. Future decarbonization strategies should therefore address infrastructure emissions through three key actions:

- (1) Ensure that carbon footprint accounting is integrated into planning and regulation, considering construction-related emissions in heating plans, subsidies, and climate strategies.
- (2) Promote low-emission construction materials and methods, especially using natural stone pavement and optimized back-filling processes that cut emissions.
- (3) Enhance construction coordination and logistics, for example, by bundling excavation projects across utilities to reduce repeated works and fuel-intensive transport.

Achieving climate-neutral district heating requires coupling

renewable heat generation with low-emission, material-efficient, and well-coordinated network construction. Addressing these embodied emissions today will determine whether district heating systems can achieve long-term climate neutrality targets and serve as a sustainable backbone of urban heat supply.

### CRediT authorship contribution statement

**Xenia Malcher:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Conceptualization.  
**Helena Przystacki:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation.  
**Joachim Seifert:** Writing – review & editing, Validation. **Matthias Finkbeiner:** Writing – review & editing, Validation, Supervision.

### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used OpenAI's ChatGPT to improve the language, clarity, and coherence of the

manuscript. All generated text was reviewed, edited, and approved by the authors, who take full responsibility for the content of the published article.

### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Xenia Malcher reports were provided by TU Berlin University. Xenia Malcher reports a relationship with TU Berlin University that includes: .  
 If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgements

The authors would like to thank the inputs and constructive feedback of Robert Zachrau and Michael Trompelt from *BEW* and Stefan Reeg, which have improved the quality of the manuscript.

### Nomenclature Acronyms

BEW	Berliner Energie und Wärme GmbH
CCPP	Combined Cycle Power Plant
CF	Carbon Footprint
CHP	Combined Heat and Power
CSDDD	Corporate Sustainability Due Diligence Directive
CSR	Corporate Sustainability Reporting Directive
DH	District Heating
DHS	District Heating System
DN	Diameter Nominal (pipe size specification)
EOL	End of Life
ESRS	European Sustainability Reporting Standards
FU	Functional Unit
GHG	Greenhouse gases
HP	Heat Pump
ISO	International Organization for Standardization
KPIs	Key Performance Indicators
kg	Kilogram
kWh	Kilowatt hour
MJ	Megajoule
P2H	Power to Heat
RES	Renewable Energy Sources

### Variables

<b>CO<sub>2</sub></b>	Carbon dioxide
$A_{net}$	Share of network emissions in total annual emissions [%]
$E_{comb,heat}$	Combustion emissions allocated to heat [kg CO <sub>2</sub> /a]
$E_{net, annual}$	Annual network emissions [kg CO <sub>2</sub> /a]
$E_{net, total}$	Total network emissions [kg CO <sub>2</sub> ]
$E_{plant}$	Plant-construction emissions [kg CO <sub>2</sub> /a]
$E_{total}$	Total combustion emissions [kg CO <sub>2</sub> /a]
$EF_{plant}$	Emission factor for plant construction [kg CO <sub>2</sub> /MJ]
$EF_{net,km}$	Emission factor per kilometer of network length [kg CO <sub>2</sub> /km]
$L_{net}$	Installed network length [km]
$Q_{heat}$	Annual useful heat [MJ/a]
sheet	Heat share
tlife	Lifetime [a]

### Data availability

Data will be made available on request.

### References

AGFW, 2023. AGFW-Hauptbericht Fernwärme: 30 Prozent Klimaneutrale Besser Als Übriger Warmemarkt. "Wärmeerzeugung - Fernwärme AGFW [Online]. Available: <https://www.agfw.de/energiewirtschaft-recht-politik/energiewende->

- politik/aktuelles-aus-dem-bereich/newsdetail/agfw-hauptbericht-fernwaerme-30-pr-ozent-klimaneutrale-waermeerzeugung-fernwaerme-besser-als-uebriger-waermemar-kt?utm\_source=chatgpt.com.
- BEW Berliner Energie und Wärme, 2025. Wärme Und Energie Für Berlin [Online]. Available: [https://www.bew.berlin/?utm\\_source=chatgpt.com](https://www.bew.berlin/?utm_source=chatgpt.com).
- Brogaard, LK, Christensen, TH, 2013. Quantifying capital goods for waste incineration: balancing resource consumption and environmental impacts. *Waste Manag.* <https://doi.org/10.1016/j.wasman.2013.06.015>.
- Council, EPA, 2020. Regulation (EU) 2020/852 of 18 June 2020 on the Establishment of a Framework to Facilitate Sustainable Investment and Amending Regulation (EU) 2019/2088. *Official Journal of the European Union*.
- Council, EPA, 2022. Directive (EU) 2022/2464 of 14 December 2022 Amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU as Regards Corporate Sustainability Reporting. *Official Journal of the European Union*.
- Council, EPA, 2023. Directive (EU) 2023/1791 of 13 September 2023 on Energy Efficiency and Amending Regulation (EU) 2023/955. *Official Journal of the European Union*.
- Council, EPA, 2024. Directive (EU) 2024/1760 of 13 June 2024 on corporate sustainability due diligence and amending directive (EU) 2019/1937 and regulation (EU) 2023/2859. *Off. J. Eur. Union*.
- Enegelmann, P., Kohler, T. B., Meyer, R., 2021. Systemische Herausforderung der Wärmewende. *Umweltbundesamt Hamburg*.
- Energie-Agentur, Deutsche, 2023. Wie gelingt die Dekarbonisierung der Fernwärme? *dena.de*.
- European Investment Bank, 2023. EIB Project Carbon Footprint Methodologies - Methodologies for the Assessment of Project Greenhouse Gas Emissions and Emission Variations.
- Famiglietti, J., Gerevini, L., Spirito, G., Pozzi, M., D'eneri'e, A., 2021. Environmental life cycle assessment scenarios for a district heating network. An Italian case study. *Energy Rep.* 7 (4), 368–379.
- Fritsche, U., Rausch, L., 2008. Bestimmung Spezifischer treibhausgas-Emissionsfaktoren Für Fernwärme. *Federal Environment Agency, Darmstadt*.
- Guest, G., Cherubini, F., Strömman, AH, 2011. Life cycle assessment of biomass-based combined heat and power plants. *J. Ind. Ecol.* <https://doi.org/10.1111/j.1530-9290.2011.00362.x>.
- I. 1, 2018. International Organization for Standardization, *Greenhouse Gases – Carbon Footprint of Products – Requirements and Guidelines for Quantification*. International Organization for Standardization, Geneva.
- International Organization for Standardization, 2006. *Environmental Management - Life Cycle Assessment - Principles and Framework*.
- Jeandaux, C., Videau, J., Prieur-Vernat, A., 2021. Life cycle assessment of district heating systems in Europe: case study and recommendations. *Sustainability* 13 (20), 11256. *ENGIE Lab CRIGEN Stains France*.
- Kaczmarczyk, G., Kunz, A., Fertig, T., Peters, R., Bar, K., 2024. Environmental impact assessment of two geothermal projects in France using life cycle assessment and the product environmental footprint approach. *Energies.* <https://doi.org/10.3390/en17106050>.
- T., Zschokke, M., 2021. Life cycle inventories of heating systems. *Bundesamt für Kagi, Umwelt*.
- Lacirignola, M., Meany, BH, Padey, P., Blanc, I., 2014. A simplified model for the estimation of life-cycle greenhouse gas emissions of enhanced geothermal systems. *Geothermal Energy* 2 (1), 8.
- Lokesh, K., Densley-Tingley, D., Marsden, G., 2022. Measuring Railway Infrastructure Carbon: a 'Critical' In Transport's Journey to net-zero.
- Maaß, C., Mohring, P., Purkus, A., Sandrock, M., Freiberger, L., Kleinertz, B., 2021. Grüne Fernwärme für Deutschland - Potenziale, Kosten, Umsetzung. *Bundesverband der Energie- und Wasserwirtschaft. Hamburg*.
- Malcher, X., Gonzalez-Salazar, M., 2024. Strategies for decarbonizing European district heating: evaluation of their effectiveness in Sweden, France, Germany, and Poland. *Energy* 304.
- Malcher, X., Tenorio-Rodriguez, FC, Finkbeiner, M., Gonzalez-Salazar, M., 2025a. Decarbonization of district heating: a systematic review of carbon footprint and key mitigation strategies. *Renew. Sustain. Energy Rev.*, 115602.
- Malcher, X., Tenorio-Rodriguez, F., Finkbeiner, M., Gonzalez-Salazar, M., 2025b. Reducing the carbon footprint of district heating: strategic approaches within the avoid-shift-improve (ASI) framework. *Energy Strategy Rev.* 62, 101890. <https://doi.org/10.1016/j.esr.2025.101890>.
- MindLogistics. "Life cycle assessment," Januar 2024 [Online]. Available: <https://mind-logistik.de/knowhow/life-cycle-assessment/>. September 2025.
- Moser, S., Gahleitner, A., Pflügl, M., 2025. Endbericht: Klimaneutrale Fernwärme - Analyse Von Klimaneutralen Fernwärme-Produkten Und Deren Zertifizierte Anrechenbarkeit Im Betrieblichen (Universitäten) CO2-Accounting. *Johannes Kepler Universität at, Linz*.
- Parajuli, R., 2014. Life cycle assessment of district heat production in a straw fired CHP plant. *Biomass Bioenergy* 68, 115–134.
- Persson, C., Froling, M., Svanstrom, M., 2006. Life cycle assessment of the district heat distribution system - part 3: use phase and overall discussion (10 pp). *Int. J. Life Cycle Assess.* 11 (6), 437–446. *Digitala Vetenskapliga Arkivet*.
- Soldal, E., 2021. LCA of Infrastructure for District Energy. *remote control*.
- Soldal, E., Modahl, I., 2021a. Life cycle assessment of infrastructure for district energy. In: *NORSUS Norwegian Institute for Sustainability Research. Report OR.13.21*.
- Soldal, E., Modahl, IS, 2021b. LCA of Infrastructure for District Energy. *Norsus*.
- Soukka, R., Luoranen, M., Lankinen, R., Hirvonen, M., 2018. Carbon Footprint of Heating Options for a New Residential Area. *Lappeenranta University of Technology LUT, Finland*, pp. 1–11.
- Tien, P., Wang, H., Tokbolat, S., Boukhanouf, R., Calautit, J., Darkwa, J., 2025. Application of life cycle assessment for enhancing sustainability of district heating: a multi-level approach. *Energy Rep.* 13, 5077–5096.
- Tzouganakis, P., Fotopoulou, M., Rakopoulos, D., Romanchenko, D., Nikolopoulos, N., 2025. District heating system analysis and design optimization. *Energy* 326, 136349.
- UIC/IFEU (International Union of Railways/Institut für Energie- und Umweltforschung Heidelberg GmbH), 2021. *Carbon Footprint of Railway Infrastructure*.
- Umweltbundesamt, 2025. *Public emissions via thru.de. Umweltbundesamt [Online]. Available: https://app.thru.de/detail-suche*.
- Ustinovichius, E., Kaklauskas, J., Zavadskas, A., Mitkus, A., Mitkus, L., 2020. A Review of Life Cycle Assessment (LCA) for District Heating Systems.
- VWB AG, 2023. *Dekarbonisierungsfahrplan [Online]. Available: https://www.bew.berlin/binaries/content/assets/website/downloads/dekarbonisierungsfahrplan---vattenfall-waerme-berlin-ag.pdf/*.
- Vauchez, M., Famiglietti, J., Autelitano, K., 2023. Life Cycle Assessment of District Heating Infrastructures: a Comparison of Pipe Typologies in France. *Energies, Champs-sur-Marne, France*.
- Zhang, Y., Sattar, S., Cook, D., Johnson, K., Fung, J., 2024. Systematic Review of Embodied Carbon Assessment and Reduction in Buildings Life Cycles. *US Department of Commerce, National Institute of Standards and Technology, USA*.