The Role of Exergy and Emissions in Municipal Heat Planning: Insights from Hamburg

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Abstract

As part of municipal heat planning, large cities such as Hamburg are required to develop a heat plan by the end of June 2026. A central challenge is the substitution of heat supply in urban areas currently connected to the gas network. For a sustainable heat supply, district heating networks mainly compete with decentralized heat supply using air-to-water heat pumps. The decision to implement a district heating network often relies on linear heat density as a key criterion. This study examines heat planning in three Hamburg districts, comparing current primary energy, greenhouse gas emission, and resource exergy factors for different heat supply options. The results suggest that the primary energy factor is influenced by political frameworks, while the greenhouse gas emission factor depends on the applied accounting methodology. The resource exergy factor provides a physically consistent evaluation metric for assessing the efficiency of local heat supply options and is the only factor investigated in this study that can distinguish among renewable energy sources. Considering the current electricity mix and the assumptions made, combined heat and power plants and waste heat utilization in district heating networks outperform air-to-water heat pumps. The study also reveals a prevailing tendency toward decentralized heat supply as a substitute for gas-connected districts, which poses significant lock-in risks. These risks stem primarily from the recent abolition of the so-called 65 % renewable energy obligation, which may prolong the use of fossil-fuel-based heating systems. At the same time, large-scale deployment of decentralized heat pumps may substantially increase electricity demand, so that both developments may adversely affect the energy transition. The findings suggest that linear heat density alone is insufficient and underscore the necessity of a holistic, locally differentiated assessment framework. Integrating exergy analysis and life cycle assessment into future municipal heat planning to assess efficiency and material consumption is proposed as a holistic approach to effectively achieve climate-neutral heat supply in Hamburg.

Introduction

Heating in buildings represents a crucial sector for meeting Hamburg's climate protection goals, as it accounts for around 30 % of both the city's final energy consumption and its greenhouse gas (GHG) emissions (FHH & BUKEA, 2024). The Heat Planning Act (WPG), embedded in the 2023 Climate Protection Plan, requires large cities and municipalities to prepare a heat plan by 2026 and 2028, respectively (WPG, 2023; FHH, 2023). Municipal heat planning is intended to provide a holistic framework for the systematic transformation of regional heat supply, involving relevant stakeholders in the planning process (BUKEA, 2025a).

According to the regional report of the German Association of Energy and Water Industries (BDEW), approximately 43 % of residential buildings in Germany were supplied by a central gas boiler in 2023. In Hamburg, around 53 % of residential buildings were connected to the gas network in the same year (BDEW, 2025). Hamburg's climate strategy envisages a gradual transition towards sustainable, low-carbon heat supply solutions. The phase-out of conventional natural gas supply is legally mandated by 2045; corresponding strategies foresee that parts of the existing gas network will be gradually decommissioned or repurposed for alternative energy carriers (Sandrock et al., 2025). According to the WPG, possible alternatives include repurposing gas networks by replacing natural gas with "green" gases, connecting buildings to district heating networks, or implementing decentralized heat supply systems. Until now, the Building Energy Act (GEG) has required a minimum share of renewable energy in new heating systems (WPG, 2023; GEG, 2020). However, a recent key issues paper by the German government proposes abolishing this requirement (the so-called 65 % rule), which would again allow the installation of fossil gas and oil heating

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systems in the future (Bundesregierung, 2026).

This paper aims to analyse the evaluation criteria used in municipal heat planning in Hamburg. Heat supply alternatives are assessed from both GHG emission and resource exergy perspectives, with a particular focus on district heating systems and decentralised air-to-water heat pumps. The analysis is conducted for three case-study neighbourhoods with different local conditions. The alternatives are evaluated using primary energy, GHG emission, and resource exergy factors, and the gaps in the current evaluation framework are identified.

State of knowledge

Municipal heat planning in Hamburg

Municipal heat planning in the Free and Hanseatic City of Hamburg (FHH) aims to assess the suitability of climate-neutral options for supplying building and process heat. The planning process is defined in Section 13 of the Heat Planning Act (WPG) and comprises several steps, ranging from suitability testing to the development of an implementation strategy with concrete measures for achieving the target scenario.

Guidelines published by the Federal Ministry of Housing, Urban Development and Construction (BMWSB) require that the suitability of both district heating networks and hydrogen networks be assessed. Among other factors, the building structure of a neighbourhood can be used to evaluate the suitability of district heating. In areas with dense single-family housing, the economic operation of a heating network can only be ruled out if no existing heating network is present in the sub-area or its immediate vicinity and, at the same time, no favourable renewable energy source or unavoidable waste heat source can be utilised (BMWSB, 2024).

For the city of Hamburg, the Authority for the Environment, Climate, Energy and Agriculture (BUKEA) defines the following key assessment criteria for municipal heat planning:

- heat demand density
- surface characteristics of the installation area
- economic feasibility

According to the BUKEA guidelines, district heating networks and air-to-water heat pumps are considered the dominant future technologies for Hamburg's heat supply. District heating networks are prioritised in the guidelines because they enable the efficient and cost-effective distribution of renewable heat sources and unavoidable waste heat. Furthermore, the decision cascade proposed by BUKEA suggests that heat pumps are prioritised over other decentralised heat supply concepts (BUKEA, 2025a).

The resulting preliminary target scenario was published on 16 March 2026 in the Hamburg Heat Register, and the corresponding report was released by FHH & BUKEA (2026).

Linear heat density

The linear heat density of a district heating network is defined as the ratio of heat demand to the network route length (with supply and return pipes counted as a single route). In the Hamburg Heat Register, linear heat density is reported separately for renovated and unrenovated buildings in units of MWh/(m·a). In the context of municipal heat planning, Dochev et al. recommend using linear heat density as a key indicator, as it accounts for the network length and therefore requires hypothetical network modelling (Dochev et al., 2018).

The following table provides an overview of typical linear heat densities in various countries, as analysed in the International Energy Agency (IEA) status report on district heating systems.

Table1 : Typical linear heat densities for district heating systems in different countries

Country	Share of district heating in the final energy mix for heat supply* (Rambøll, 2020)	Typical linear heat densities (Nussbaumer & Thalmann, 2014)	Typical heat losses (Nussbaumer & Thalmann, 2014)
Germany	14 %	2.0 MWh/(ma)	17 %
Denmark	65 %	0.7 MWh/(ma)	25 %
Finland	38 %	1.9 MWh/(ma)	14 %
Switzerland	4 %	1.9 MWh/(ma)	12 %
Austria	14 %	1.1 MWh/(ma)	19 %

*The figures from (Rambøll, 2020) have been rounded to whole numbers

In general, the higher the linear heat density of an area, the more likely it is considered as a district heating area. Various reference values are used for evaluation. The guidelines published by BMWSB classify areas with a linear heat density of 0.7 MWh/(m·a) or higher as having "medium suitability" for district heating (BMWSB, 2024). In practice, a value of 1.5 MWh/(m·a) is often applied as the threshold for the economically viable operation of a heating network. This value serves primarily as an economic benchmark for network operators in Germany to ensure that investment costs and network losses remain proportionate to the amount of heat delivered (Pfnür et al., 2016). For municipal heat planning in Hamburg, the Heat Register specifies threshold values of 1.5 MWh/(m·a) for new development areas and 2 MWh/(m·a) for existing building areas (FHH & BUKEA, 2019).

The comparison of linear heat densities in Table 1 shows that the average values in Germany, Finland, and Switzerland are considerably higher than those in Austria and Denmark. Interestingly, Denmark has the highest share of district heating, suggesting that even areas with relatively low linear heat densities can technically support a widespread district heating network. For Hamburg, the theoretical techno-economic potential of district heating is estimated at approximately 80 % of the building heat demand (BUKEA, 2025a).

Primary energy factor

The non-renewable primary energy factor (PEF) is defined as the ratio of non-renewable primary energy to final energy. The approach was developed in studies by the Wuppertal Institute for Climate, Environment and Energy in the 1990s and has become established in the energy assessment of buildings. Its application is regulated in Section 22 of the GEG. According to the GEG, only the non-renewable portion of primary energy is assessed. Some of the primary energy factors specified in the GEG are based on political decisions and therefore deviate from a physical definition (GEG, 2020).

Emission factor

The greenhouse gas (GHG) emission factor (EF) is a parameter used to assess the climate impact of processes or products. It is defined by the ratio of GHG emissions caused to the final energy provided and is specified in the GEG in the unit g CO_2 equivalent per kWh. For the calculation of the EF, a time horizon of 100 years is usually considered. District heating operators report a specific GHG emission factor for the respective network as part of the energy assessment in accordance with AGFW worksheet FW 309-1. The methodological derivation and the parameters and GHG emission factors required for the calculation for district heating systems are presented in detail in this worksheet. (AGFW, 2023) In the Hamburg Heat Register, heating networks are characterised using the GHG emission factor according to FW 309-1 (corresponding to the calculation in Annex 9 of the GEG) as well as the GHG emission factor determined by the reference value method (also known as the Finnish method). The calculation according to FW 309-1 is based on the electricity credit method, which results in lower GHG emission factors for heat generated in CHP plants under the current electricity mix. FW 309-6 (2023) describes the Carnot method, based on Carnot efficiency, which provides a physically grounded approach for allocating heat and electricity production. Nevertheless, most district heating certifications apply only the electricity credit method according to FW 309-1. The Umweltbundesamt (2016) provides an overview of the relevant allocation methods for CHP.

Resource exergy factor

The resource exergy factor (REF) is a key metric of resource exergy analysis (REA) and enables the thermodynamic evaluation and comparison of energy systems. REF is defined as the ratio of resource exergy consumption to the final energy delivered and can be calculated for various energy systems and fuels following the methodology outlined in the REA (Jentsch, 2025).

An exergy-based assessment considers not only the quantity of energy but also its quality, allowing exergy losses to be identified and optimization potentials to be highlighted comprehensively. Conventional primary energy or GHG emission factors do not permit a meaningful comparison between renewable energy sources, as they are often assigned zero. However, a comparison of the resource exergy consumption of a hydrogen combustion boiler with that of a fossil-fuel combined heat and power (CHP) plant demonstrates that renewable energies are not inherently equivalent, and resource consumption must be considered in a future climate-neutral energy system to avoid indirect GHG emissions due to inefficiencies (Jentsch, 2024).

The following simplified formulas from the REA were applied to calculate the REFs in this study (Jentsch, 2025):

Air-to-water heat pumps:

$$f_{R,WP} = \frac{f_{R,el}}{APF} \qquad \text{Equation 1}$$

Where

$f_{R,el}$ =REF of the drive energy

APF =Annual performance factor

The calculation according to equation 1 is only applicable under the assumption that the outside air temperature corresponds to the reference temperature T_0 and the heat pump is electrically operated.

Heating plants/boilers:

$$f_{R,HB,i} = \frac{f_{R,i}}{\eta_{th}} \qquad \text{Equation 2}$$

Where

$f_{R,i}$ =REF of the fuel

η_{th} =annual thermal efficiency; related to the Higher Heating Value

CHP plants:

$$f_{R,CHP,i} = f_{R,i} \cdot \frac{\alpha_{th}}{\eta_{th}} \qquad \text{Equation 3}$$

The allocation factor α_{th} (5) is based on the Carnot factor f_C (4):

$$f_C = 1 - \frac{T_0}{T_{mn}} \qquad \text{Equation 4}$$

$$\alpha_{th} = \frac{\eta_{th} \cdot f_C}{\eta_{el} + \eta_{th} \cdot f_C} \qquad \text{Equation 5}$$

η_{el} =annual electrical efficiency

T_0 =reference temperature

T_{mn} =logarithmic average temperature of the district heating network (annual average of supply and return temperatures)

District heating system:

$$f_{R,DH} = \frac{\sum(x_i \cdot f_{R,i}^{plant}) + \omega \cdot f_{R,el}}{1 - e_{loss}} \qquad \text{Equation 6}$$

x_i =share of the generation plant i

$f_{R,i}^{plant}$ =plant-specific REF

ω =share of pump power consumption in relation to the produced heat (district heating: 0.015; waste heat: 0.02 according to (IEA, 2022))

e_{loss} =relative heat losses as a share of heat production (assumed to be 14% according to (IEA, 2022))

Table 2 summarises the key parameters considered in this study.

Table2 : Key parameters considered in the analysis

Key parameter	Unit	Definition	Source	Evaluation
Primary energy factor PEF	-	$\frac{primary\ energy}{final\ energy}$ *	FW 309-1/ Geoportal Hamburg	Comparison of energy sources based on primary energy consumption (non-renewable)
GHG emission factor EF	$\frac{g\ CO_2 equiv.}{kWh}$	$\frac{greenhouse\ gas\ emissions}{final\ energy}$	FW 309-1/ Geoportal Hamburg	Estimation of greenhouse gas emissions, comparison of energy sources
Resource exergy factor REF	-	$\frac{ressource\ exergy}{final\ energy}$	Calculation according to (Jentsch, 2025)	Assessment of thermodynamic efficiency & optimisation potential

*PEFs specified in the Building Energy Act often deviate from this definition

Electrification of heat demand

Several studies analyse potential transformation pathways for the energy transition, considering different levels of electrification (dena, 2018; Trutnevyte, 2019; Thelen et al., 2024). The Fraunhofer Institute study prioritises direct electrification in the building, transport and industry sectors as the most cost-effective option (Thelen et al., 2024). However, full electrification of all sectors conflicts with the principle of diversification and increases the vulnerability of the energy system to failures (Li, 2005). According to iSelect (2025), Germany is already among the ten countries with the highest risk of large-scale blackouts, with previous studies documenting the catastrophic effects of power outages on the population (Petermann et al., 2011).

Additionally, an electrified scenario with numerous decentralized heat pumps is likely to impose significant electrical loads on the power grid, necessitating its expansion or reinforcement. The current study by Fakhrooeian et al. (2024) concludes that most existing electricity grids are not designed to provide the additional energy required for charging electric vehicles and operating heat pumps.

System temperatures

Despite the recommendations made during the development of the district heating transformation strategy (Maaß et al., 2015), there have been few initiatives to date aimed at lowering the system temperature in Hamburg's city network. Lowering flow and return temperatures in existing district heating networks is, however, constrained by multiple factors, including the technical limitations of the network (e.g., pipe dimensions and hydraulic restrictions), the existing building stock with high heating requirements, and economic and institutional conditions such as investment costs and pre-existing contractual arrangements.

However, there are several neighbourhood and sub-networks that already operate at lower supply and return temperatures. From an exergetic point of view, lowering the supply and return temperatures could offer significant advantages: heat losses would be reduced, and more waste heat sources and renewable energies could be integrated into the network (Schmidt, 2018).

Methodology

This study examines three urban areas in Hamburg that are currently supplied by the municipal gas network. Preliminary heat planning has already been completed for all areas. In the Hamburg Heat Register, most of these areas are designated as decentralised supply areas, excluding existing building-related heat network structures (Geoportal Hamburg).

In order to evaluate the heat planning from an environmental perspective, primary energy, GHG emission and resource exergy factors of the district heating networks were calculated and compared to air-water heat pumps. For the Hamburg Othmarschen case study, direct utilisation of waste heat in a local heating network was assumed. The results were subsequently compared, and the relevance of the evaluated indicators was assessed, with a discussion of aspects not captured by the evaluation.

PEFs and EFs for the heating networks were obtained from the Hamburg Heat Register (Geoportal Hamburg). For the heat pump and CHP variants, the respective factors were calculated in accordance with the GEG (GEG, 2020). REFs are calculated in accordance with the the REA methodology (Jentsch, 2025). Annual utilisation rates and other assumptions were adapted from the IEA (2022). The compositions of the district heating mixes were based on the available certificates according to AGFW FW 309, Parts 1 and 7 (HEnW, 2022 & HEnW 2025a) and on documents provided by network operators (E.ON SE, (2023) & EAM Natur Energie GmbH, (2021)). Supply and return temperatures were taken from the operators' Technical Connection Conditions (TABs) where available (HEnW, 2025b & HEnW, 2025c). For networks without publicly accessible TABs, temperatures were requested directly from the operators. The arithmetic mean values of the minimum and maximum supply and return temperatures from the TABs were assumed as the average annual network temperatures.

Case study 1: Hamburg Alsterdorf

The garden city of Alsterdorf "Gartenstadt Alsterdorf" is composed primarily of single-family homes, most of which were built in the 1930s. Heating is mainly provided by gas or oil boilers. The linear heat density in the neighbourhood ranges from 1 to 1.5 MWh/(m·a). Despite its close proximity to the city's district heating network, the area was classified as "unsuitable for district heating" in the Hamburg Heat Register preliminary target scenario due to its relatively low linear heat density (see Figure 1). The adjacent network is Hamburg's city network, operated by Hamburger Energiewerke (HEnW).

Figure1: Preliminary target scenario for the heat supply of the "Gartenstadt Alsterdorf" neighbourhood (map excerpt from the Hamburg Heat Register; scale 1:5,000; accessed 17 March 2026). Blue: decentralized heat supply; red: existing district heating networks; light red/beige: district heating expansion likely; pink: decentralized and district heating both possible; black dotted area: study area.

Case study 2: Hamburg Neuallermöhe and Nettelnburg

The Neuallermöhe and Nettelnburg neighbourhoods (formally part of Bergedorf) have different building structures. Neuallermöhe is dominated by multi-family houses and modern, well-insulated new buildings, whereas Nettelnburg, particularly outside the S-Bahn corridor, consists mainly of detached and semi-detached houses. The settlement in Nettelnburg was built in the 1960s, implying a comparatively low insulation standard of the building envelope. Due to the differing settlement patterns, the linear heat densities also vary. In some multi-family buildings, linear heat densities may exceed 5 MWh/(m·a), whereas values in Nettelnburg range between 1 and 1.5 MWh/(m·a). Several heating networks operate in the surrounding area, with the largest operated by HenW, EAM Natur Energie GmbH and HanseWerk Natur. Despite the proximity to multiple heating networks and some existing building networks, a decentralised heat supply is planned for most of the buildings not yet connected to the network. Some areas are identified as optimally suited for district heating; however, their implementation would require initiative by the building owners themselves (areas highlighted in beige in Figure 2).

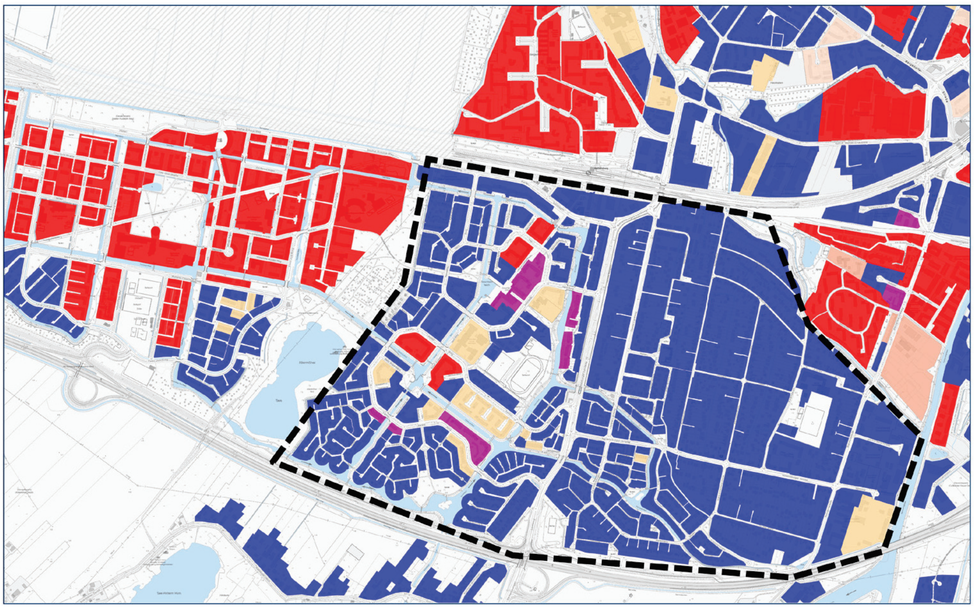

Figure2: Preliminary target scenario for the heat supply in the Neuallermöhe and Nettelnburg districts (map excerpt from the Hamburg Heat Register, scale 1:10,000; accessed: 17 March 2026). Blue: decentralized heat supply; red: existing district heating networks; light red/beige: district heating expansion likely; pink: decentralized and district heating both possible; black dotted area: study area.

Case study 3: Hamburg Othmarschen

The district of Othmarschen, located in the borough of Hamburg-Altona, features a heterogeneous building structure. Old villas and detached houses dominate along the Elbe river, while apartment buildings predominate near the S-Bahn. In addition to the Hamburg municipal heating network, smaller local heating networks are present in the immediate vicinity, such as the Bahrenfeld and Lyserstraße networks. The preliminary target scenario developed by BUKEA predominantly foresees decentralized heat supply solutions for most residential buildings. Exceptions mainly include non-residential buildings, such as schools and daycare centers (areas highlighted in beige in Figure 3).

Zimmermann et al. (2025), in their spatial assessment of waste heat potential in Hamburg, identify a theoretically high waste heat potential for Othmarschen. According to their evaluation methodology, the waste heat is classified as level 3, corresponding to an annual volume of over 10,000 MWh at temperatures above 100 °C. The study, however, does not specify individual sources for each district.

High temperature waste heat sources relevant for heat planning primarily arise from industrial production (e.g. steel, chemical industry, glass, paper), waste disposal and energy conversion (BMWSB, 2024). The Hamburg Heat Register lists the German Electron Synchrotron DESY and Airbus Operations GmbH as nearby waste heat sources.

To account for waste heat utilisation efficiency in this study, direct use of the waste heat potential via a local heating network is assumed for Othmarschen. In practice, direct feed-in is often not feasible, as waste heat usually requires a temperature boost via a heat pump. Nevertheless, direct use is theoretically possible for high-temperature waste heat above 100 °C and low flow temperatures in the building heating system. Due to the absence of detailed data, direct waste heat utilisation is assumed in this analysis.

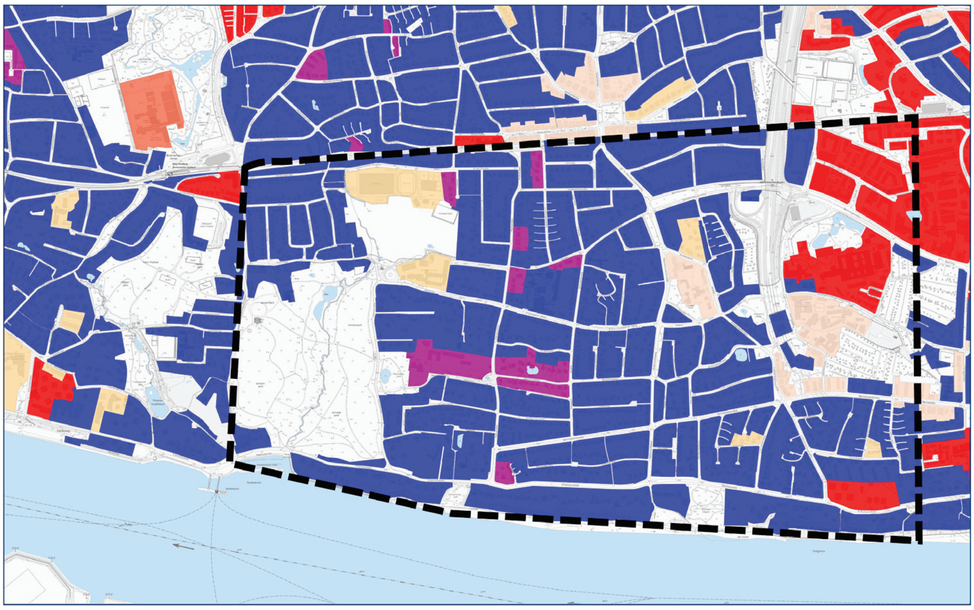

Figure3: Preliminary target scenario for the heat supply in the Othmarschen district (map excerpt from the Hamburg Heat Register, scale 1:10,000; accessed: 11 March 2026). Blue: decentralized heat supply; red: existing district heating networks; light red/beige: district heating expansion likely; pink: decentralized and district heating both possible; black dotted area: study area.

Results and Discussion

The calculated factors, along with the underlying assumptions, are detailed in Table 3. The potential local heat supply options were evaluated against three scenarios: pure waste heat utilization, decentralized air-to-water heat pump operation with APFs of 3 and 4, and a coal-fired CHP configuration. Due to unknown assumptions in the Hamburg Heat Register, GHG emissions for the waste heat, heat pump and CHP variants were not calculated using the Finnish method.

The results demonstrate significant differences in assessment logic across the various methods. According to the GEG and FW 309-1, CHP plants are strongly favoured in terms of PF and EF. This preference results from electricity credit method, which values exported electricity with a high GHG emission factor of 860 g CO_2 equivalent/kWh and deducts it from the total emissions. As a result, EF values for CHP are significantly lower compared to the Finnisch method, which benchmarks cogeneration against separate generation of electricity and heat. For perspective, the latest GHG emission factor of the German electricity mix in 2023 is 445 g CO_2 equivalent/kWh, which is lower than the GEG reference value (UBA, 2024). This discrepancy illustrates how the choice of assessment methodology strongly influences which heat supply alternatives are classified as low-emission. For future GHG emission assessments, the Carnot method could be applied in certificates and in the Heat Register, as it enables a thermodynamically consistent allocation of electricity and heat in CHP plants.

The REF results show a differentiated picture. CHP plants are particularly advantageous from an exergetic perspective. According to the REF methodology, conventional coal or natural gas CHP plants can outperform individual heat pumps operated with the current electricity mix (see Table 3.). Among the investigated networks, only one existing system—characterized by a high share of heat supplied by a wood-fired power plant operated by HanseWerk Natur GmbH—achieves a better REF than a decentralised air-source heat pump with an APF of 3. The primary reason for this is the high proportion of natural gas boilers in the district heating mixes analyzed, which diminishes the exergetic efficiency of these systems. Therefore, increasing the share of CHP in local district heating networks could substantially enhance their thermodynamic efficiency. Upon exclusion of the electricity credit method, utilization of waste heat via local heating networks emerges as the most efficient and environmentally sustainable option, considering both exergy and greenhouse gas emissions.

Table 3: Results for the factors used to evaluate primary energy consumption, greenhouse gas emissions and resource exergy consumption

Heat supply options:		HEnW Alsterdorf	HEnW Allermöhe/ Bergedorf-West	EAM Glasbläserhöfe/ Am Güterbahnhof	HWN Lohbrügge	Waste heat utilisation (Othmarschen)	Heat pump APF=3	Heat pump APF=4	Coal-fired CHP
Energy source	*REF (Jentsch, 2025)*	*Shares*	*Shares*	*Shares*	*Shares*	*Shares*	*Shares*	*Shares*	*Shares*
Hard coal CHP	$1.16\cdot\frac{\alpha_{th}}{\eta_{th}}$	28.2 %	-	-	-	-	-	-	100 %
Natural gas CHP	$1.26\cdot\frac{\alpha_{th}}{\eta_{th}}$	23.2 %	48 %	-	-	-	-	-	-
Natural gas boiler	1.26	19.9 %	24 %	32 %	19 %	-	-	-	-
Heating oil boiler	1.22	2 %	-	-	-	-	-	-	-
Biogenic waste CHP	$1\cdot\frac{\alpha_{th}}{\eta_{th}}$	12 %	-	55 %	-	-	-	-	-
Biogenic waste	1	-	-	13 %	5 %	-	-	-	-
Wood-fired power plant	$1.16\cdot\frac{\alpha_{th}}{\eta_{th}}$	-	-	-	76 %	-	-	-	-
Incineration of waste wood	1.02	4.9 %	-	-	-	-	-	-	-
Waste heat from waste CHP	$1\cdot\frac{\alpha_{th}}{\eta_{th}}$	4.1 %	-	-	-	-	-	-	-
Industrial waste heat	$=f_C$	2 %	-	-	-	100 %	-	-	-
Waste heat from wastewater	$APF\cdot f_{C,ww}$	3.7 %	-	-	-	-	-	-	-
Electricity grid	2.63	-	9 %	-	-	-	33.3 %	25 %	-
Environmental heat	0	-	19 %	-	-	-	66.7 %	75 %	-
Annual average supply/return temperature	-	111.5/40 °C	87.5/30 °C	80/50 °C	85/50 °C	70/40 °C	-	-	111.5/40 °C
Primary energy factor PEF according to FW 309-1/GEG		**0.3**	**0.46**	**0.24**	**0.23**	**0**	**0.6***	**0.45***	**0.31****
Emission factor EF FW 309-1/GEG in g CO_2 eq. /kWh		**64**	**28**	**0**	**0**	**40**	**187***	**140***	**7****
Emission factor EF Finnish method in g CO_2 eq./kWh		**258**	**238**	**139**	**43**	**-**	**-**	**-**	**-**
Resource exergy factor REF		**0.89**	**0.96**	**1.01**	**0.85**	**0.32**	**0.88**	**0.66**	**0.56**

*The PEF and EF of the heat pump were calculated using an electricity PEF of 1.8 and an electricity EF of 560 g equivalent/kWh; (FW 309-1:2023).

** The PEF and EF of the coal-fired CHP were calculated using a PEF of 1.1 and an EF of 300 g equivalent/kWh for hard coal, and a PEF of 2.8 and an EF of 860 g equivalent/kWh for the exported electricity mix (FW 309-1:2023).

The analysis acknowledges several critical factors that were not incorporated into the current assessment methods, including economic efficiency and material/resource consumption comparisons between district heating and decentralized heat pumps. Incorporating a holistic approach that combines exergy analysis with life cycle assessment (LCA) in future municipal heat planning could provide a more comprehensive evaluation of system efficiency and material use, especially relevant as renewable energy sources proliferate. This is crucial because the current primary energy and emission factors do not distinguish between different types of renewables, potentially obscuring their true sustainability profiles.

The case study analysis suggests that municipal heat planning in Hamburg currently leans toward promoting decentralized heat supply solutions in areas connected to the natural gas network. However, this approach may lead to several significant challenges:

- **Retention of fossil fuel heating systems:** The upcoming repeal of the 65% renewable energy obligation may cause many homeowners to continue using gas or oil systems.
- **Persistent low insulation standards:** Older buildings in decentralized areas with poor insulation are likely to rely on fossil fuels for longer, often supplemented by hybrid systems with heat pumps.
- **Rising electricity demand:** As heating electrification and growth in electric vehicle use increase, electricity prices might climb, and significant grid expansion and fortification may be necessary.
- **Grid dependency and blackout risk:** Increased reliance of all sectors (mobility, electricity, and heating) on the electricity grid combined with high share of renewables raise the risk of power outages.
- **Untapped waste heat potential:** Existing waste heat resources may remain underutilized.

Conclusion

The analysis indicates that municipal heat planning in Hamburg is largely influenced by economic considerations, but relying on linear heat density as a key criterion has notable limitations. In some neighboring countries, alternative linear heat density thresholds are considered economically viable, highlighting the context-specific nature of planning criteria. Developing a resilient and environmentally sound heat infrastructure therefore requires a more comprehensive, holistic approach that accounts for political, economic, and technical factors. Among the investigated factors, the primary energy factor (PEF) appears to be politically dependent, while the GHG emission factor (EF) varies significantly depending on the calculation methodology. For the assessment of GHG emissions, the electricity credit method is outdated, and a scientifically robust approach based on standardized methodologies must be applied to ensure a fair comparison between CHP plants and decentralized solutions. The resource exergy factor (REF) is proposed as a politically neutral and valuable metric for initial assessments of local heating options, providing a more objective basis for decision-making and complementing GHG emission assessments. The analysis reveals that several critical aspects of sustainable heat planning are not fully captured by current evaluation tools. Looking forward, the integration of exergy analysis with life cycle assessments (LCA) is seen as a promising approach to gain a more holistic understanding of system efficiency and material consumption. Such combined methods could significantly contribute to the development of more sustainable and resilient heat infrastructures.

Based on a qualitative assessment of the case studies, the results suggest that current strategies, which promote decentralized solutions, could lead to long-term infrastructure lock-in. For example, heat pumps installed today are likely to operate throughout their lifespan, potentially limiting flexibility and adaptation to future technological or policy changes. Moreover, recent policy shifts, such as the potential repeal of the 65% renewable obligation in buildings, might lead residents to retain fossil-fuel heating systems longer, resulting in environmentally less favorable outcomes. Conversely, district heating networks, benefiting from existing infrastructure and transformation strategies, are comparatively more aligned with climate goals and indicate a techno-economic potential in Hamburg capable of supplying up to 80% of the city's building heat demand.

The study results indicate that waste heat utilization generally represents the most sustainable heat supply option. Lowering system temperatures would further facilitate the integration of waste heat and renewable energy sources into district heating networks. Therefore, it is recommended to identify areas in Hamburg with high waste heat potential and to explore the development of low-temperature subnetworks or local heating networks to optimize utilization.

Literature

AGFW – The Energy Efficiency Association for Heating, Cooling and CHP e. V. (2023). FW 309-1:2023 – Energy assessment of district heating and cooling: Primary energy and emission factors according to the electricity credit method. AGFW.

AGFW – The Energy Efficiency Association for Heating, Cooling and CHP e. V. (2023). FW 309-6: Energy evaluation of district heating and district cooling – Emission factors according to the work allocation method and the Carnot method. AGFW.

BDEW Bundesverband der Energie- und Wasserwirtschaft. (2025). Wie heizt Deutschland? Ergebnisse der BDEW-Studie 2023 [How Germany Heats: Results of the BDEW Study 2023].

BMWSB Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen. (2024). Leitfaden Wärmeplanung: Empfehlungen zur methodischen Vorgehensweise für Kommunen und andere Planungsverantwortliche. [Heat Planning Guide: Recommendations for Methodological Approaches for Municipalities and Other Planning Authorities].

Bundesregierung; Fraktionen der CDU/CSU & SPD. (2026, February 24). Eckpunkte zum neuen Gebäudemodernisierungsgesetz [Key Points of the New Building Modernization Act].

BUKEA Behörde für Umwelt, Klima, Energie und Agrarwirtschaft (2025a). Leitlinien klimaneutrale Wärmeversorgung von Gebäuden: Kommunale Wärmeplanung der Freien und Hansestadt Hamburg [Guidelines for Climate-Neutral Heat Supply in Buildings: Municipal Heat Planning of the Free and Hanseatic City of Hamburg]. Freie und Hansestadt Hamburg.

dena Deutsche Energie-Agentur. (2018). dena-Leitstudie Integrierte Energiewende: Impulse für die Gestaltung des Energiesystems bis 2050. [dena Integrated Energy Transition Study: Impulses for Shaping the Energy System until 2050]. Deutsche Energie-Agentur GmbH.

Dochev, I., Peters, I., Seller, H., & Schuchardt, G. K. (2018). Analysing district heating potential with linear heat density: A case study from Hamburg. Energy Procedia, 149, 410–419. https://doi.org/10.1016/j.egypro.2018.08.205

EAM Natur Energie GmbH. (2021). Hamburg Am Guterbahnhof Glasbläserhöfe Informationsblatt 2021 [Hamburg Am Guterbahnhof Glasbläserhöfe Information Sheet 2021]. Retrieved March 2026.

E.ON SE. (2023). Hamburg-Lohbrügge-Nord – Lieferjahr 2023: Anteil eingesetzter Energieträger und Wärme- oder Kältegewinnungstechnologien im Gesamtenergiemix [Hamburg-Lohbrügge-Nord – Supply Year 2023: Share of Energy Carriers and Heat or Cooling Generation Technologies in the Overall Energy Mix]. Retrieved March 2026.

Fakhrooeian, P., Pitz, V., & Scheppat, B. (2024). Systematic evaluation of possible maximum loads caused by electric vehicle charging and heat pumps and their effects on common structures of German low voltage grids. World Electric Vehicle Journal, 15(2), 49. https://doi.org/10.3390/wevj15020049

FHH Freie und Hansestadt Hamburg, BUKEA Behörde für Umwelt, Klima, Energie und Agrarwirtschaft. (2019). Wärmekataster Handbuch. [Heat register handbook]

FHH Freie und Hansestadt Hamburg. (2023). Klimaschutzplan 2023: Energie, Gebäude und Wärmeversorgung [Climate Protection Plan 2023: Energy, Buildings, and Heat Supply]. Hamburg: Senatskanzlei.

FHH Freie und Hansestadt Hamburg, BUKEA Behörde für Umwelt, Klima, Energie und Agrarwirtschaft. (2024). Gebäudewärme.

FHH Freie und Hansestadt Hamburg, BUKEA Behörde für Umwelt, Klima, Energie und Agrarwirtschaft. (2026). Bericht zum Wärmeplan der Freien und Hansestadt Hamburg [Report on the heat plan of the Free and Hanseatic City of Hamburg].

GEG. (2020) Gesetz zur Einsparung von Energie und zur Nutzung erneuerbarer Energien zur Wärme- und Kälteerzeugung in Gebäuden [Building Energy Act: Law on Energy Savings and the Use of Renewable Energies for Heating and Cooling in Buildings].

HenW Hamburger Energiewerke GmbH. (2022). Bescheinigung nach AGFW FW 309 Teil 5 und 7 für das Stadtnetz Hamburg [Certificate according to AGFW FW 309 Parts 5 and 7 for the Hamburg City Network].

HenW Hamburger Energiewerke GmbH. (2025a). Bescheinigung nach AGFW FW 309 Teil 1 und 7 für das Wärmenetz „Verbundsystem Allermöhe / Bergedorf-West“ [Certificate according to AGFW FW 309 Parts 1 and 7 for the “Allermöhe / Bergedorf-West” District Heating Network].

HenW Hamburger Energiewerke GmbH. (2025b). Technische Anschlussbedingungen (TAB-Allermöhe / Burgwedel-Schnelsen) [Technical Connection Conditions (TAB-Allermöhe / Burgwedel-Schnelsen)].

HenW Hamburger Energiewerke GmbH. (2025c). Technische Anschlussbedingungen (TAB-Stadtnetz) [Technical Connection Conditions (TAB-City Network)].

IEA International Energy Agency. (2022). GHG emissions and resource exergy savings from district heating in Europe and China: Final project report. IEA Technology Collaboration Programme on District Heating and Cooling.

iSelect. (2025, Oktober). The Global Energy Outage Report. iSelect.

Jentsch, A. (2024). REA: Resource Exergy Analysis – A Key to Climate Sustainability. International Sustainable Energy Conference - Proceedings, 1. https://doi.org/10.52825/isec.v1i.1055

Jentsch, A. (2025). REA: Resource Exergy Analysis – Calculation Guide for Energy Systems including District Heating and District Cooling (Version 1.1). AGFW | The Energy Efficiency Association for Heating, Cooling and CHP e. V.

Landesbetrieb Geoinformation und Vermessung Hamburg. Geoportal Hamburg [online map service]. Freie and Hansestadt Hamburg. https://geoportal-hamburg.de/, retrieved March 18, 2026.

Li, X. (2005). Diversification and localization of energy systems for sustainable development and energy security. Energy Policy, 33(17), 2237–2243. https://doi.org/10.1016/j.enpol.2004.05.002

Maaß, C., Sandrock, M., & Schaeffer, R. (2015). FERNWÄRME 3.0: Strategien für eine zukunftsorientierte Fernwärmepolitik [DISTRICT HEATING 3.0: Strategies for a Future-Oriented District Heating Policy]. HIR Hamburg Institut Research GmbH.

Nussbaumer, T., & Thalmann, S. (2014). Status report on district heating systems in IEA countries (IEA Bioenergy Task 32, Swiss Federal Office of Energy & Verenum). Verenum; Swiss Federal Office of Energy.

Petermann, T., Bradke, H., Lüllmann, A., Poetzsch, M., & Riehm, U. (2011). Was bei einem Blackout geschieht: Folgen eines langandauernden und großräumigen Stromausfalls [What Happens in a Blackout: Consequences of a Long-Lasting and Widespread Power Outage].

Pfnür, A., Winiewska, B., Mailach, B., & Oschatz, B. (2016). Dezentrale vs. zentrale Wärmeversorgung im deutschen Wärmemarkt: Vergleichende Studie aus energetischer und ökonomischer Sicht. [Decentralised vs. centralised heat supply in the German heating market: A comparative study from an energy and economic perspective]. Technical University of Darmstadt, Research Centre for Commercial Real Estate Management.

Rambøll. (2020). WEDISTRICT_WP2_D2.3: District Heating and Cooling stock at EU level.

Sandrock, M., Bürger, V., & Jaeschke, N. (2025). Entwicklungsszenarien für neue Klimaziele – Aktualisierung Klimaschutzzielszenario (Szenario B) [Development Scenarios for New Climate Targets – Update of the Climate Protection Target Scenario (Scenario B)]. Behörde für Umwelt, Klima, Energie und Agrarwirtschaft der Freien und Hansestadt Hamburg.

Schmidt, D. (2018). Low temperature district heating for future energy systems. Energy Procedia, 149, 595–604. https://doi.org/10.1016/j.egypro.2018.08.224

Thelen, C., Ganter Næss, L., Nolte, H., Kaiser, M., Jürgens, P., Müller, P., Senkpiel, C., & Kost, C. (2024). Paths to a climate-neutral energy system in Germany: Federal states in the transformation process. Fraunhofer Institute for Solar Energy Systems ISE.

Trutnevyte, E., Bauer, N., Kriegler, E., Pye, S., & Brecha, R. (2019). Reviewing the role of electrification in energy system decarbonisation scenarios for Germany. Energy Strategy Reviews, 26, 100397. https://doi.org/10.1016/j.esr.2019.100397

UBA Umweltbundesamt. (2024). Entwicklung der spezifischen Treibhausgas Emissionen des deutschen Strommix in den Jahren 1990 – 2023 [Development of Specific Greenhouse Gas Emissions of the German Electricity Mix from 1990 to 2023] (Climate Change, 23/2024).

Umweltbundesamt. (2016). Die Nutzung von Exergieströmen in kommunalen Strom-Wärme-Systemen zur Erreichung der CO_2-Neutralität von Kommunen bis zum Jahr 2050: Endbericht [The use of exergy flows in municipal electricity-heat systems to achieve carbon neutrality of municipalities by 2050: Final report] (Climate Change 35/2016).

WPG. (2023). Gesetz für die Wärmeplanung und zur Dekarbonisierung der Wärmenetze [Heat Planning and Decarbonization of Heating Networks Act]. Bundesgesetzblatt.

Zimmermann, T., Gerlach, M.-J., Landsberg, F., Pieper, H., Möhring, P., & Wiechers, E. (2025, September 2). Räumliche Erfassung von Abwärmepotenzialen in Hamburg: Abschlussbericht [Spatial Survey of Waste Heat Potentials in Hamburg: Final Report]. Hamburg Institut & PlanEnergi.