

Deliverable 5.4

Technology transfer to district heating sector

Drafted by: Dhivakaran Jayakumar

Date: 29/10/2026

Grant agreement No: 101069672

Project start date: 1st September 2022

Duration: 54 months

Funded by the European Union

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BASIC INFORMATION ON THE DELIVERABLE	
DISSEMINATION LEVEL	Public
DUE DATE OF DELIVERABLE	31/12/2026
ACTUAL SUBMISSION DATE	29/10/2026
WORK PACKAGE	WP5 – Maximizing Technical & Commercial Impact
TASK	T5.4 – Technology transfer to district heating
TYPE	Report
NUMBER OF PAGES	102

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Date	Version	Description
18/05/2026	0.1	First/second draft
23/09/2026	0.2	First revision
29/10/2026	1.0	Final version

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This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101069672 (SPIRIT).

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EHPA: EUROPEAN HEAT PUMP ASSOCIATION

MYK: NV MAYEKAWA EUROPE SA

SINLOC: SINLOC-SISTEMA INIZIATIVE LOCALI SPA

EURAC: ACCADEMIA EUROPEA DI BOLZANO

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ABBREVIATIONS AND ACRONYMS

SPIRIT: Implementation of sustainable heat upgrade technologies for industry

COP: Coefficient of performance

CRF: Capital recovery factor

DBDH: Danish Board of District Heating

DH: District heating

DN: Nominal diameter (pipe size)

E-boiler: Electric boiler

EU: European Union

FC: Fuel cost

HP: Heat pump

HTHP: High-temperature heat pump

LCoH: Levelized cost of heat

NG: Natural gas

O&M: Operation and maintenance

OH: Operating hours

OMC: Operation and maintenance cost

PETA: Pan-European Thermal Atlas

TCI: Total capital investment

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1. EXECUTIVE SUMMARY

This deliverable evaluates the potential for transferring high-temperature heat pump (HTHP) technology from industrial applications to the district heating (DH) sector across ten European countries: Denmark, Germany, Poland, France, Austria, Finland, Czechia, Italy, Sweden, and Slovakia. The analysis focuses on the role of HTHPs in decarbonizing existing district heating systems through the utilization of industrial excess heat and other low-grade heat sources, while maintaining economically competitive heat supply. The assessment combines thermodynamic feasibility, industrial excess heat availability, transmission constraints, and levelized cost of heat (LCoH) analysis under current and future decarbonization scenarios.

The study demonstrates that the technical feasibility of large-scale HTHP deployment is strongly influenced by district heating network temperatures and national electricity-to-gas price ratios. Countries with lower network temperatures and favourable electricity pricing, such as Denmark, Finland, Sweden, France, and Italy, allow economically viable heat pump operation even when supplied by low-temperature heat sources such as ambient air, seawater, or low-grade industrial waste heat. In contrast, countries with higher district heating supply temperatures, notably Austria and parts of Germany, require higher temperature industrial heat sources to ensure attractive heat pump performance.

Industrial excess heat emerges as a substantial and largely underutilized resource across Europe. The analysis based on the PETA database indicates significant recoverable heat potentials, particularly in Germany, France, Italy, Poland, and Sweden. In several countries, direct utilization of high-temperature excess heat can already supply a considerable share of district heating demand, while additional lower-temperature excess heat can be upgraded through HTHPs. The results further show that transport of industrial excess heat over considerable distances is technically feasible for large industrial sites, especially refineries and chemical facilities where recoverable heat quantities are substantial.

Three decarbonization scenarios were investigated: the current energy mix, a transitional “New Scenario” where fossil fuels are replaced while retaining part of the biomass contribution, and a fully decarbonized scenario in which both fossil fuels and biomass are replaced by waste heat and heat pumps. Across almost all countries, the transition to HTHP-based district heating enables significant reductions in fossil fuel consumption while maintaining or reducing overall heat supply costs. Particularly

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strong results are observed in France, Austria, Finland, Sweden, and Poland, where the calculated average LCoH falls substantially as fossil fuels are replaced by waste heat recovery and electrified heat supply.

The economic assessment reveals that industrial excess heat integrated through heat pumps consistently achieves lower LCoH values than biomass and, in many cases, lower costs than natural gas- and coal-based heat production. Direct utilization of excess heat offers the lowest heat supply costs wherever sufficient temperature levels are available. Although reduced operating hours increase the LCoH of heat pumps, the technologies remain competitive across all investigated countries. The analysis therefore indicates that decarbonization through industrial excess heat recovery and electrification can simultaneously support climate objectives and improve the economic competitiveness of district heating systems.

Overall, the results highlight that HTHPs constitute a key enabling technology for the transition toward low-carbon district heating. The combination of direct waste heat utilization and heat pumps upgrading industrial excess heat is capable of eliminating a significant share of fossil heat generation, while ambient-source heat pumps provide additional flexibility where industrial heat availability is insufficient. The findings demonstrate that sector coupling between industry and district heating represents one of the most effective pathways for accelerating heat decarbonization across Europe.

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2. INTRODUCTION

District heating systems have evolved significantly over time and are commonly classified by generation. First-generation DH systems (1880–1930) used steam at temperatures below 200 °C, mainly produced from fossil fuels and distributed through concrete ducts.

Second-generation systems (1930–1980) shifted to pressurized superheated water above 100 °C, also mainly generated from fossil fuels and distributed through water pipes in concrete ducts. This reduced heat losses and improved energy efficiency compared with the first-generation systems.

Third-generation systems (1980–2020) operate with hot water below 100 °C and represent a major improvement, as heat can be supplied not only by fossil fuels but also by renewable sources such as biomass, solar thermal energy, and industrial waste heat. These systems use pre-insulated pipes, which further reduce losses, improve efficiency, and lower emissions.

Fourth-generation DH systems operate at even lower temperatures, typically from 50 °C – 60 °C and are mainly based on renewable and low-carbon heat sources, including biomass, geothermal energy, solar thermal, industrial waste heat, wind and solar power via centralized heat pumps, and seasonal thermal storage. These systems generally use pre-insulated flexible twin pipes. Their lower operating temperatures further reduce distribution losses and improve overall system efficiency.

At present, most European district heating networks operate at temperatures in the range of 90 °C – 150 °C, and their energy mix is still largely dominated by fossil fuels, particularly natural gas and coal, while renewable and low-carbon sources such as biomass, industrial waste heat, geothermal energy, and heat pumps still account for a smaller share.

Countries such as Sweden, Denmark, and Finland are among the leaders in renewable-based district heating generation, relying mainly on biomass, heat pumps, and other low-carbon technologies. However, in most European countries, district heating remains largely fossil based. High-temperature heat pumps (HTHPs) could play a significant role in decarbonizing heat supply within existing district heating networks by upgrading low-temperature waste heat from industrial processes or

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ambient sources. When powered by renewable electricity, they can enable a near-zero-emission heat supply.

This deliverable examines the potential for integrating High Temperature Heat Pumps (HTHPs) into district heating systems. Particular attention is given to the synergies between heat pump technology and industrial applications, especially in relation to heat source availability and source temperature, with the aim of supplying heat at higher efficiency.

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3. METHODOLOGY

This deliverable examines the role of heat pumps integrated into district heating networks. The current European district heating mix remains largely dominated by fossil-fuel-based technologies, primarily natural gas and coal. This dominance is mainly attributed to the widespread availability of these fuels and as their unit cost of energy is typically lower compared with electricity.

To enable an economically viable replacement of fossil-fuel-based systems with electrically driven vapor-compression heat pumps, a minimum coefficient of performance (COP) must be achieved. This threshold is referred to as the break-even COP and is defined as the COP required to ensure equal fuel costs between the conventional fossil-fuel-based system and the electrified heat pump system. Consequently, operating at a COP above the break-even COP results in fuel cost savings for the electrified system.

In the present work, the break-even COP is estimated using Equation (1) and is calculated as the ratio between the electricity price and the natural gas price.

$$\mathrm{COP}_{\mathrm{Break-even}} = \frac{P_{\mathrm{elec}}}{P_{\mathrm{NG}}} \tag{1}$$

Using the national gas and electricity prices, from Table 1, in equation (1) determines national break-even COP values. To which degree it is feasible to attain practical COP values that exceed the break-even COP, depends on both the efficiency of the heat pump, the temperature of the district heating network and the temperature of the applied heat source.

To estimate the efficiency of the heat pump, the Lorenz efficiency polynomial proposed by Andersen et al.[13] is applied as seen in Equation (2). Here the Lorenz efficiency is an Ideal Cycle efficiency defined as the ratio between the attained COP of the heat pump to that of the COP of the corresponding Lorenz cycle, Equation (3). Here the COP of the Lorenz cycle can be determined as seen in Equation (3) based on the entropic average temperatures of the sink and source.

$$\eta_{\mathrm{Lorenz}} = 0.486 + 10^{-4} \cdot \left(27.1 \cdot \Delta T_{\mathrm{lift}} - 0.0737 \cdot \Delta T_{\mathrm{lift}}^2 - 2.0 \cdot T_{\mathrm{so,\,in}} - 13.0 \cdot \Delta T_{\mathrm{so}} - 5.15 \cdot \Delta T_{\mathrm{si}}\right) \tag{2}$$

$$\eta_{\mathrm{Lorenz}} = \frac{\mathrm{COP}}{\mathrm{COP}_{\mathrm{Lorenz}}} \tag{3}$$

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$$\mathrm{COP}_{\mathrm{Lorenz}} = \frac{\bar{T}_H}{\bar{T}_H - \bar{T}_C} = \frac{\bar{T}_H}{\Delta \bar{T}_{\mathrm{lift}}} \tag{4}$$

The applied Lorenz efficiency polynomial assesses the Lorenz efficiency of the best available heat pump based on the temperature lift and the sink and source temperature glide. The temperature lift is defined as the temperature difference between the DH forward temperature and the heat source inlet temperature. The sink temperature glide is defined as the difference between the forward and return temperature of the DH network, while the source temperature glide will depend on the availability of the applied heat source.

By combining Equations (1)–(4) with the fuel price information from Table 1 and the temperature levels of the corresponding district heating networks, the minimum required heat source temperature can be determined by equating the break-even COP with the estimated heat pump COP, as shown in Equation (5). This procedure yields the heat source temperature required to ensure that the heat pump COP exceeds the break-even COP and, consequently, the minimum source temperature needed to achieve fuel cost savings.

$$\mathrm{COP}_{\mathrm{Break-even}} = \mathrm{COP}_{\mathrm{Lorenz}}\, \eta_{\mathrm{Lorenz}} \tag{5}$$

This approach, however, requires an assumption regarding the heat source temperature glide. The temperature glide should be selected in accordance with the capacity rate of the heat source: high capacity rates imply low source temperature glides, whereas low capacity rates are associated with higher temperature glides.

The integration concept of a high-temperature heat pump into a district heating network is illustrated in Figure 1. Potential heat sources include industrial excess heat, low-grade waste heat, and ambient heat. The temperature level of the available heat source has a direct influence on the COP of the heat pump.

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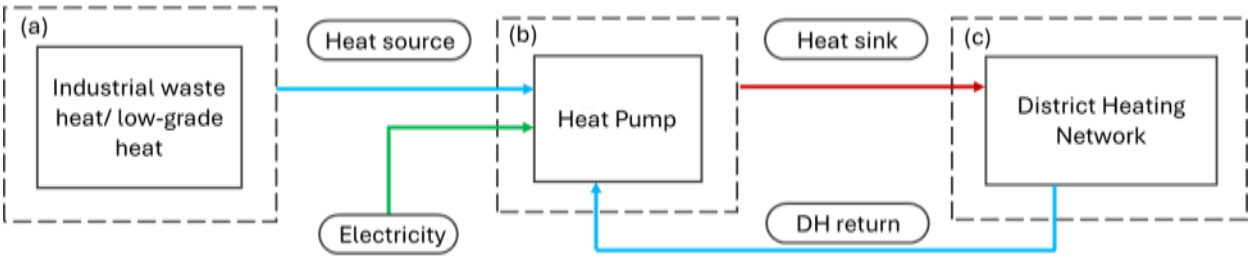


Figure 1: Integration of high-temperature heat pump within the district heating network

Therefore, the minimum heat source temperature required for efficient heat pump operation is estimated for each country. This supports the identification of synergies between industry and district heating systems by mapping industrial sectors with excess heat potential at the required temperature level. Table 1 presents the electricity and natural gas prices for selected European countries, based on [2] and [3].

Table 1: Electricity and natural gas prices

Country	Electricity price (€/kWh)	NG price (€/kWh)
Denmark	0.115	0.048
Poland	0.117	0.072
Germany	0.178	0.057
France	0.132	0.058
Finland	0.074	0.067
Austria	0.172	0.053
Czechia	0.156	0.062
Italy	0.145	0.053
Sweden	0.077	0.073
Slovakia	0.155	0.070

Only the maximum network temperatures of the district heating network for each country are considered and are treated as representative overall network

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temperatures, even though the temperatures of individual regional networks are generally lower. Due to the limited availability of detailed data on the temperature levels of individual networks, and the substantial effort required to compile such information, this simplifying assumption is adopted for the analysis.

Exploiting industrial excess heat as a heat source for district heating requires either that the excess heat be available in close proximity to the network or that it is economically and technically viable to transport the heat to the network. The viability of such heat transmission pipelines depends on detailed knowledge of local labor and material costs, as well as local topographical and geological conditions. As this information was not readily available, the maximum feasible heat transport distance was instead estimated based on acceptable heat loss criteria. Specifically, acceptable heat loss ratios of 10 %, 20 %, and 50 % were considered, and the corresponding maximum transport distances were determined using a heat loss calculation.

The heat loss in the transmission lines is estimated in by Equations (6) and (7).

$$\dot{Q} = L_{\text{pipe}} \cdot \pi \cdot D_{\text{pipe}} \cdot q_{\text{loss}} \tag{6}$$

$$q_{\text{loss}} = U\left(T_{\text{pipe}} - T_{\text{ground}}\right) \tag{7}$$

Here, U, denotes the overall heat transfer coefficient, T_{ground} is the ground temperature (assumed to be 15 °C) and T_{pipe} is the average pipe temperature. , calculated as the arithmetic mean temperature of the country specific DH forward and return temperature. Finally, $\dot{Q}$ represents the total heat loss along the pipe and L_{pipe} is the pipe length. The heat loss percentage is defined as the ratio of the total heat loss over the entire pipe length to the amount of excess heat transferred to the district heating network. A U-value of 0.5 $\text{W m}^{-2}\,\text{K}^{-1}$ was selected, estimated based on [11] and [12], corresponding to a high-quality twin steel pipe of nominal diameter DN150.

The Levelized Cost of Heat (LCoH) is the cost per unit heat delivered including the cost of investment and maintenance of the system [10]. It is estimated based on the equation:

$$\text{LCoH} = \frac{\text{TCI} \cdot \text{CRF} + \text{FC}_{\text{ref fuel}} + \text{OMC}_{\text{system}}}{\dot{Q} \cdot \text{OH}} \tag{8}$$

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Here, TCI is the Total capital investment and CRF is the Capital Recovery Factor which converts the present value into an annuity over the project lifetime at a specified effective discount rate i_{eff}.

CRF is determined as seen in Equation (9) Where, i_{eff} is the effective interest rate, assumed to be 5 %, Lifetime is the system lifetime assumed to 25 years.

$$\text{CRF} = \frac{i_{\text{eff}}(1+i_{\text{eff}})^{\text{Lifetime}}}{(1+i_{\text{eff}})^{\text{Lifetime}}-1} \tag{9}$$

FC is the annual fuel cost, OMC is the annual operation and maintenance cost, $\dot{Q}$ is the supplied heat and OH is the annual operating hours.

The annual operating cost due to fuel consumption, FC, is determined as seen in equation (10), where, $C_{\text{ref fuel}}$ is the fuel cost of the reference system, η_{system} is the system efficiency, $\dot{Q}$ is the supplied heat and OH is the annual operating hours.

$$\text{FC}_{\text{ref fuel}} = C_{\text{ref fuel}} \cdot \frac{\dot{Q}}{\eta_{\text{system}}} \cdot \text{OH} \tag{10}$$

For the heat pumps the fuel cost is associated with the supplied electricity which is determined as seen in equation (11)

$$\text{FC}_{\text{elec}} = C_{\text{elec}} \cdot \frac{\dot{Q}}{\text{COP}} \cdot \text{OH} \tag{11}$$

Total capital investment (TCI) of the system is determined by equation (12), where $\text{TCI}_{\text{specific}}$ is the specific investment cost in (M€/MW)

$$\text{TCI}_{\text{system}} = \text{TCI}_{\text{specific}} \cdot \dot{Q} \tag{12}$$

The Operation and Maintenance cost (OMC) of the system is determined by equation (12), where, $\text{OMC}_{\text{Fixed}}$is the specific Fixed O&M cost in (€/MW-year) and OMC_{Var} is the specific variable O&M cost in (€/MWh-year).

$$\text{OMC}_{\text{system}} = \text{OMC}_{\text{Fixed}} \cdot \dot{Q} + \text{OMC}_{\text{Var}} \cdot \dot{Q} \cdot \text{OH} \tag{13}$$

Table 2, shows estimates of the specific Investment and Operation and Maintenance cost for each investigated technology. The cost data are taken from the Danish Energy Agency (Danish Technology catalogue)[8].

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Table 2: Investment and Operation and Maintenance cost for different heat technologies

Technology	Specific investment (M€/MW)	Fixed O&M (€/MW-year)	Variable O&M (€/MWh-year)
HP (excess heat)	0.95	2127	3.07
HP (ambient)	1.10	2127	0.86
Biomass Boiler	0.75	34772	2.08
Natural gas boiler	0.06	2074	1.17
Coal boiler	0.50	32600	2.08

The specific investment and Operation and Maintenance cost for district heating transmission lines are shown in Table 3. This data is used to estimate the Levelized Cost of Heat for direct utilization of waste heat within the district heat network. The cost data are taken from the Danish Energy Agency (Danish Technology Catalogue) [9].

Table 3: Specific investment and Operation and Maintenance cost for district heating transmission lines

Investment cost, single line (€/MW-m)	**11.89**
Investment costs; Heat exchanger station (€/MW)	140162
Investment costs; Pump station (€/MW)	127473
Fixed O&M (€/MW-km-year)	100

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For each technology the following assumptions are considered:

- LCoH of all heat source technologies are accessed for two different operating hours, to address both full load 8760 hours and part load operations 4000 hours. The latter is included to acknowledge that not all heating technologies operate throughout the year.
- The effective interest rate i_{eff} is equals to 5 % for all technology.
- The Electricity and Natural gas price for each investigated country is shown in Table 1 and are taken from Eurostat [2][3].
- The biomass price for Denmark is taken from The Danish Energy Agency [4], due to the lack of country-specific biomass price data for other countries, the Danish biomass price is assumed to be representative and is therefore applied uniformly across all countries in the analysis.
- Due to the lack of country-specific coal price data, the coal price is assumed to be equal to the natural gas price for each individual country in the analysis.
- LCoH estimates are based on Danish cost data for specific investment and O&M costs from the Danish Energy Agency [8] and [9]. These were subsequently scaled to other countries using the Eurostat price index for labor and equipment cost, seen in Table 4 [5][6][7].

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Table 4: Cost index for different countries with Denmark as reference member states

Country	Price index 2016 (Home appliances)	Labour cost index 2016 (construction)	Equipment and maintenance 2016
Denmark	1.00	1.00	1.00
Austria	0.82	0.81	0.90
Czechia	0.80	0.24	0.63
Finland	0.94	0.87	0.92
France	0.93	0.80	0.84
Germany	0.89	0.69	0.82
Italy	0.94	0.60	0.87
Poland	0.66	0.19	0.52
Slovakia	0.81	0.24	0.66
Sweden	1.01	1.02	0.98

The total recoverable industrial excess heat from energy-intensive industries in different EU countries is estimated based on data from the PETA database [1] and [19]. Within the Heat Roadmap Europe project, recoverable excess heat potentials have been assessed for energy-intensive sectors including the chemical industry, iron and steel industry, paper and pulp industry, refineries, the non-metallic minerals industry, and the non-ferrous metals industry, covering a total of 1608 industrial sites across Europe.

Table 5, presents the excess heat temperature levels and the corresponding recoverable excess heat for each investigated industry. The recoverable excess heat is estimated by assuming that the material streams leaving the industrial processes are cooled from their respective excess heat temperature levels down to 25 °C.

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Table 5: Excess heat temperature level, recoverable excess heat potential for each industry

Industry type	Excess heat temperature range (°C)	Excess heat per industry (PJ/year)
Chemical	150-260	0.989
Iron & steel	130-1700	0.518
Paper & printing	170-260	0.104
Refinery	Up to 260	3.03
Non-metallic minerals	200-1400	0.244
Non-ferrous metals	Up to 700	0.156

Based on the PETA map [1], [19], the number and type of industrial facilities present in each country are identified. For the direct recovery of industrial waste heat and its integration into district heating networks, the primary technical barrier is the distance between the industrial plant and the district heating network.

Therefore, the maximum feasible distance between individual industrial plants and the district heating network is estimated for varying acceptable heat loss levels of 10 %, 20 %, and 50 % of the total recoverable excess heat. The resulting maximum feasible transport distances for each industrial sector are presented in Table 6.

For the chemical industry, the maximum recoverable excess heat obtained by cooling the exhaust or excess heat stream from 260 °C down to 25 °C is approximately 0.989 PJ/year, corresponding to an average load of about 31.4 MW. With an acceptable heat loss of 10 %, the maximum feasible distance between the industrial site and the district heating network is approximately 46 km. For an acceptable heat loss of 50 % the corresponding maximum transport distance increases to more than 200 km.

Similarly, refineries exhibit the highest recoverable excess heat potential of approximately 3.03 PJ/year, corresponding to an average load of approximately 96 MW. For an acceptable heat loss of 10 %, the maximum feasible distance to the

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district heating network is around 140 km, increasing to more than 200 km for higher acceptable heat loss levels.

In contrast, the paper and pulp industry has the lowest recoverable excess heat potential, approximately 0.104 PJ/year or 3.29 MW. For an acceptable heat loss of 10 %, the plant would have to be located within approximately 4.8 km of the district heating network. For the iron and steel industry, a total recoverable excess heat of approximately 0.518 PJ/year, corresponding to 16.4 MW, results in a maximum feasible distance of about 24 km at a 10 % acceptable heat loss. Finally, for the non-metallic minerals industry, a total recoverable excess heat of approximately 0.244 PJ/year or 7.73 MW corresponds to a maximum feasible distance of around 11 km at a 10 % acceptable heat loss.

Table 6: Plant feasible distance

Industry	U (W/m²-K)	f = 10 % (km)	f = 20 % (km)	f = 50 % (km)
chemical	0.5	46	92	232
Iron & steel	0.5	24.3	48	121
Paper & printing	0.5	4.8	9.7	24
Refinery	0.5	142	280	>300
Non-metallic minerals	0.5	11	23	57
Non-ferrous metals	0.5	7	15	37

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Figure 2 Compared shares of district heating (in energy sources to meet heating demands from residential/service sectors) and renewable energy in gross final consumption for heating and cooling (year 2022)-Source Euroheat and Power [16]

Figure 2 shows the market share of district heating and the share of renewable energy in the gross final consumption of heating and cooling across various European countries. In the present analysis, the district heating market share from Figure 2 is used to estimate the amount of heat supplied by district heating relative to the total heat demand of the residential and service sectors. A detailed description of the heat supply shares for each country is provided in Section 4.

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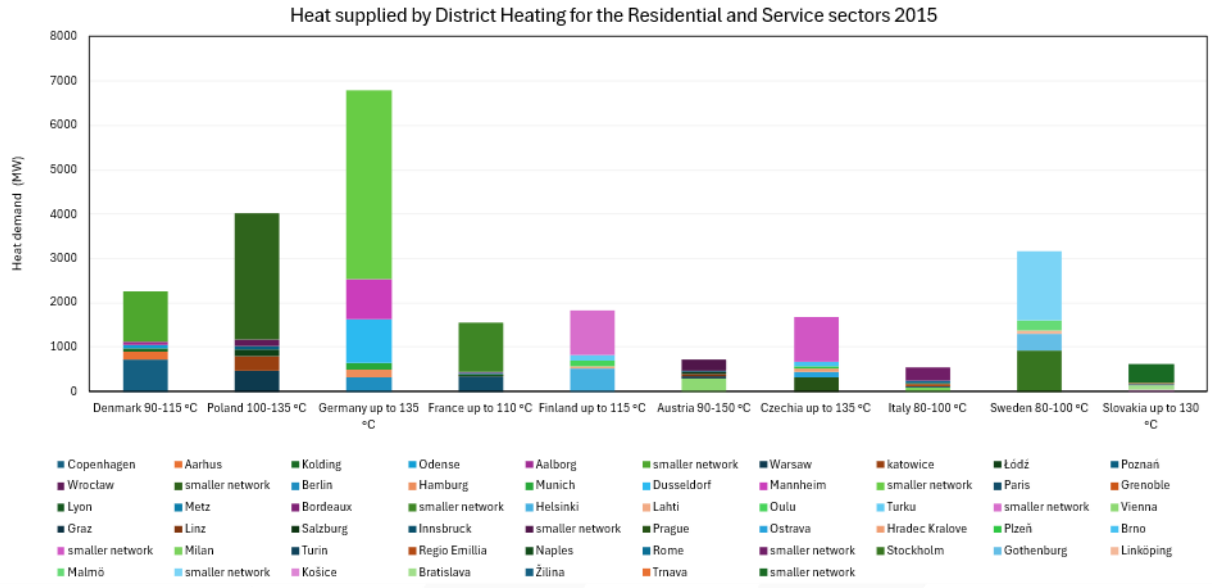


Figure 3: Heat supplied by district heating for the residential and service sector in 2015

The total heat demand of the residential and service sectors for European countries in 2015 is estimated based on data from PETA [19]. Using the district heating market shares shown in Figure 2, the corresponding amount of heat supplied by district heating is derived.

Figure 3 illustrates the amount of heat supplied by district heating to the residential and service sectors in 2015 for various European countries, based on PETA data [19]. The figure highlights the heat supplied by the five largest district heating networks in each country, while the combined contribution of all remaining networks is grouped into a “smaller networks” category. Countries with the highest district heating supply, including Germany, Poland, Sweden, Denmark, and Finland, also have well-established district heating infrastructures. A detailed description of the heat supplied for each country is provided in Section 4.

3.1 Decarbonization Scenarios

For each country, the decarbonization of district heating through the integration of heat pumps is assessed based on three factors: 1) the temperature and quantity of the available excess heat, 2) the distance between the industrial facilities and the district heating network, and 3) the cost of heat generation.

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Three scenarios are compared for each country. All scenarios refer to the heat demand of the residential and service sectors supplied by district heating:

- **Current Scenario**, based on the existing energy mix of district heat generation in each country.
- **New Scenario**, in which fossil fuels are phased out and replaced by direct waste heat utilization and heat pumps, while biomass-based heat generation is maintained or reduced depending on the available waste heat and excess heat potential.
- **Fully Decarbonized Scenario**, in which fossil fuels and biomass-based heat generation are fully replaced by direct waste heat utilization and heat pumps using industrial excess heat and ambient heat sources.

In the minimum heat source temperature figures of each country, the blue bars represent heat pumps integrated in the transmission network and the orange bars heat pumps integrated in the distribution network. Source glides between 5 K and 55 K are shown, covering low-glide heat sources (seawater, return condensate) and high-glide heat sources (industrial excess heat, low-grade heat, ambient heat).

The levelized cost of heat results should be interpreted in light of the cost assumptions described above: biomass prices are assumed constant across all countries, coal prices are assumed comparable to natural gas prices, and the cost indices are based on the year 2016. Actual values may therefore differ depending on current energy prices, taxes, subsidies, regulatory frameworks and the operating hours of each technology.

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4. DESCRIPTION OF COUNTRIES

4.1 Denmark



Denmark is one of the pioneers of district heat supply, with an installed capacity of 27.4 $GW_{thermal}$ in 2023. Almost 66 % of the total heat demand of the residential and service sector was covered by district heating in 2022 [16]. The installed district heating capacity in Denmark over the years is shown in Table 7. In which Copenhagen, Aarhus, Kolding, Odense and Aalborg are the top 5 district heating networks with high heat demands of 722 MW, 172 MW, 69 MW, 84 MW, and 79 MW, respectively. The forward and return temperature of the transmission and distribution network is shown in Table 8, estimated from Ommen et al.[20], DBDH [21].

Table 7: District heating installed capacity Denmark

Installed capacity (GW_{th})	2018	2021	2022	2023
	25	25.8	25.3	27.4

Table 8: Transmission and distribution network temperatures

Temperature level	Transmission Network (°C)	Distribution Network (°C)
Forward temperature	90-115	70-90
Return temperature	55	35-45

The energy mix of the Danish district heating networks from 2018 - 2023 is shown in Table 9. In 2023, biomass was the predominant energy source for district heat

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generation, accounting for approximately 64 % of total supply. This was followed by waste heat, which includes industrial excess heat, flue gas condensation, and tertiary and non-biogenic waste, with a share of about 11.4 %, and by heat pumps and electric boilers, contributing approximately 8.5 %. Fossil fuels, mainly natural gas and coal, together accounted for up to 13 % of district heat generation.

Table 9: Energy source mix in the generation of district Heat

Energy source	2018	2021	2022	2023
Coal	13 %	7.5 %	10 %	7.4 %
Natural gas	15 %	6.7 %	3.3 %	5.7 %
Oil	1 %	-	-	-
Biomass	55 %	69 %	65 %	64 %
Waste heat	12 %	11 %	13 %	11.4 %
Solar	2 %	2.4 %	2.8 %	2.8 %
Geothermal	-	-	-	-
Heat pump & E-boiler	2 %	3.1 %	6.2 %	8.5 %
Other	-	-	-	-

The lower network operating temperatures and the high share of industrial waste and excess heat within the existing network make heat pumps an attractive heat supply technology for decarbonization and for reducing dependence on fossil-fuel-based district heat generation.

4.1.1 Decarbonization strategy

a) Assessment of industrial excess heat

The assessment of the potential to integrate industrial excess heat and other heat sources into the district heating network begins with estimating the minimum heat source temperature required to ensure economically viable electrification through the implementation of a heat pump. This estimate provides the basis for identifying feasible heat sources, such as industrial excess heat, ambient air, or seawater, which can be used to supply heat to the heat pump.

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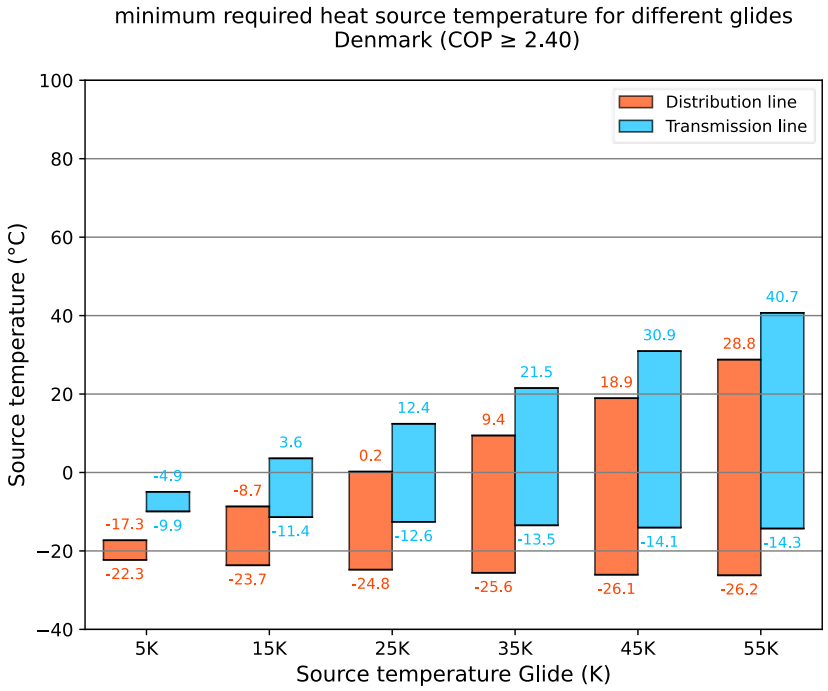


Figure 4: Minimum required heat source temperature

High-temperature heat pumps integrated within district heating networks can be either centralized or decentralized and can deliver heat either to the transmission network or the distribution network.

The minimum heat source temperature required by a heat pump integrated within the district heating network is estimated based on the approach presented in Section 3. Figure 4 shows the derived minimum heat source temperatures for Denmark, where the blue bars represent heat pumps integrated into the transmission network, while the orange bars represent heat pumps integrated into the distribution network. Further, the minimum heat source temperature was estimated for heat source temperature glides ranging from 5 K to 55 K, thereby estimating the minimum heat source temperature for different heat source capacity rates.

For low heat source temperature glides of 5 K, indicative of abundant heat sources such ambient air or seawater, the heat pump can operate with an economically viable COP with the heat source temperatures down to approximately −5 °C. This demonstrates the high energy efficiency of the heat pump under low-glide operating conditions. In contrast, for a high heat source temperature glide of 55 K, indicative of limited capacity heat sources such industrial excess heat, a heat source temperature

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of approximately 40 °C is required. Consequently, any heat source temperature above -5 °C results in a COP exceeding the minimum economically viable threshold.

Based on data provided by the PETA maps [1], the total recoverable industrial excess heat in Denmark has been estimated. The PETA map assesses excess heat both before and after internal heat recovery. In the present analysis, values after internal heat recovery are applied, thereby emphasizing the need for individual industrial sites to minimize their excess heat before its utilization for district heating generation. In addition, the PETA map categorizes excess heat into three levels, where Level 1 corresponds to cooling the excess heat stream to 25 °C, Level 2 to 55 °C, and Level 3 to 95 °C.

For Denmark, this results in a Level 1 estimate of approximately 4 PJ per year, corresponding to about 127 MW. Of this, approximately 1.5 PJ per year (47.5 MW) can be recovered above 55 °C (Level 2) and 1.1 PJ per year (34.8 MW) above 95 °C (Level 3). The levels are cumulative: Level 1 includes the heat recoverable at Levels 2 and 3.

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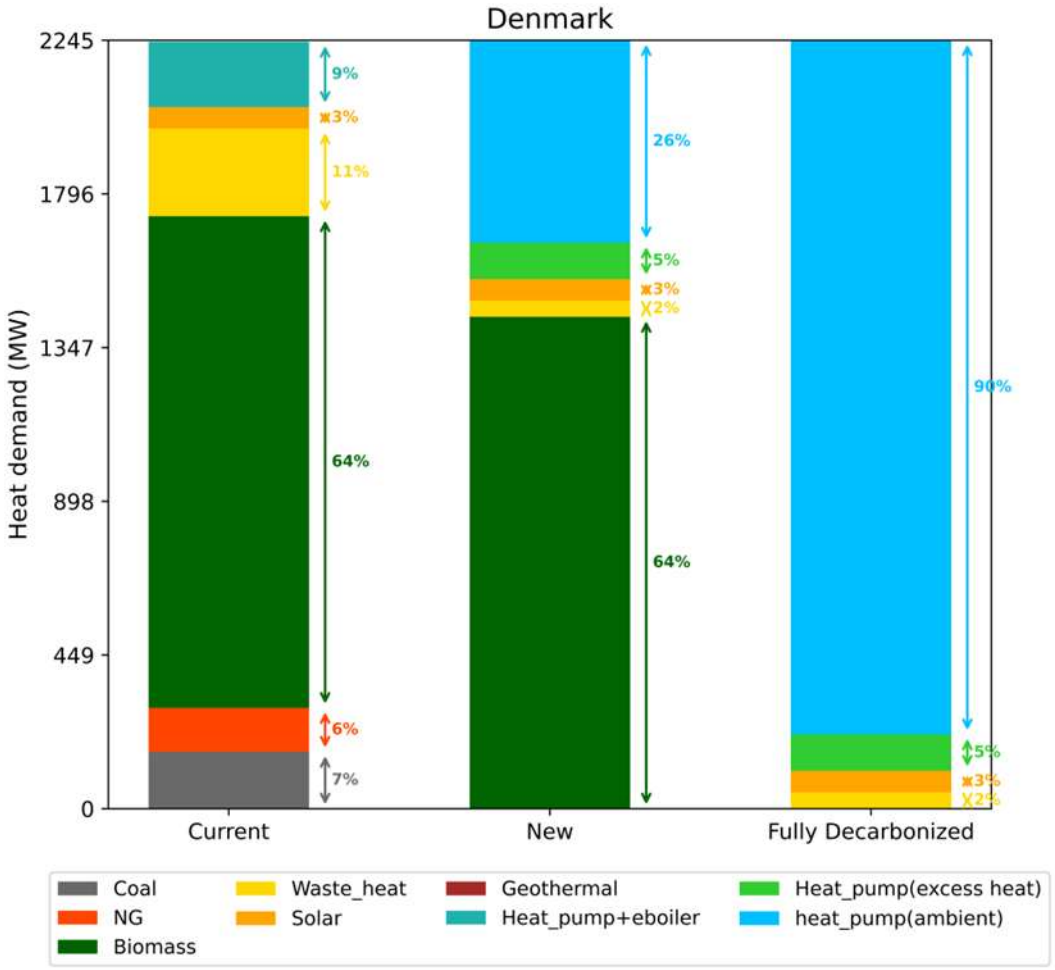


Figure 5: Decarbonization strategy for the transition of Denmark's district heating generation

Figure 5 shows the decarbonization strategy for Denmark under three scenarios defined in Section 2.1.

In the New Scenario, direct utilization of waste heat covers approximately 47.5 MW, corresponding to about 2 % of the heat demand. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 (55 °C to 25 °C) use approximately 79 MW of excess heat as heat source and, with an average COP of 3.9, cover about 5 % of the heat demand. As this is not sufficient to replace the fossil fuel–based heat generation, heat pumps using ambient heat sources cover approximately 26 % of the heat demand, while biomass is maintained at its current share of 64 %.

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In the Fully Decarbonized Scenario, waste heat, industrial excess heat and solar heat together cover only about 10 % of the heat demand because the available excess heat is limited. To eliminate biomass from the energy mix, the remaining 90 % must be supplied by heat pumps using ambient heat sources. These heat pumps can achieve an average COP of approximately 2.9, which is above the minimum economic COP of 2.40 for Denmark.

b) Economic assessment

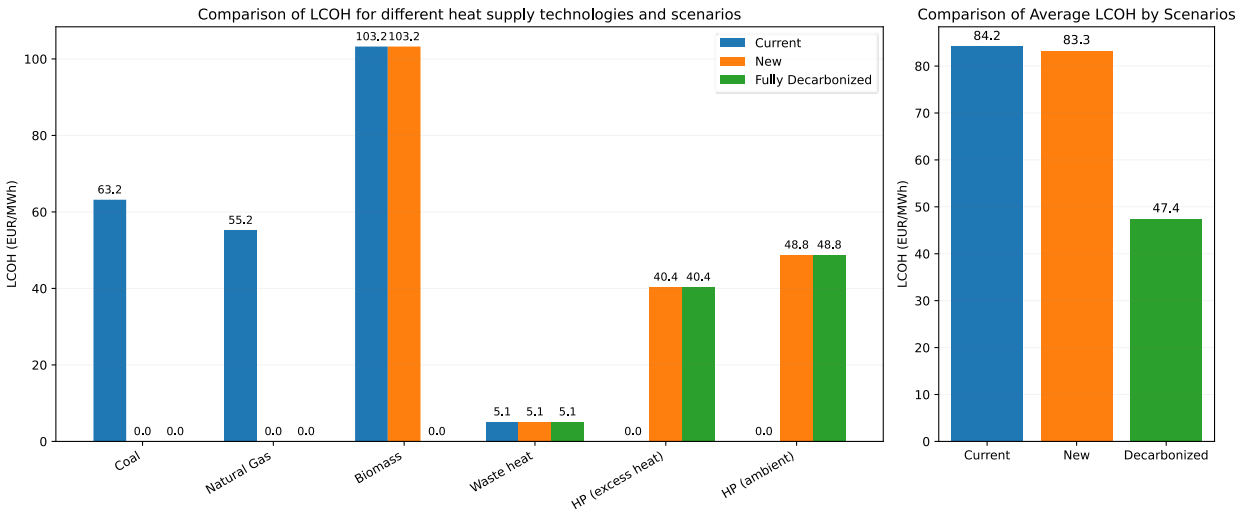


Figure 6: Comparison of LCoH across heat supply technologies and decarbonization scenarios for 8760 operating hours per year

The Figure 6, compares the LCoH across different heat-supply technologies for 8760 hours operating hours per year. The LCoH is presented for all individual technologies under the three defined scenarios: Current, New, and Fully Decarbonized. Further, the average LCoH with the scenario specific energy mix is also presented.

In the Current Scenario, fossil-based heat supply such as coal and natural gas, have LCoH values of approximately 63 €/MWh and 55 €/MWh, respectively, while heat supply from biomass appears at a significantly higher cost of 103 €/MWh.

In the New Scenario, due to the increased share of heat supplied by heat pumps using industrial excess heat and ambient heat sources, coal and natural gas are phased out. Biomass remains in the energy mix with a LCoH of approximately 103 €/MWh, while heat supplied by heat pumps using industrial excess heat and ambient heat exhibits LCoH of around 40€/MWh and 49€/MWh, respectively

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In the Fully Decarbonized Scenario, fossil and biomass fuels are eliminated, and the system relies only on heat pumps utilizing waste heat, industrial excess heat and ambient heat sources. The district heat supply by heat pumps utilizing waste heat has a competitive LCoH of approximately 5 €/MWh. Heat pumps utilizing industrial excess heat achieve a LCoH of around 40 €/MWh while ambient air heat pumps reach a LCoH of 50 €/MWh.

Finally, comparing the average LCoH for the three scenarios shows a downward trend from 84 €/MWh in the Current Scenario to 83 €/MWh in the New Scenario, dropping sharply to 47 €/MWh in the Fully Decarbonized Scenario. This highlights that the shift to low-carbon and high-efficiency technologies leads to significantly lower heating costs.

Similarly to Figure 6, Figure 7 presents the LCoH of different heat-supply technologies for 4000 operating hours per year, thus addressing the economic performance of heat pumps that only operate during the heat season.

In the Current Scenario, fossil-based based heat supply such as coal and natural gas, achieve LCOH values of around 72 €/MWh and 66 €/MWh, respectively, while heat supply from biomass achieves approximately 115 €/MWh.

Whereas, in the New Scenario, with the increased share of heat pumps using industrial excess heat and ambient heat sources the use coal and natural gas is avoided, while biomass remains at 115 €/MWh. Heat supply from heat pumps using industrial excess heat or ambient air heat sources achieve LCoH values of around 50 €/MWh and 60 €/MWh, respectively.

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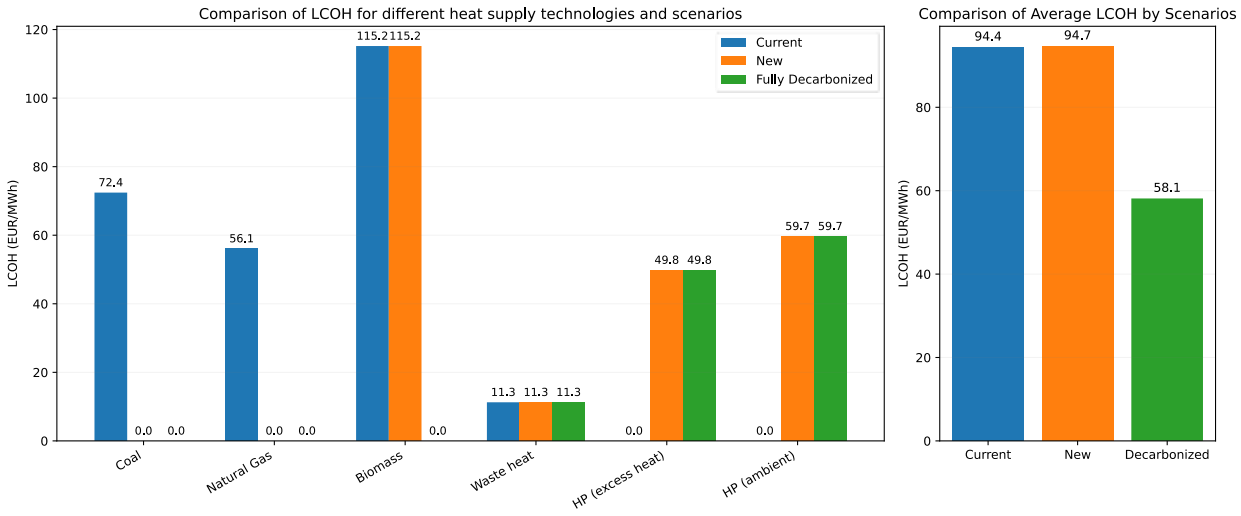


Figure 7: Comparison of LCoH across heat supply technologies and decarbonization scenarios for 4000 operating hours

In the Fully Decarbonized Scenario, heat supplied from waste heat exhibits a low LCoH of approximately 10.7 €/MWh. Heat supplied by heat pumps utilizing industrial excess heat has a LCoH of around 50€/MWh, while heat pumps using ambient heat sources reach approximately 60 €/MWh.

Finally, for 4000 operating hours per year, the average levelized cost of heat in the Current Scenario was 94€/MWh. This value was unchanged in the New Scenario and reduced to 58 €/MWh in the Fully Decarbonized Scenario. Compared to the results presented in Figure 6, where the heat pumps operate throughout the entire year, the reduced number of operating hours results in increases in the levelized cost of heat of 7 %, 16 %, and 31 % for the Current, New, and Fully Decarbonized Scenarios, respectively.

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4.2 Germany



Germany is one of the countries with the largest installed district heating (DH) capacity, amounting to approximately 40.6 GW_{th} in 2023. District heating covers about 10% of the total heat demand in the residential and service sectors in Germany, corresponding to approximately 6,791 MW [16]. The installed district heating capacities are presented in Table 10.

Berlin, Hamburg, Munich, Düsseldorf, and Mannheim are the five largest DH networks, with heat capacities of 308 MW, 185 MW, 160 MW, 977 MW, and 906 MW, respectively.

The forward and return temperatures of the transmission and distribution networks are shown in Table 11. According to DBDH [21], the forward temperature may reach up to 135 °C in the transmission system and 120 °C in the distribution system, while the return temperatures are approximately 55 °C and 45 °C for the transmission and distribution networks, respectively.

Table 10: District heating installed capacity Germany

Installed capacity (GW_{th})	2018	2021	2022	2023
	47.4	45	44	40.6

Table 11: Transmission and distribution network temperatures

Temperature level	Transmission Network (°C)	Distribution Network (°C)
Forward temperature	110-135	Up to 120
Return temperature	45-55	up to 45

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The energy mix of the German district heating network over the years is summarized in Table 12. For 2023, fossil fuels remain the dominant source for district heat generation, with natural gas accounting for 45 % and coal for 23 %.

This is followed by biomass and waste heat, comprising industrial excess heat, flue gas condensation, and tertiary and non-biogenic waste, which together contribute approximately 20.9 % and 10 %, respectively.

A relatively small share, up to 0.8%, is supplied by geothermal energy.

Table 12: Energy source Mix in the Generation of District Heat

Energy source	2018	2021	2022	2023
Coal	26 %	21 %	21 %	23 %
Natural gas	38 %	49.5 %	50 %	44.8 %
Oil	1 %	-	-	-
Biomass	20 %	20 %	20 %	20.9 %
Waste heat	14 %	8.6 %	8.8 %	10 %
Solar	-	0.3 %	-	-
Geothermal	1 %	0.3 %	0.8 %	0.8 %
Heat pump & E-boiler	-	0.3 %	-	-
Other	-	-	-	-

4.2.1 Decarbonization strategies

a) Assessment of industrial excess heat

The assessment of industrial excess heat potential begins with estimating the minimum heat source temperature required by the heat pump. This estimation serves as a basis for identifying feasible heat sources, such as industrial excess heat, ambient air, or seawater, which can be utilized as heat source for the heat pump.

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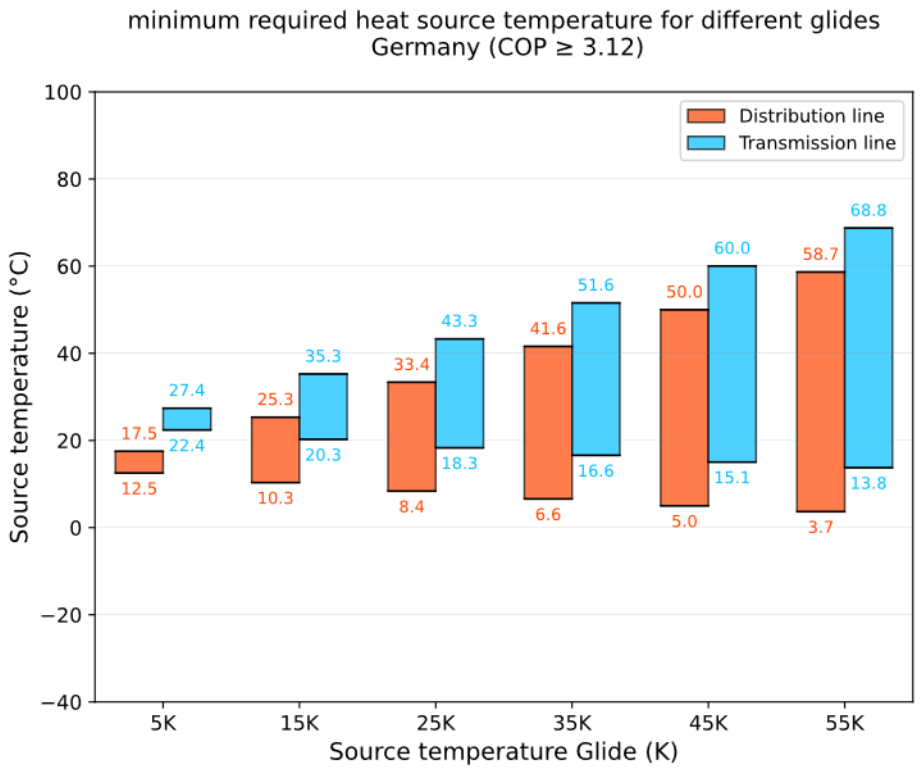


Figure 8: Minimum Required Heat Source Temperature

The required minimum heat source temperature for a high-temperature heat pump integrated in the German district heating network is shown in Figure 8.

It is estimated that for the low glide of 5 K a heat source temperature of approximately 30 °C is required for the transmission network while approximately 20 °C is required for the distribution network. For the high glide heat sources of 55 K a heat source of 70 °C is required for the transmission network and 60 °C required for the distribution network.

Based on the PETA map [1], the total recoverable industrial excess heat in Germany after maximum internal heat recovery has been estimated. For Germany, this results in a Level 1 estimate of approximately 133 PJ per year, corresponding to an average heat load of approximately 4211 MW. Of this, approximately 53 PJ per year can be recovered above 55 °C (Level 2) and 38 PJ per year above 95 °C (Level 3).

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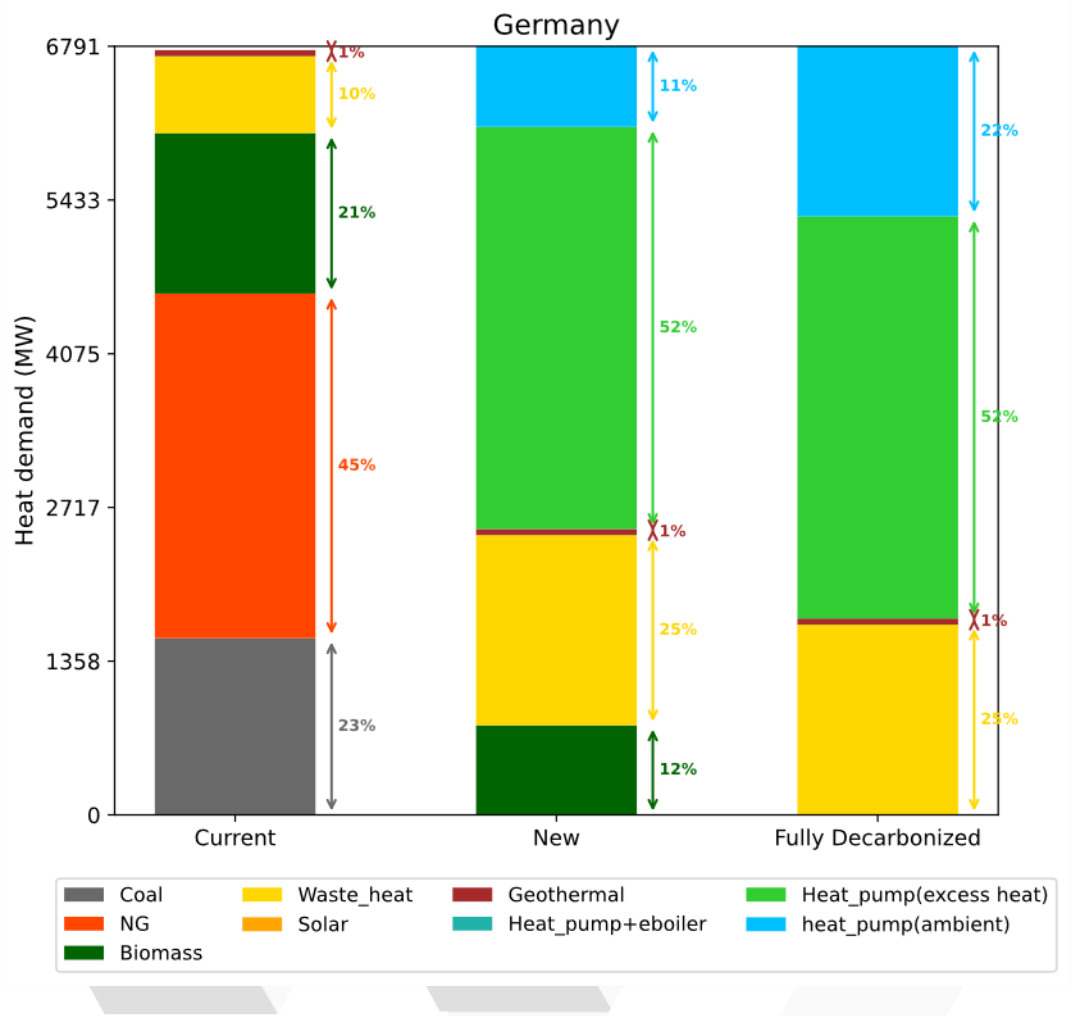


Figure 9: Decarbonization strategy for the transition of Germany's district heating generation

Figure 9, shows the decarbonization strategy for Germany under three scenarios defined in Section 2.1.

In the New Scenario, direct utilization of waste heat covers approximately 25 % of the heat demand. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 (55 °C to 25 °C) use approximately 2530 MW of excess heat as heat source and, with an average COP of 3.47, cover about 52 % of the heat demand. Ambient-air heat pumps cover a further 11 %, which eliminates fossil fuels from the energy mix. The share of biomass is reduced from 21 % to 12 %.

In the Fully Decarbonized Scenario, direct waste heat utilization and excess heat pumps are complemented by ambient-air heat pumps, which must cover

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approximately 22 % of the heat demand to eliminate biomass and fully decarbonize the energy mix. These heat pumps achieve an average COP of 2.74.

b) Economic assessment

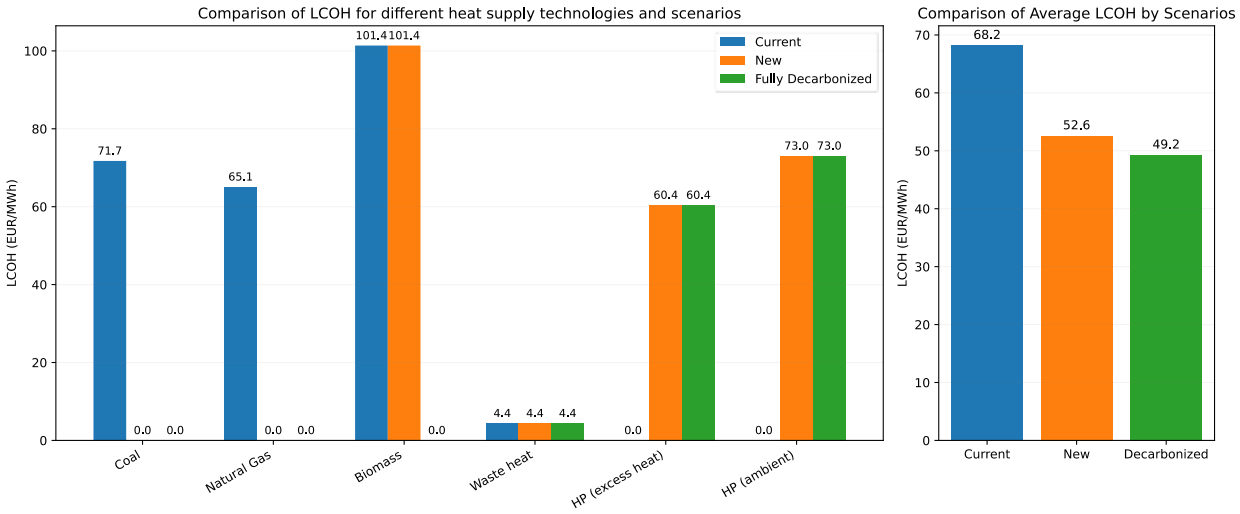


Figure 10: Comparison of LCoH across heat supply technologies and decarbonization scenarios for full load 8760 operating hours

Figure 10 compares the LCoH across different heat supply technologies for full load operating hours of 8760 hours and for the three scenarios; Current, New, and Fully Decarbonized. In the Current Scenario, fossil-based heat supply such as coal and natural gas, attain a LCoH value of approximately 72 €/MWh and 65 €/MWh, respectively, while heat supply from biomass appears at a significantly higher cost of 101 €/MWh.

In the New Scenario, with the increased share of heat pumps using industrial excess heat and ambient air, coal and natural gas are phased out, while the LCoH of biomass remains at 98 €/MWh. The heat supply from heat pumps using excess heat and ambient air attains an LCoH values of approximately 60 €/MWh and 74 €/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and Biomass based heat supply are eliminated, and the system relies mainly on direct waste heat utilization and heat pumps. The heat supply with waste heat has a low LCoH at ~5 €/MWh, heat pump using industrial excess heat attain an LCoH around 60 €/MWh while ambient air heat pumps yield 74 €/MWh.

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Finally, the comparison of average LCoH shows a downward trend from 68 €/MWh in the Current Scenario to 53 €/MWh in the New Scenario and dropping to 49 €/MWh in the Fully Decarbonized Scenario. This highlights that the shift to low-carbon and high-efficiency technologies leads to significantly lower heating costs.

Similarly, Figure 11, compares the LCoH across different heat-supply technologies for 4000 operating hours, to address the part load operating behaviour of the technologies.

In the Current Scenario, fossil-based based heat supply such as coal and natural gas, has an LCoH values of approximately 79 €/MWh and 66 €/MWh, respectively, while heat supply from biomass attains a value of approximately 111 €/MWh.

In the New Scenario, with the increased share of heat pump using industrial excess heat and ambient air, the use of coal and natural gas are phased out, while biomass remains at 111 €/MWh. Heat supply from heat pumps using excess heat and ambient heat attain LCoH values of 66 €/MWh and 82 €/MWh, respectively.

In the Fully Decarbonized Scenario, the heat supply with waste heat has a low LCoH at approximately 9 €/MWh, heat pump utilizing industrial excess heat attain an LCoH around 66 €/MWh while ambient air heat pumps yield approximately 82 €/MWh.

Finally, the average LCoH for 4000 operating hours, decreases by approximately 18 % from the current to the New Scenario, while, the LCoH for the Fully Decarbonized Scenario is reduced by 23 % compared to the Current Scenario.

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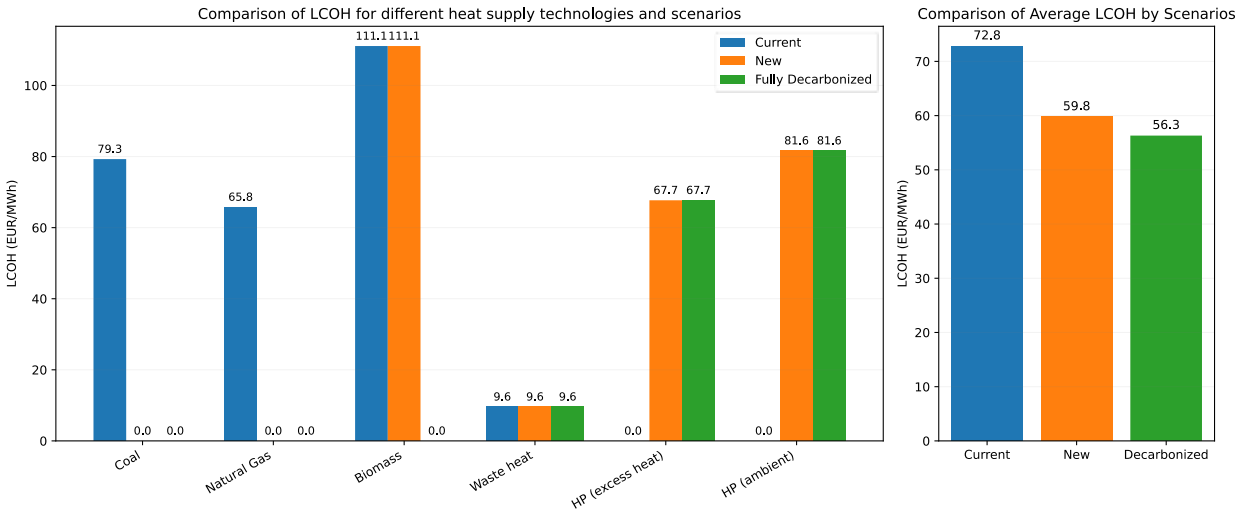


Figure 11: Comparison of LCoH across heat supply technologies and decarbonization scenarios for part load of 4000 operating hours

4.3 Poland



Poland is the second largest EU country with respect to the installed district heating capacity. In 2023, district heating in Poland covered approximately 42 $GW_{thermal}$, corresponding to approximately 40 % of the total heat demand for the residential and service sector [16]. Table 13, shows the installed district heating capacity of Poland over the period from 2018 - 2023. Warsaw, Kraków, Łódź, Poznań, Wrocław are the 5 largest district heating networks in Poland with heat capacities of 473 MW, 321 MW, 160 MW, 66 MW, and 145 MW respectively. The forward and return temperature of the transmission and distribution network is shown in Table 14 [23]. The Polish transmission networks have a forward and return temperature of up to 135 °C and 70 °C, respectively. While the distribution networks have a forward and return temperature of up to 125 °C and 60 °C, respectively.

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Table 13: District heating installed capacity Poland

Installed capacity (GW_{th})	2018	2021	2022	2023
	43	43	43	42

Table 14: Transmission and distribution network temperatures

Temperature level	Transmission Network (°C)	Distribution Network (°C)
Forward temperature	135	Up to 125
Return temperature	70	up to 60

The average energy mix for the generation of district heating in Poland is shown in Table 15. Fossil fuels remain the main energy source for the generation of district heating in Poland with approximately 73.5 % by coal and 12.7 % by natural gas. While the renewables only account for up to 14 %.

Table 15: Energy source mix in the generation of district heating

Energy source	2018	2021	2022	2023
Coal	72 %	76 %	76 %	73.5 %
Natural gas	8 %	9 %	9 %	12.7 %
Oil	3 %	-	-	-
Biomass	10 %	9 %	9.7 %	7.7 %
Waste heat	2 %	5.7 %	4.4 %	3 %
Solar		-	0.5 %	-
Geothermal	-	-	-	1.2 %
Heat pump & E-boiler	-	-	-	1.7 %
Other	5 %	-	-	-

4.3.1 Decarbonization Strategies

a) Assessment of industrial excess heat

The assessment of industrial excess heat potential begins with estimating the minimum heat source temperature required by the heat pump. This estimation serves

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as a basis for identifying feasible heat sources, such as industrial excess heat, ambient air, or seawater, which can be utilized as heat source for the heat pump.

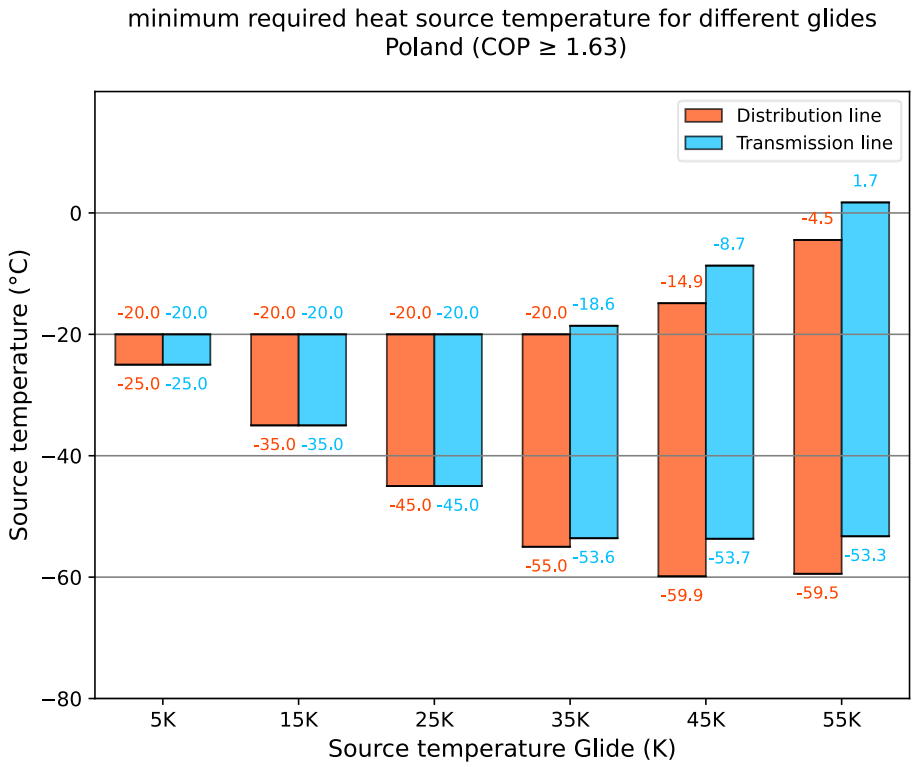


Figure 12: Minimum required heat source temperature

The required minimum heat source temperature for a high-temperature heat pump integrated in the Polish district heating network is shown in Figure 12.

The low minimum-economic COP of approximately 1.6, ensure viable heat pump operation even with heat source temperatures below 0 °C. Thus, heat sources such as ambient air, seawater or low-temperature industrial excess heat can be used as potential heat source. The estimated heat source temperature requirements for Poland suggest that the utilization of low grade industrial waste heat, ambient air or seawater are all feasible sources for economically viable heat pumps. This subsequently suggest that high-temperature heat pumps may be an attractive choice for the decarbonization of the Polish district heating generation.

Based on the PETA map [1], the total recoverable industrial excess heat in Poland after maximum internal heat recovery has been estimated. For Poland, this results in a Level

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1 estimate of approximately 41.6 PJ per year (1319 MW). Of this, approximately 20 PJ per year can be recovered above 55 °C (Level 2) and 16 PJ per year above 95 °C (Level 3).

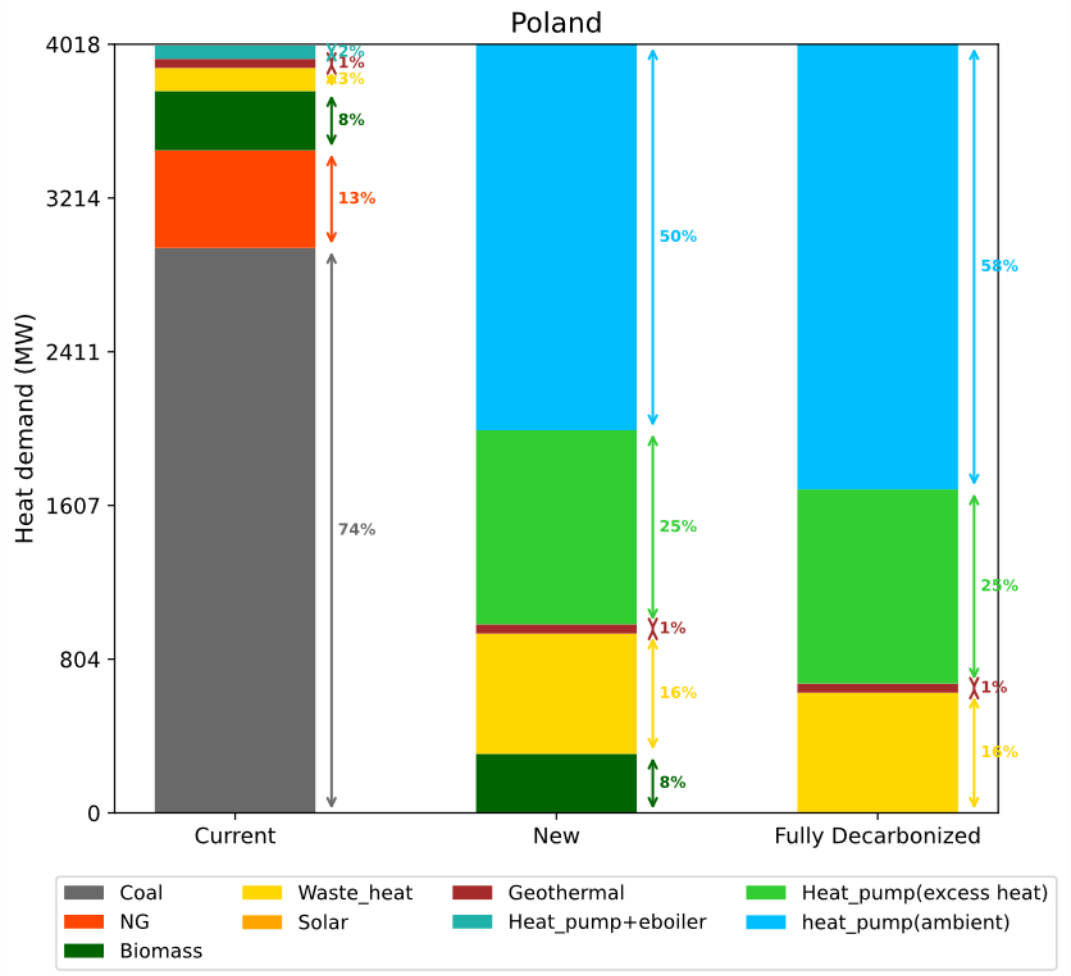


Figure 13: Decarbonization strategy for the transition of Poland's district heating generation

Figure 13, shows the decarbonization strategy for Poland under three scenarios defined in Section 2.1.

In the New Scenario, direct utilization of waste heat (approximately 628 MW) covers about 16 % of the heat demand. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 (55 °C to 25 °C) use approximately 691 MW of excess heat as heat source and, with an average COP of 3.13, cover about 25 % of the heat demand.

As the current energy mix is dominated by coal (more than 70 %), these two sources together cover about 41 % of the heat demand, which is not sufficient to replace all

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fossil fuels. Ambient-air heat pumps therefore play a crucial role and cover approximately 50 % of the heat demand, corresponding to about 2017 MW, while biomass is maintained at around 8 %.

In the Fully Decarbonized Scenario, ambient-air heat pumps must cover approximately 58 % of the heat demand, in addition to direct waste heat and excess heat pumps, to eliminate biomass and achieve full decarbonization. These heat pumps can achieve an average COP of 2.57, which is just above the minimum economic COP of 1.63 for Poland.

b) Economic assessment

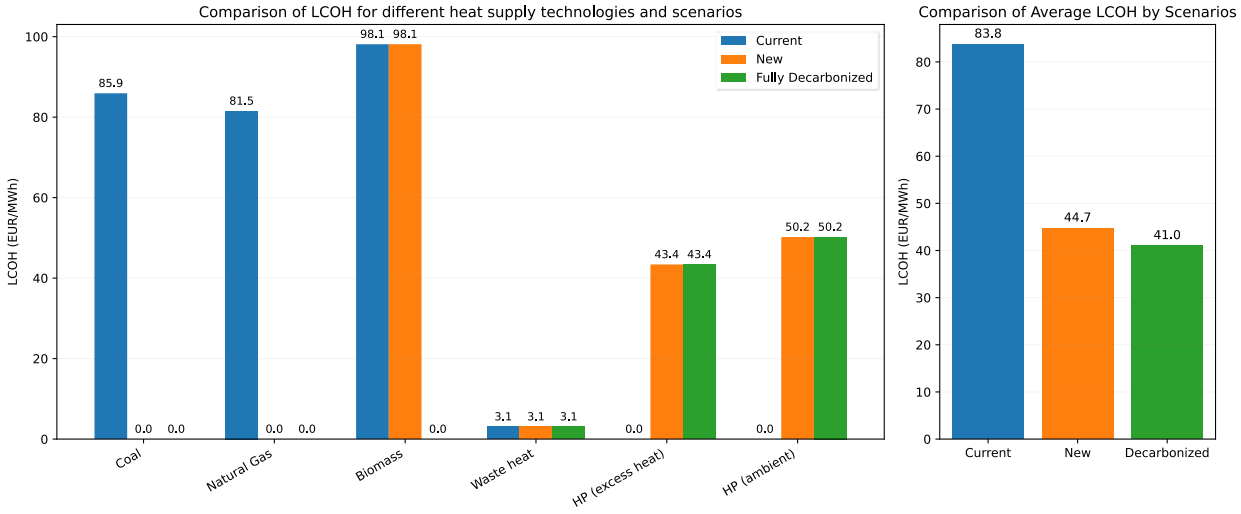


Figure 14: Comparison of LCoH across heat supply technologies and decarbonization scenarios for full load 8760 operating hours

Figure 14 compares the LCoH across different heat supply technologies for full load operating hours of 8760 hours and for the three scenarios; Current, New, and Fully Decarbonized.

In the Current Scenario, fossil-based heat supply such as coal and natural gas, attain a LCoH value of approximately 86 €/MWh and 82 €/MWh, respectively, while heat supply from biomass appears at a significantly higher cost of 98 €/MWh.

In the New Scenario, with the increased share of heat pumps using industrial excess heat and ambient air heat pumps, the use of coal and natural gas are phased out, while biomass remains at 98 €/MWh. Heat supply from heat pumps using excess heat

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and ambient air attain a LCoH values of approximately 43 €/MWh and 50 €/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and biomass-based heat supply are eliminated, and the system relies solely on waste heat and heat pumps. The heat supply from direct utilization of waste heat attains a very low LCoH at approximately 5 €/MWh. Heat pumps utilizing industrial excess heat attain a LCoH around 43 €/MWh while ambient air heat pumps attain 50 €/MWh.

Finally, the comparison of average LCoH shows a downward trend from 84 €/MWh in the Current Scenario to 45 €/MWh in the New Scenario, dropping to 41 €/MWh in the Fully Decarbonized Scenario. This highlights the shift to low-carbon and high-efficiency technologies leads to significantly lower heating costs.

Similarly, Figure 15, compares the LCoH across different heat-supply technologies for 4000 operating hours, to address the part load operating behaviour of the technologies.

In the Current Scenario, fossil-based heat supply such as coal and natural gas, has an LCOH values of around 91 €/MWh and 82 €/MWh, respectively, while the LCoH of biomass is 104 €/MWh. The biomass cost is found to be comparatively higher among all technologies due to higher operation and maintenance cost of the system.

In the New Scenario, with the increased share of heat pumps using industrial excess heat and ambient air, the use of coal and natural gas is phased out, while biomass remains at 104 €/MWh. Heat supply from heat pumps using excess heat and ambient air attain an LCoH value of approximately 47 €/MWh and 55 €/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and biomass-based heat supply are eliminated, and the system relies solely on direct waste heat utilization and heat pumps. The heat supply with waste heat attains a very low LCoH at ~6.5 €/MWh, heat pump industrial excess heat LCoH around 47 €/MWh and ambient source heat pumps at 55 €/MWh.

Finally, for 4000 operating hours per year, the average levelized cost of heat in the Current Scenario was 88€/MWh. This value was reduced to 49€/MWh in the New Scenario and further reduced to 45€/MWh in the Fully Decarbonized Scenario. Compared to the results presented in Figure 14, where the heat pumps operate throughout the entire year, the reduced number of operating hours results in increases

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in the levelized cost of heat of 3 %, 8 %, and 13 % for the Current, New, and Fully Decarbonized Scenarios, respectively.

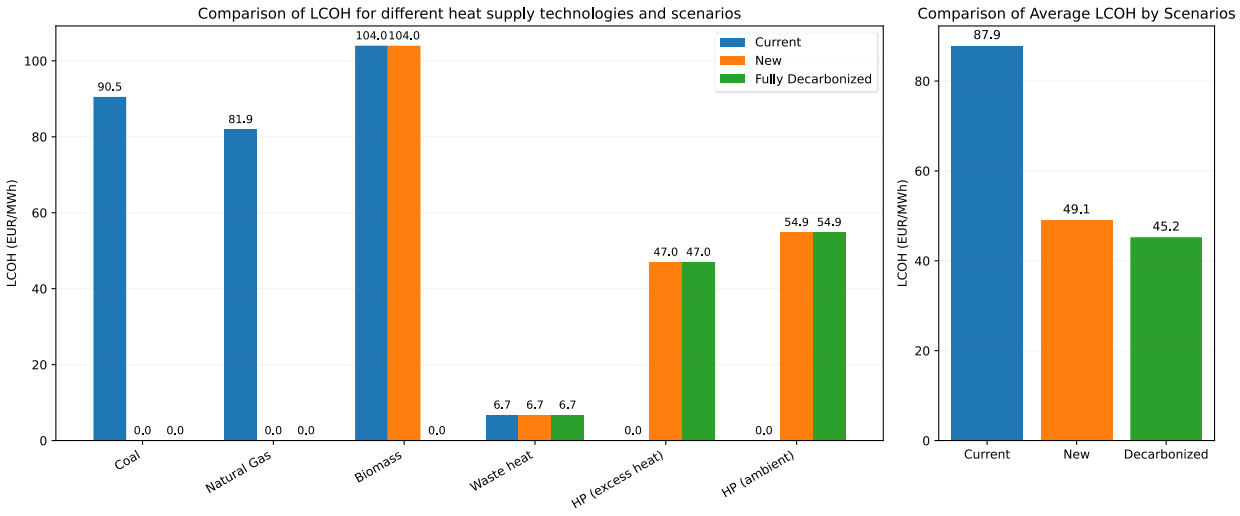


Figure 15: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for part load 4000 operating hours

4.4 France



France is one of the EU countries with the lowest share of district heating. Of the total heat demand for the residential and service sector only 5 %, correspond to approximately 1548 MW [16], is covered by district heating. The installed district heating capacity in 2023 was approximately 26 $GW_{thermal}$, and the installed capacity over the years is shown in Table 16. Paris, Grenoble, Lyon, Bordeaux and Metz are the five largest district heating networks in France with a heat demand of 337 MW, 51 MW, 25 MW, 12 MW, and 8 MW, respectively. The forward and return temperature of the transmission and distribution networks are shown in Table 17, estimated from Euroheat and Power [16]. The transmission network has a forward and return temperature of up

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to 110 °C and 60 °C, respectively. The distribution network has a forward and return temperature of up to 100 °C and 50 °C, respectively.

Table 16: District Heating Installed Capacity France

Installed capacity (GW_{th})	2018	2021	2022	2023
	23	27	26.8	26

Table 17: Transmission and Distribution Network Temperatures

Temperature level	Transmission Network (°C)	Distribution Network (°C)
Forward temperature	110	100
Return temperature	55-60	50

Table 18, shows the energy-mix for the generation of district heating in France over the past 8 years. Biomass covers about 42 % and other renewables, including heat pumps and waste heat cover about 25 %. Around 33 % of heat generation is still supplied by natural gas. However, the moderate forward temperatures and the minimum economic COP of 2.28, provides a significant potential for high-temperature heat pump integration for heat supply in the French district heat network.

Table 18: Energy Source Mix in the Generation of District Heat

Energy source	2018	2021	2022	2023
Coal	4 %	3 %	1.8 %	-
Natural gas	37 %	36.4 %	32.4 %	33 %
Oil	1 %	-	-	-
Biomass	50 %	50.7 %	40.6 %	42 %
Waste heat	3 %	1.6 %	16.5 %	16.3 %
Solar	-	-	-	-
Geothermal	4 %	4.6 %	4.8 %	5.6 %
Heat pump & E-boiler	1 %	2 %	2.4 %	3 %
Other	-	1.7 %	1.2 %	-

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4.4.1 Decarbonization Strategies

a) Assessment of industrial excess heat

The assessment of industrial excess heat potential begins with estimating the minimum heat source temperature required by the heat pump. This estimation serves as a basis for identifying feasible heat sources, such as industrial excess heat, ambient air, or seawater, which can be utilized as heat source for the heat pump.

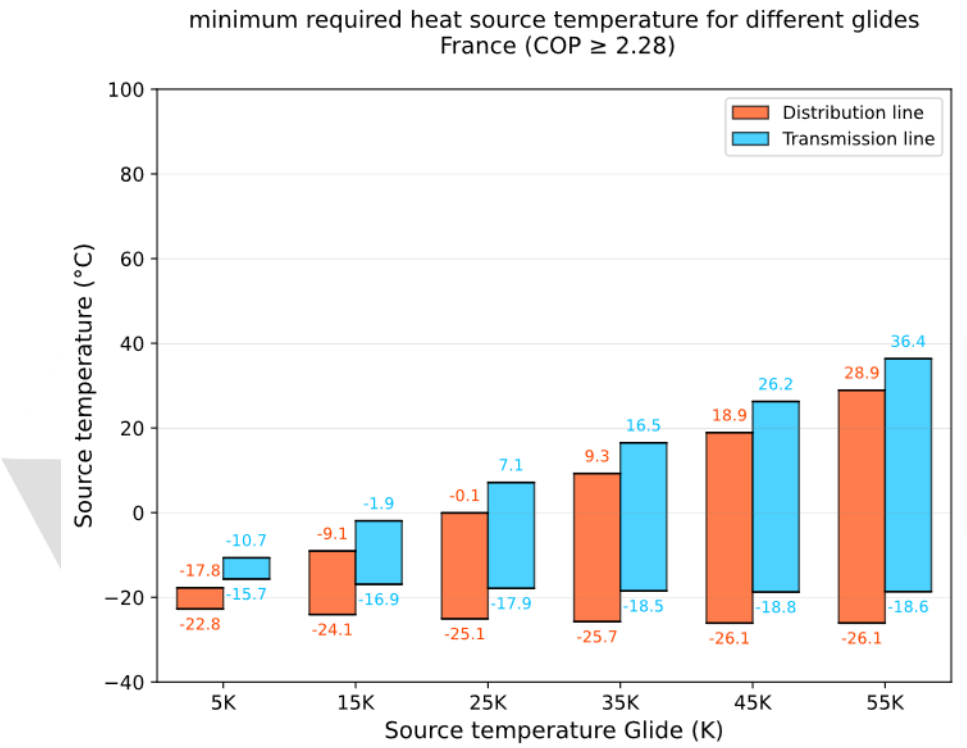


Figure 16: Minimum Required Heat Source Temperature

The required minimum heat source temperature for a high-temperature heat pump integrated in the French district heating network is shown in Figure 16.

With a minimum economic COP of 2.28, a heat pump integrated within the French district heating networks may be a viable solution even with heat source temperatures below 0 °C. Thus, allowing the utilization of ambient heat sources such air or water.

As seen, for a low glide heat source the required minimum temperature is approximately -10 °C for the transmission network and approximately -17 °C for the

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distribution network. For the high glide heat sources, a minimum heat source temperature of 36 °C is required for the transmission network while 29 °C is required for the distribution network.

The low heat source temperature requirements enhance the feasibility of utilizing ambient air or seawater as heat sources. However, the utilization of high-grade industrial excess heat is still expected to result in higher economic and energy efficiency.

Based on the PETA map [1], the total recoverable industrial excess heat in France after maximum internal heat recovery has been estimated. For France, this results in a Level 1 estimate of approximately 73 PJ per year (2308 MW). Of this, approximately 28 PJ per year can be recovered above 55 °C (Level 2) and 10 PJ per year above 95 °C (Level 3).

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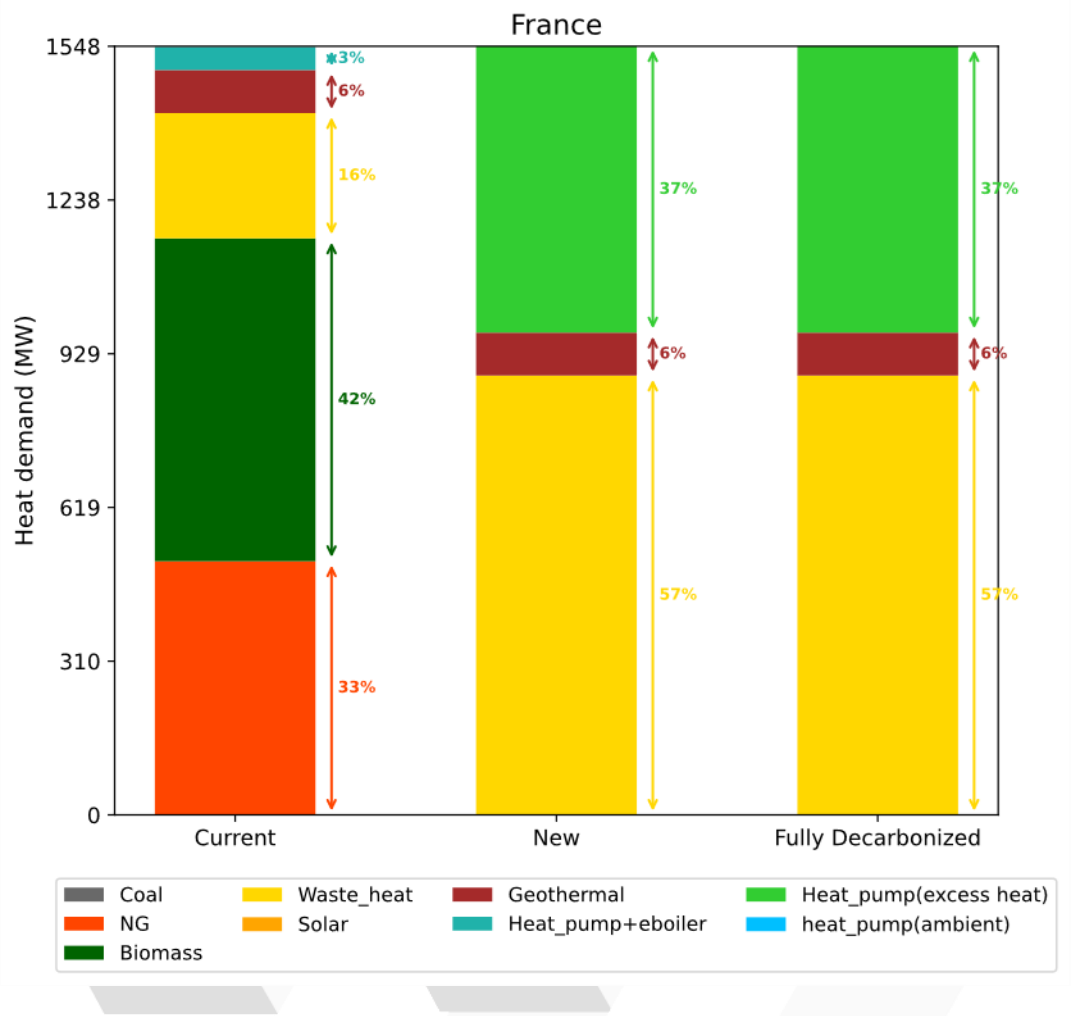


Figure 17: Decarbonization strategy for the transition of France's district heating generation

Figure 17, shows the decarbonization strategy for France under three scenarios defined in Section 2.1.

In the New Scenario, the direct utilization of waste heat can cover approximately 884.7 MW, corresponding to around 57 % of total heat demand, and geothermal heat is maintained at around 6 %. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 have an available source potential of approximately 1423 MW. With an average COP of 3.86, about 425 MW of this source heat is sufficient to deliver approximately 573 MW, covering 37 % of heat demand. Together, direct waste heat utilization, geothermal heat and industrial excess heat pumps cover the total heat demand for district heating. Thereby it is possible to eliminate the use of fossil fuel and biomass in the district heat generation in the New Scenario.

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b) Economic assessment

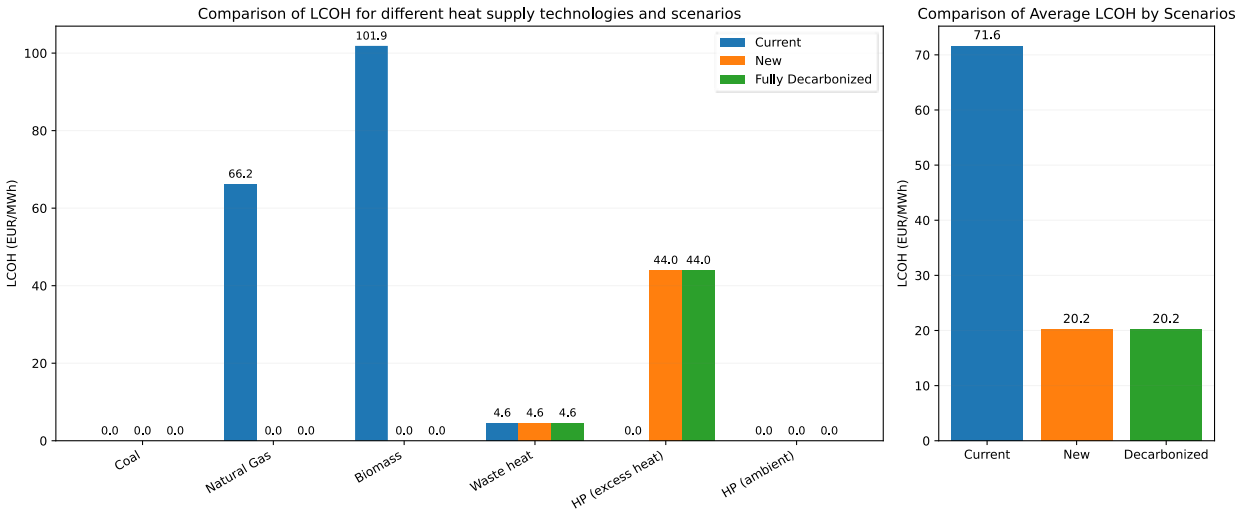


Figure 18: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for full load of 8760 operating hours

Figure 18 compares the LCoH across different heat supply technologies for full load operating hours of 8760 hours and for the three scenarios; Current, New, and Fully Decarbonized.

In the Current Scenario, natural gas and biomass are the main source of heat generation, with a LCoH around 66 €/MWh and 101 €/MWh, respectively. Further, the Current Scenario includes a small amount of direct utilization of waste heat with a LCoH of around 5.1 €/MWh.

In the New Scenario, fossil fuels such as coal and natural gas are completely phased out. The fossil fuels are replaced by direct utilization of waste heat and heat pumps utilizing industrial excess heat, with an LCoH of approximately 5.1 €/MWh and 44 €/MWh, respectively.

As the New Scenario already represent a decarbonised heat supply system, the LCoH for the Fully Decarbonized Scenario remains similar to the New Scenario.

Finally, the comparison of the average LCoH shows a clear downward trend from 72 €/MWh in the Current Scenario to approximately 20 €/MWh in the New Scenario and Fully Decarbonized Scenario. This highlights the shift to low-carbon and high-efficiency technologies leads to significantly lower heating costs.

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Similarly, Figure 19, compares the LCoH across different heat-supply technologies for 4000 operating hours, to address the part load operating behaviour of the technologies.

In the Current Scenario, natural gas and biomass are the main source of heat generation, with a LCoH around 67€/MWh and 112€/MWh, respectively. The direct utilization of waste heat attains a LCoH of around 9.7 €/MWh.

In the New Scenario, fossil fuels such as coal and natural gas are completely phased out and replaced by direct utilization of waste heat and heat pumps based on excess heat, with an LCOH of approximately 9.7 €/MWh and 42 €/MWh, respectively.

Again, the Fully Decarbonized Scenario is equivalent to the New Scenarios as this is already decarbonized.

For 4000 operating hours per year, the average LCoH in the Current Scenario was 78€/MWh. This value was reduced to 27 €/MWh in the New Scenario and Fully Decarbonized Scenario. Compared to the results presented in Figure 18, where the heat pumps operate throughout the entire year, the reduced number of operating hours results in increases in the levelized cost of heat of 6 %, 27 %, and 27 % for the Current, New, and Fully Decarbonized Scenarios, respectively.

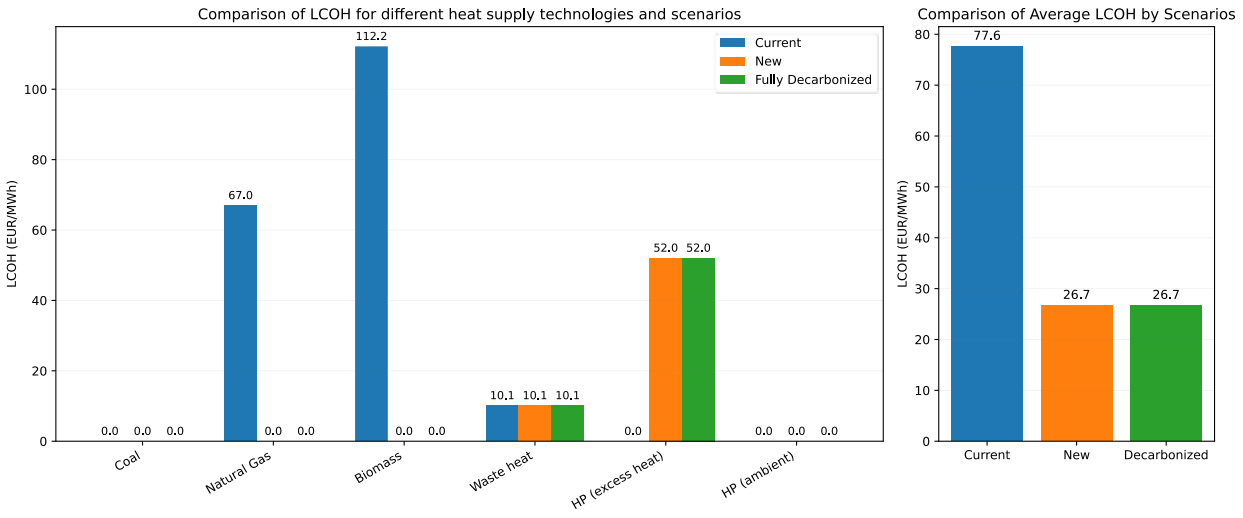


Figure 19: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for part load of 4000 operating hours

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4.5 Austria



Austria is one of the EU countries with the lowest installed district heating capacity. Approximately 17 %, corresponding to 718 MW of the total heat demand for the residential and service sector is currently covered by district heating[16]. The total installed district heating capacity in Austria was approximately 12 $GW_{thermal}$ in 2023 and the installed capacity over the years is shown in the Table 19. Vienna, Graz, Linz, Salzburg and Innsbruck are the five largest district heating networks in Austria with 293 MW, 48 MW, 61 MW, 31 MW, and 31 MW, respectively. The forward and return temperature of the transmission and distribution network are shown in Table 20, and are estimated from DBDH [26]. The transmission network has a forward and return temperature of up to 150 °C and 70 °C, respectively, while the distribution network has a forward and return temperature of up to 140 °C and 60 °C, respectively.

Table 19: District Heating Installed Capacity Austria

Installed capacity (GW_{th})	2018	2021	2022	2023
	11.2	11.5	11.8	12

Table 20: Transmission and Distribution Network Temperatures

Temperature level	Transmission Network (°C)	Distribution Network (°C)
Forward temperature	90-150	140
Return temperature	50-70	60

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The energy-mix for the generation of district heating in Austria shown in the Table 21 for the past 8 years. Biomass and natural gas were the main energy sources for district heating generation with approximately 55 % and 30 %, respectively. The share of direct waste heat utilization accounts for approximately 8.5 % while coal covers the final of 6.5 %. In total fossil fuels still covers around 35 % of the total heat generation, which can be lowered by increasing the share of renewables sources such as solar thermal, geothermal, heat pumps, and industrial waste heat utilization. The available waste heat can be integrated directly into the network or can be used as heat source for heat pumps. Thus, an increase in direct waste heat utilization and excess heat pump in the heat supply and reduce the dependency of fossil fuels.

Table 21: Energy Source Mix in the Generation of District Heat

Energy source	2018	2021	2022	2023
Coal	4 %	3.5 %	6 %	6.5 %
Natural gas	35 %	37 %	32.7 %	30 %
Oil	6 %	-	-	-
Biomass	47 %	50.5 %	52.6 %	55 %
Waste heat	8 %	5.8 %	8.6 %	8.5 %
Solar	-	-	-	-
Geothermal	-	2.9 %	-	-
Heat pump & E-boiler	-	-	-	-
Other	-	-	-	-

4.5.1 Decarbonization Strategies

a) Assessment of industrial excess heat

The assessment of industrial excess heat potential begins with estimating the minimum heat source temperature required by the heat pump. This estimation serves as a basis for identifying feasible heat sources, such as industrial excess heat, ambient air, or seawater, which can be utilized as heat source for the heat pump.

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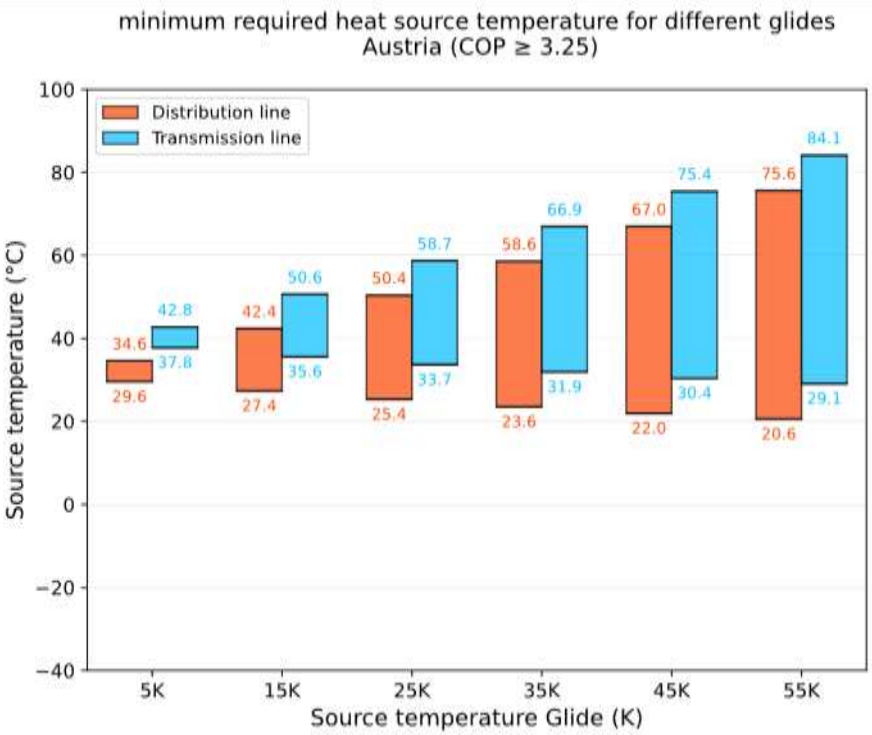


Figure 20: Minimum Required Heat Source Temperature

The required minimum heat source temperature for a high-temperature heat pump integrated in the Austrian district heating network is shown in Figure 20.

With a minimum economic COP 3.25 and with fairly high forward temperatures in the Austrian networks the minimum heat source temperature is significantly higher compared to other countries. It is estimated that for the low glide heat sources, the required heat source temperature is approximately 43 °C for the transmission network and approximately 35 °C for the distribution network. For the high glide heat sources, the required a heat source temperature is 84 °C for the transmission network and 76 °C for the distribution network.

Unlike countries like Denmark, France, and Poland, heat pump integration in the Austrian district heating networks requires high heat source temperatures with minimum temperature of approximately 35 °C -40 °C. Therefore, the only viable heat source is industrial excess heat.

Based on the PETA map [1], the total recoverable industrial excess heat in Austria after maximum internal heat recovery has been estimated. For Austria, this results in a Level

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1 estimate of approximately 18 PJ per year (561 MW). Of this, approximately 7 PJ per year can be recovered above 55 °C (Level 2) and 5 PJ per year above 95 °C (Level 3).

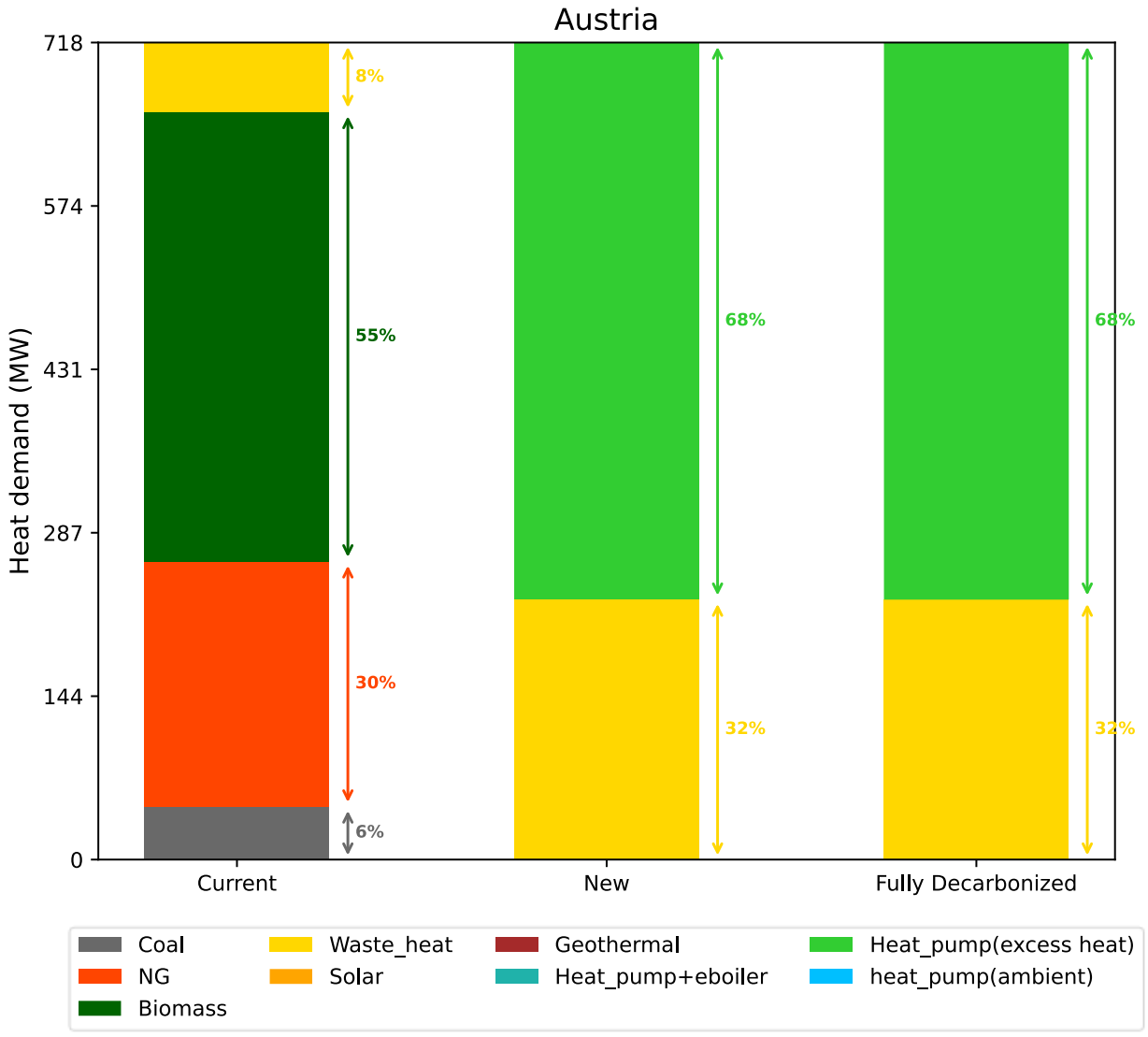


Figure 21: Decarbonization strategy for the transition of Austria's district heating generation

Figure 21, shows the decarbonization strategy for Austria under three scenarios defined in Section 2.1.

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In the New Scenario, direct utilization of waste heat covers approximately 222 MW, corresponding to about 32 % of the heat demand. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 have an available heat source potential of approximately 339 MW and, with an average COP of 3.11, cover the remaining 68 % of the heat demand. Together, direct waste heat and excess heat pumps cover the entire district heating demand, which eliminates both fossil fuels and biomass already in the New Scenario.

b) Economic assessment

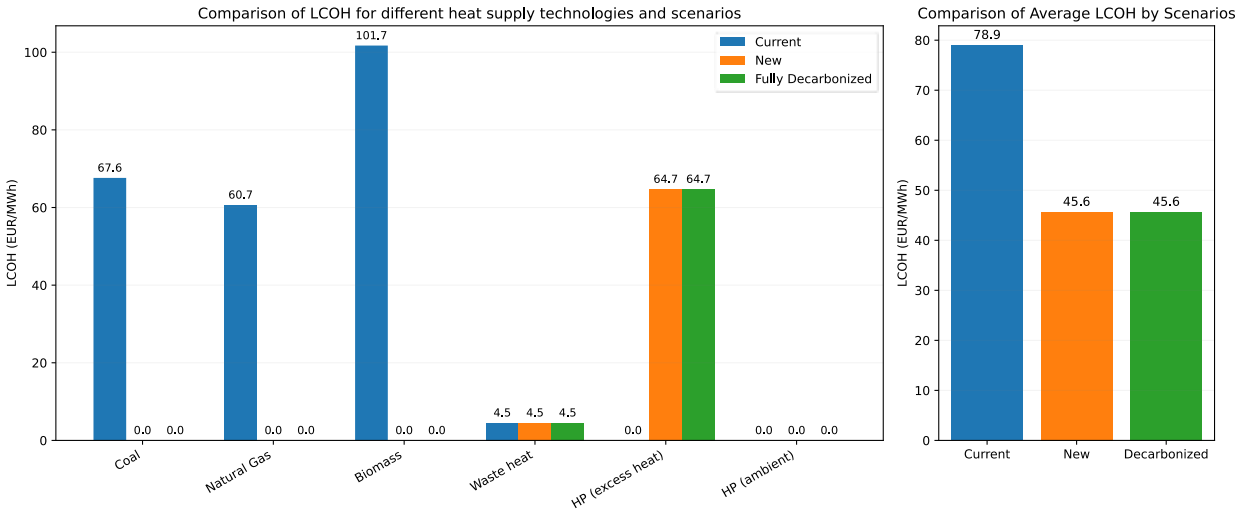


Figure 22: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for full load of 8760 operating hours

Figure 22, compares the LCoH across different heat supply technologies for full load operating hours of 8760 hours and for the three scenarios; Current, New, and Fully Decarbonized.

In the Current Scenario, natural gas and biomass are the main source of heat generation, with LCoH around 61 €/MWh and 102 €/MWh, respectively. A small amount of coal with an LCoH of approximately 68 €/MWh, and waste heat with a LCoH of around 5.1 €/MWh is also used.

In the New Scenario, fossil fuels such as coal and natural gas as well as biomass are completely phased out. The direct utilization of waste heat and heat pumps based on excess heat become more prominent, with an LCoH of approximately 5.1 €/MWh and 65 €/MWh, respectively.

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As the New Scenario already represent a decarbonised heat supply system, the LCoH for the Fully Decarbonized Scenario remains similar to the New Scenario.

Finally, the comparison of average LCoH shows a clear downward trend from 79 €/MWh in the Current Scenario to 46 €/MWh in the New Scenario and Fully Decarbonized Scenario. This highlights the shift to low-carbon and high-efficiency technologies leads to significantly lower heating costs.

Similarly, Figure 23, compares the LCoH across different heat-supply technologies for 4000 operating hours, to address the part load operating behaviour of the technologies.

In the Current Scenario, natural gas and biomass are the main source of heat generation, with LCoH around 61 €/MWh and 112 €/MWh respectively. A small amount of coal with a LCoH of approximately 76 €/MWh, and waste heat with a LCoH of around 10 €/MWh is also used.

In the New Scenario, fossil fuels such as coal and natural gas as well as biomass are completely phased out, and the direct utilization of waste heat and heat pumps based on excess heat become more prominent, with a LCoH of approximately 10 €/MWh and 72 €/MWh, respectively.

As the New Scenario already represent a decarbonised heat supply system, the LCoH for the Fully Decarbonized Scenario remains similar to the New Scenario.

Finally, for 4000 operating hours per year, the average levelized cost of heat in the Current Scenario was 86 €/MWh. This value was reduced to 53 €/MWh in the New Scenario and Fully Decarbonized Scenario. Compared to the results presented in Figure 22, where the heat pumps operate throughout the entire year, the reduced number of operating hours results in increases in the levelized cost of heat of 6 %, 18 %, and 18 % for the Current, New, and Fully Decarbonized Scenarios, respectively.

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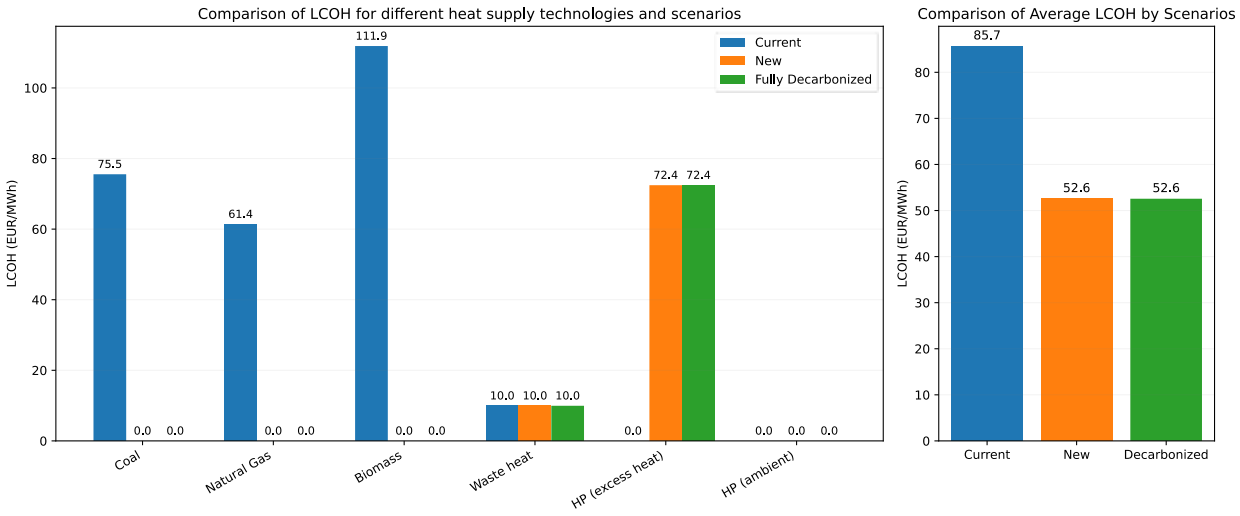


Figure 23: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for part load of 4000 operating hours

4.6 Finland



Finland's district heating system covers approximately 44 %, corresponding to 1827 MW, of the total heat demand in the residential and service sector [16]. The total installed capacity in Finland for the year 2023 was around 23 $GW_{thermal}$ as shown in Table 22. Helsinki, Lahti, Oulu and Turku are the four largest district heating networks in Finland [19], with heat demands of 515 MW, 63 MW, 117 MW, and 127 MW, respectively. The forward and return temperature of the transmission and distribution networks are shown in Table 23 [24]. The transmission network has a forward and return temperature of up to 115 °C and 60 °C, respectively. The distribution network has a forward and return temperature of up to 105 °C and 50 °C, respectively.

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Table 22: District Heating Installed Capacity Finland

Installed capacity (GW_{th})	2018	2021	2022	2023
	23.5	24	24.7	25

Table 23: Transmission and Distribution Network Temperatures

Temperature level	Transmission Network (°C)	Distribution Network (°C)
Forward temperature	115	105
Return temperature	60	50

Like Denmark, the energy-mix of Finland's district heat generation is primarily based on renewables The distribution of energy sources used for district heat production over the years is presented in the Table 24. Biomass covers around 51 %, waste heat around 16 % and small share of heat pump & E-boilers contribute with around 8.4 %. Though biomass covers a major part of heat generation, fossil fuels still account for about 24 % of the overall energy-mix, with 18 % coming from coal and 6 % from natural gas.

the moderate forward temperatures and the minimum economic COP of 1.1, provides a significant potential for high-temperature heat pump integration for heat supply in the Finish district heat network.

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Table 24: Energy Source Mix in the Generation of District Heat

Energy source	2018	2021	2022	2023
Coal	35 %	24 %	32.5 %	18 %
Natural gas	13 %	10.7 %	3.7 %	6.2 %
Oil	2 %	-	-	-
Biomass	35 %	47.6 %	48.5 %	51 %
Waste heat	-	13 %	13.2 %	16 %
Solar	-	-	-	-
Geothermal	-	-	-	-
Heat pump & E-boiler	-	4.2 %	3.7 %	8.4 %
Other	15 %	-	-	-

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4.6.1 Decarbonization Strategies

a) Assessment of Industrial excess heat

The assessment of industrial excess heat potential begins with estimating the minimum heat source temperature required by the high-temperature heat pump. This estimation serves as a basis for identifying feasible heat sources, such as industrial excess heat, ambient air, or seawater, which can be utilized as heat source for the heat pump.

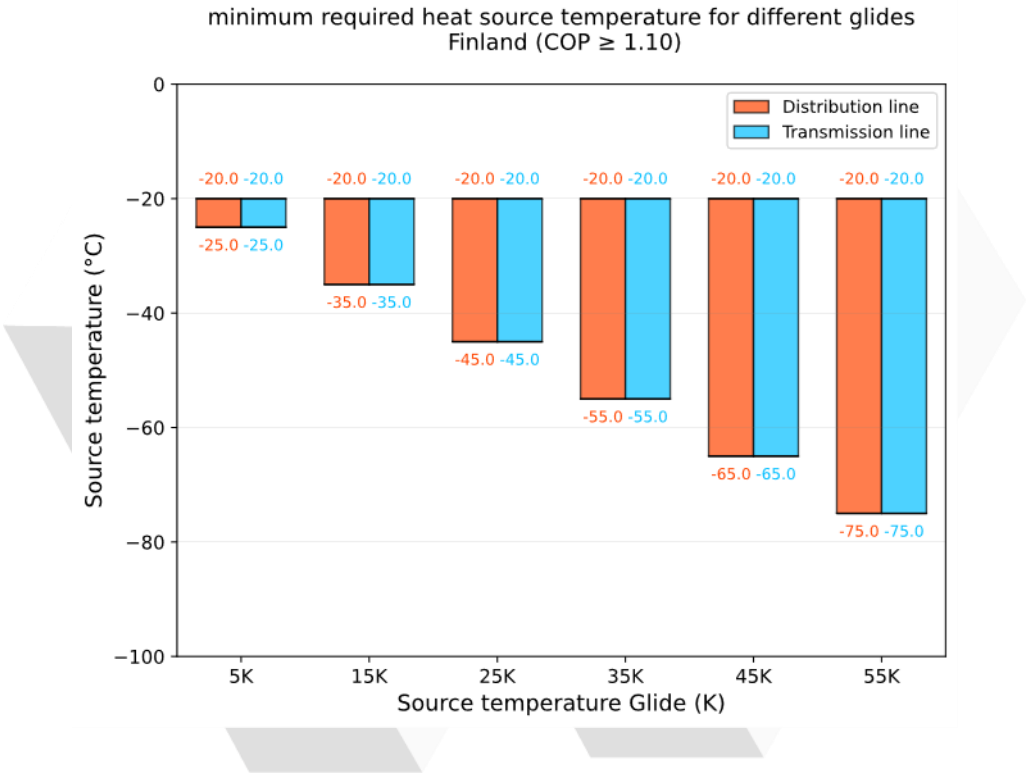


Figure 24: Minimum Required Heat Source Temperature

The required minimum heat source temperature for a high-temperature heat pump integrated in the Finnish district heating network is shown in Figure 24.

The low minimum-economic COP of approximately 1.10, and the low network operating temperatures, ensure viable heat pump operation even with heat source temperatures below 0 °C. Thus, heat sources such as ambient air, seawater or low-temperature industrial excess heat can be used as potential heat source.

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Based on the PETA map [1], the total recoverable industrial excess heat in Finland after maximum internal heat recovery has been estimated. For Finland, this results in a Level 1 estimate of approximately 25 PJ per year (805 MW). Of this, approximately 8 PJ per year can be recovered above 55 °C (Level 2) and 6 PJ per year above 95 °C (Level 3).

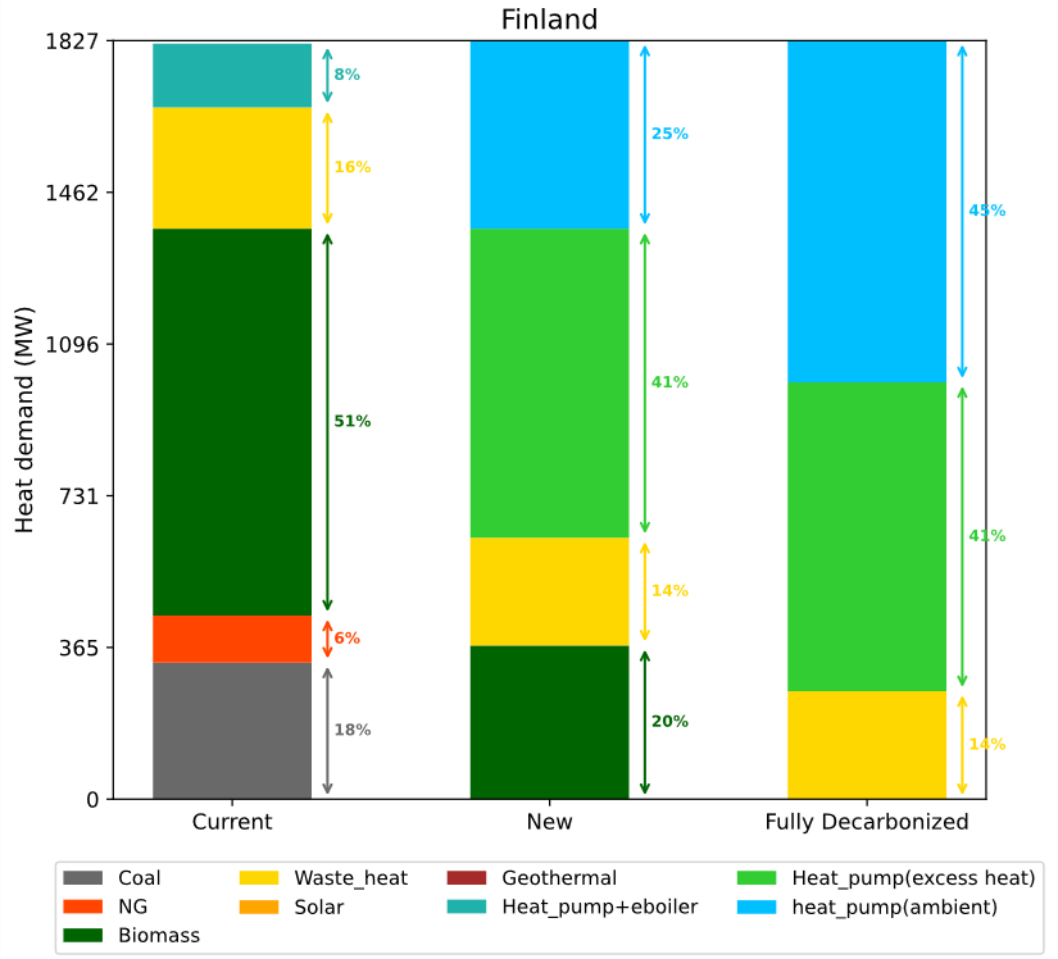


Figure 25: Decarbonization strategy for the transition of Finland's district heating generation

Figure 25, shows the decarbonization strategy for Finland under three scenarios defined in Section 2.1.

In the New Scenario, direct utilization of waste heat covers approximately 260 MW, corresponding to about 14 % of the heat demand. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 use approximately 545 MW of excess heat as heat source and, with an average COP of 3.74, cover about 41 % of the heat demand.

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Ambient-air heat pumps cover a further 25 %, which eliminates fossil fuels from the energy mix, while the share of biomass is reduced from 51 % to 20 %.

In the Fully Decarbonized Scenario, ambient-air heat pumps must cover approximately 45 % of the heat demand, in addition to direct waste heat and excess heat pumps, to eliminate biomass and fully decarbonize the energy mix. These heat pumps can achieve an average COP of 2.89, well above the minimum economic COP of 1.10 for Finland.

b) Economic assessment

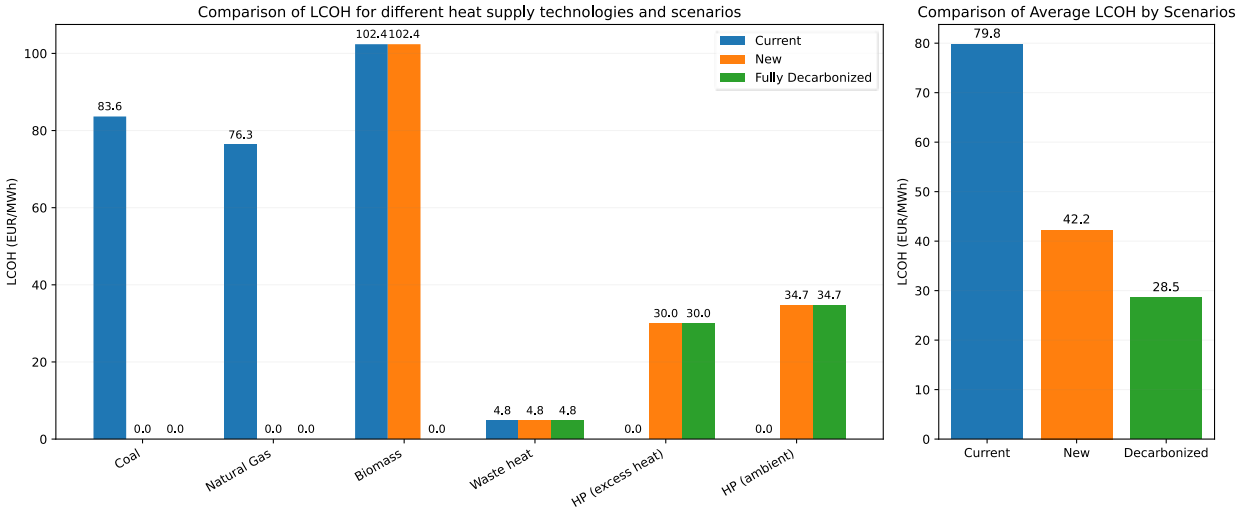


Figure 26: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for full load of 8760 operating hours

Figure 26, compares the LCoH across different heat supply technologies for full load operating hours of 8760 hours and for the three scenarios; Current, New, and Fully Decarbonized.

In the Current Scenario, fossil-based based heat supply such as coal and natural gas, has LCOH values of around 84 €/MWh and 76 €/MWh, respectively, while heat supply from biomass appears at a much higher cost of 102 €/MWh due to higher biomass prices.

In the New Scenario, with the increased share of heat pump using industrial excess heat and ambient air, coal and natural gas are phased out, while biomass remains at

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102 €/MWh. Heat supply from heat pumps using excess heat and ambient air attain LCoH values of around 30 €/MWh and 35 €/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and biomass-based heat supply are eliminated, and the system relies solely on waste heat and heat pumps. The heat supply from waste heat has a very low LCoH at ~5 €/MWh. Heat pump from industrial excess heat attains a LCoH around 30 €/MWh while ambient air heat pumps reach 35.5 €/MWh.

Finally, the comparison of average LCoH shows a clear downward trend from 80 €/MWh in the Current Scenario to 42 €/MWh in the New Scenario and dropping sharply to 29 €/MWh in the Fully Decarbonized Scenario. This highlights the shift to low-carbon and high-efficiency technologies which leads to significantly lower heating costs.

Similarly, Figure 27 compares the LCoH across different heat-supply technologies for 4000 operating hours, to address the part load operating behaviour of the technologies.

In the Current Scenario, fossil-based heat supply such as coal and natural gas, has a LCoH value of around 92 €/MWh and 77 €/MWh, respectively, while heat supply from biomass appears at a much higher cost of 113 €/MWh.

In the New Scenario, with the increased share of heat pump using industrial excess heat and ambient air, coal and natural gas are phased out, while biomass remains at 113 €/MWh. Heat supply from heat pumps using excess heat and ambient are attain a LCoH value of around 39 €/MWh and 45 €/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and biomass-based heat supply are eliminated, and the system relies solely on waste heat and heat pumps. The heat supply from waste heat has a very low LCoH at ~10 €/MWh. Heat pumps using industrial excess heat attain a LCoH around 39 €/MWh and ambient air heat pumps 45 €/MWh.

Finally, the average LCoH for 4000 operating hours, decreases a LCoH of 89 €/MWh for the Current Scenario, to 51 €/MWh in the New Scenario and 38 €/MWh in the Fully

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Decarbonized Scenario respectively when compared to the full load operating hours of all technologies.

Compared to the results presented in Figure 26, where the heat pumps operate throughout the entire year, the reduced number of operating hours results in increases in the levelized cost of heat of 6 %, 18 %, and 37 % for the Current, New, and Fully Decarbonized Scenarios, respectively.

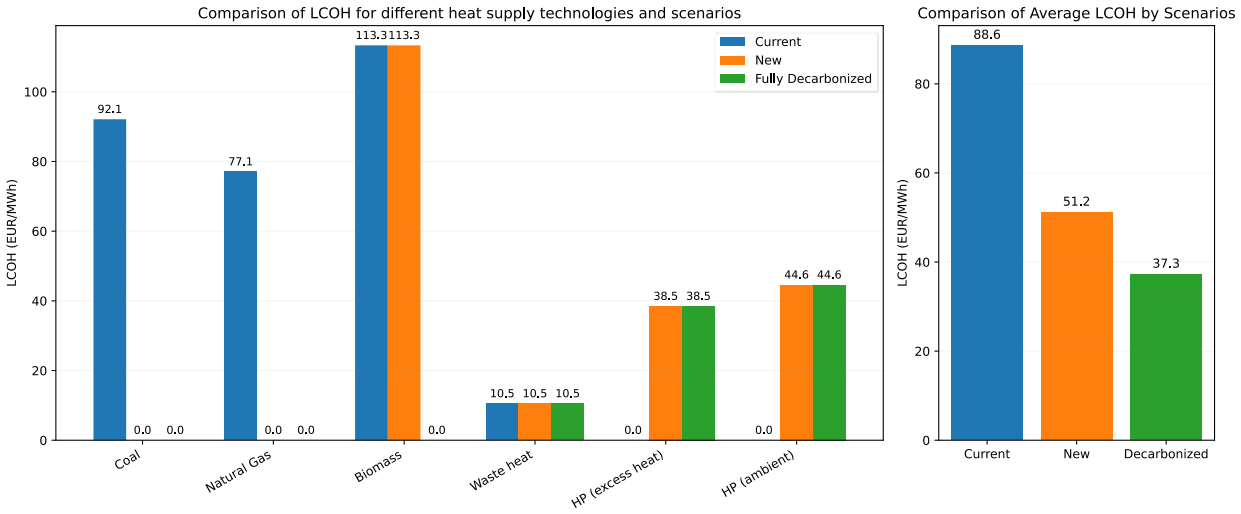


Figure 27: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for part load of 4000 operating hours

4.7 Czechia



Czechia is one of the countries with the highest district heating capacity in the EU, with around 38 $GW_{thermal}$ installed in 2023 [17]. The Installed district heating capacity over the last eight years is shown in Table 25. District heat covers around 38 %,

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corresponding to approximately 1671 MW, of the total heat demand in residential and service sectors [16]. Prague, Ostrava, Hradec Kralove, Plzeň and Brno are the five largest district heating networks in Czechia [19], with heat demands of 323 MW, 131 MW, 55 MW, 58 MW, and 101 MW, respectively. The forward and return temperature of the transmission and distribution networks are shown in

Table 26 [27]. The Transmission network with has a forward and return temperature of up to 135 °C and 60 °C respectively. The distribution network has a forward and return temperature of up to 125 °C and 50 °C, respectively.

Table 25: District Heating Installed Capacity Czechia

Installed capacity (GW_{th})	2018	2021	2022	2023
	42,6	39	38.1	38

Table 26: Transmission and Distribution Network Temperatures

Temperature level	Transmission Network (°C)	Distribution Network (°C)
Forward temperature	135	125
Return temperature	60	50

Table 27, shows the energy-mix of district heat generation over the past eight years. For the year 2023, like Poland, the primary energy-mix of Czechia is primarily fossil fuels of which coal accounts for approximately 51 % and natural gas around 28 %. Only 18 % is currently covered by renewables with biomass accounting for approximately 12 % and waste heat for approximately 5 %.

Therefore, to decarbonize the district heating generation a large share of renewables such as solar thermal, high-temperature heat pumps, geothermal or biomass should be integrated. The integration of high-temperature heat pumps could be a favourable option due of the existing utilization of waste heat in the current network.

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Table 27: Energy Source Mix in the Generation of District Heat

Energy source	2018	2021	2022	2023
Coal	60 %	56 %	60.4 %	51 %
Natural gas	25 %	28 %	29 %	28 %
Oil	-	-	-	-
Biomass	5 %	12.6 %	7.4 %	12 %
Waste heat	-	3 %	3 %	5 %
Solar	-	-	-	-
Geothermal	-	-	-	-
Heat pump & E-boiler	-	-	-	-
Other	10 %	-	-	-

4.7.1 Decarbonization Strategies

a) Assessment of Industrial excess heat

The evaluation of industrial excess heat starts by estimating the minimum heat source temperature required by the high-temperature heat pump. To identify the viable heat sources - such as industrial excess heat, ambient air, or seawater that are suitable to utilize as heat source for the heat pump.

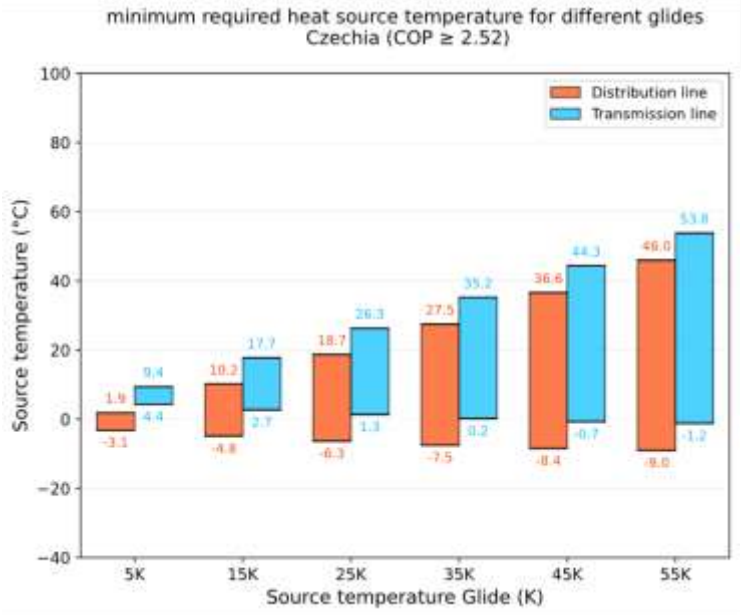


Figure 28: Minimum Required Heat Source Temperature

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The required minimum heat source temperature for a high-temperature heat pump integrated in the Czech district heating network is shown in Figure 28.

It is estimated that for a low glide heat source the required minimum heat source temperature is approximately 10 °C for the transmission network and approximately 2 °C for the distribution network. For a high glide heat source, the required heat source temperature increases to approximately 54 °C transmission network and approximately 46 °C for distribution network. The relatively low temperature requirements enhance the feasibility of utilizing ambient air or seawater as heat sources. Utilization of high-grade industrial waste heat will result in higher economic savings and energy efficiency.

Based on the PETA map [1], the total recoverable industrial excess heat in Czechia after maximum internal heat recovery has been estimated. For Czechia, this results in a Level 1 estimate of approximately 13 PJ per year (406 MW). Of this, approximately 6 PJ per year can be recovered above 55 °C (Level 2) and 5 PJ per year above 95 °C (Level 3).

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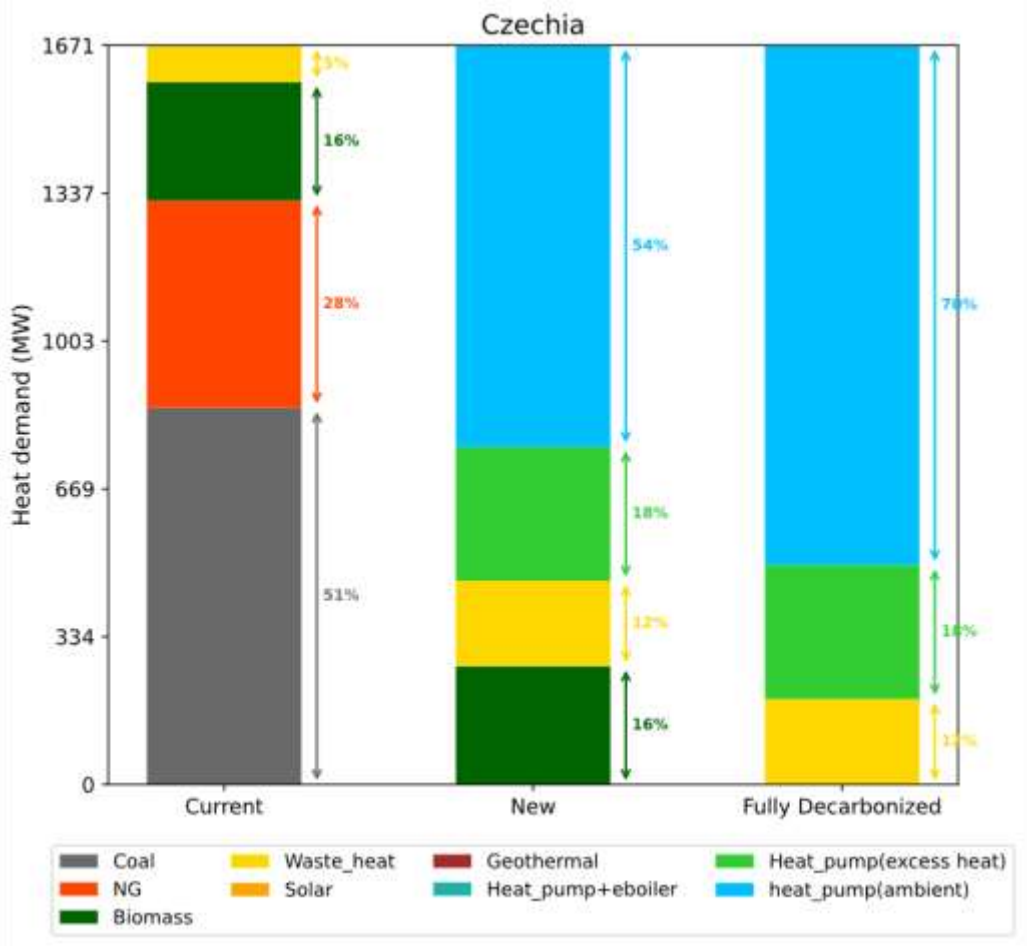


Figure 29: Decarbonization strategy for the transition of Czechia's district heating generation

Figure 29, shows the decarbonization strategy for Czechia under the three scenarios defined in Section 2.1.

In the New Scenario, direct utilization of waste heat covers approximately 193 MW, corresponding to about 12 % of the heat demand. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 use approximately 212 MW of excess heat as heat source and, with an average COP of 3.35, cover about 18 % of the heat demand. Together, these sources cover only about 30 % of the heat demand, while fossil fuels currently supply around 79 %. Ambient-air heat pumps therefore play a vital role: with an average COP of 2.7, approximately 907 MW (54 % of the heat demand) is required to eliminate fossil fuels, while biomass is maintained at around 16 %.

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In the Fully Decarbonized Scenario, direct waste heat (12 %) and excess heat pumps (18 %) are fully exploited, and the remaining 70 % of the heat demand must be supplied by ambient-air heat pumps to eliminate biomass. These heat pumps can achieve an average COP of 2.7, which is above the minimum economic COP of 2.52 for Czechia.

b) Economic assessment

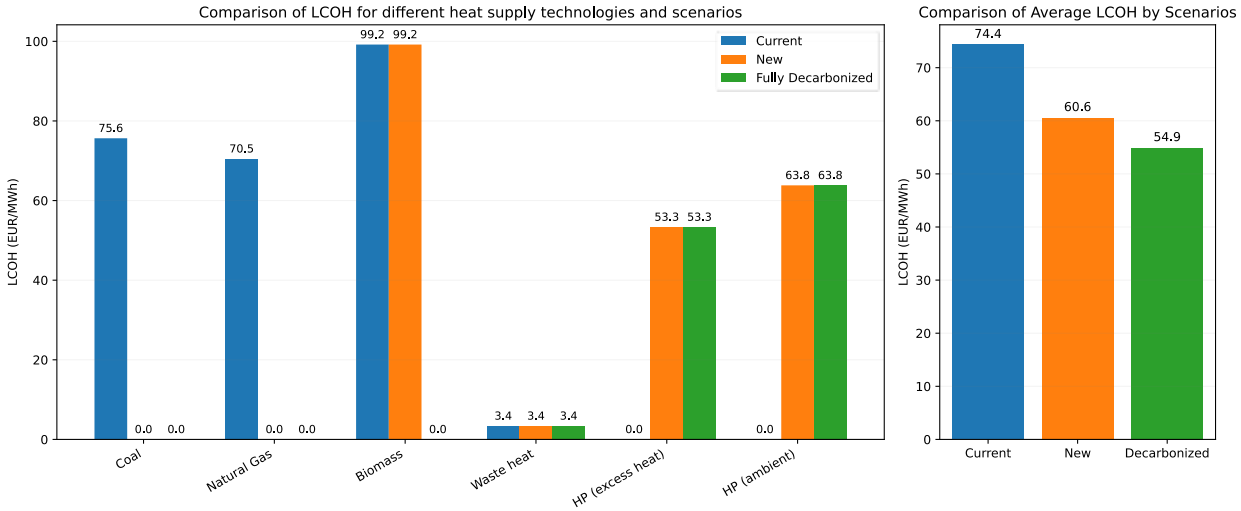


Figure 30: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for full load of 8760 operating hours

Figure 30, compares the LCoH across different heat supply technologies for full load operating hours of 8760 hours and for the three scenarios; Current, New, and Fully Decarbonized.

In the Current Scenario, fossil-based heat supply such as coal and natural gas, has a LCoH value of around 76 €/MWh and 71 €/MWh, respectively. Heat supply from biomass appears at a much higher cost of 99 €/MWh due to higher biomass prices.

In the New Scenario, with the increased share of heat pumps using industrial excess heat and ambient air, the use of coal and natural gas are phased out, while biomass remains at 99 €/MWh. Heat supply from heat pumps using excess heat and ambient air attain LCoH values of around 53 €/MWh and 64€/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and biomass are eliminated, and the system relies solely on waste heat and heat pumps. The heat supply with waste heat

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has very low LCoH at ~5 €/MWh, while heat pumps using industrial excess heat attain a LCoH of around 53 €/MWh and ambient air heat pumps 64 €/MWh.

Finally, the comparison of average LCoH shows a downward trend from 74 €/MWh in the Current Scenario to 61 €/MWh in the New Scenario and dropping to 55 €/MWh in the Fully Decarbonized Scenario. This highlights the shift to low-carbon and high-efficiency technologies which leads to significantly lower heating costs.

Similarly, Figure 31, compares the LCoH across different heat-supply technologies for 4000 operating hours, to address the part load operating behaviour of the technologies.

In the Current Scenario, fossil-based based heat supply such as coal and natural gas, has a LCOH values of around 81 €/MWh and 71 €/MWh, respectively, while heat supply from biomass appears at a much higher cost of 106 €/MWh due to the high biomass prices.

In the New Scenario, with the increased share of heat pumps using industrial excess heat and ambient air, the use of coal and natural gas are phased out, while biomass remains at 106 €/MWh. Heat supply from heat pumps using excess heat and ambient air attain a LCoH values of around 58 €/MWh and 70 €/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and biomass are eliminated, and the system relies solely on waste heat and heat pumps. The heat supply with waste heat has a very low LCoH at ~7 €/MW. Heat pumps using industrial excess heat attain a LCoH around 58 €/MWh and ambient air heat pumps 70 €/MWh.

Finally, for 4000 operating hours per year, the average levelized cost of heat in the Current Scenario was 79 €/MWh. This value was reduced to 61 €/MWh in the New Scenario and 60 €/MWh in the Fully Decarbonized Scenario. Compared to the results presented in Figure 30, where the heat pumps operate throughout the entire year, the reduced number of operating hours results in increases in the levelized cost of heat of 4 %, 8 %, and 27 % for the Current, New, and Fully Decarbonized Scenarios, respectively.

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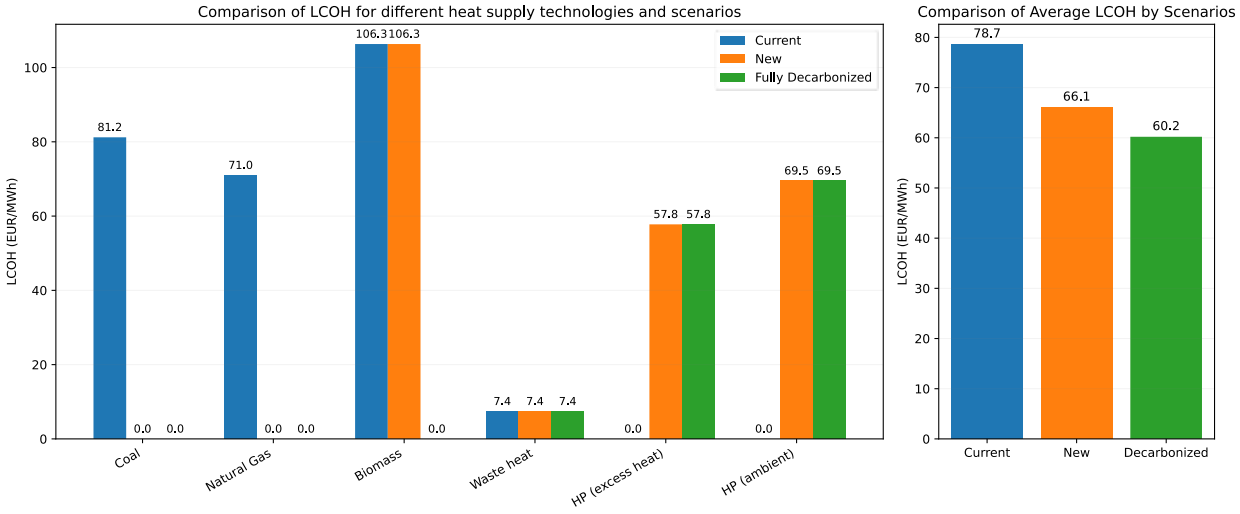


Figure 31: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for part load of 4000 operating hours

4.8 Italy



Italy is one of the EU countries with the least installed district heating capacity. Approximately 9.7 $GW_{thermal}$ was installed in 2023 [17], covering only 2 % of the heat demand for the residential and service sectors [16]. Milan, Turin, Regio Emillia, Naples and Rome are the largest district heating networks in Italy according to PETA [19], with heat demand of 99 MW, 25 MW, 33 MW, 46 MW, and 32 MW respectively. The forward and return temperature of the transmission and distribution network are shown in Table 29 [16]. The transmission network has a forward and return temperature of up to 90 °C and 60 °C, respectively. The distribution network has a forward and return temperature of up to 80 °C and 50 °C, respectively.

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Table 28: District Heating Installed Capacity Italy

Installed capacity (GW_{th})	2018	2021	2022	2023
	8.9	9.2	9.5	9.7

Table 29: Transmission and Distribution Network Temperatures

Temperature level	Transmission Network (°C)	Distribution Network (°C)
Forward temperature	90	80
Return temperature	60	50

Table 30, shows the energy-mix in the generation of district heating over the last eight years. In 2023, Italy's district heating network was primarily driven by the combustion of natural gas, covering approximately 62 % of the heat demand. The remaining demand is covered by renewables, where biomass accounts for 23 %, waste heat for around 9 %, Geothermal for around 2.1 %, and heat pumps & E-boilers for approximately 2 %.

The low network operating temperatures and with the high share of industrial waste and excess heat within the current network makes the high-temperature heat pump an attractive choice as a means to decarbonize the district heating sector and reduce the dependency on fossil fuels.

Table 30: Energy Source Mix in the Generation of District Heat

Energy source	2018	2021	2022	2023
Coal	2 %	-	-	-
Natural gas	70 %	66 %	67 %	63 %
Oil	1 %	-	-	-
Biomass	10 %	21 %	20.5 %	23 %
Waste heat	15 %	9.2 %	7 %	9 %
Solar	-	-	-	-
Geothermal	1 %	2.8 %	5.2 %	2.1 %
Heat pump & E-boiler	1 %	0.9 %	0.9 %	1.9 %
Other	-	-	-	-

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4.8.1 Decarbonization Strategies

a) Assessment of Industrial excess heat

The evaluation of industrial excess heat starts by estimating the minimum heat source temperature required by the high-temperature heat pump. To identify the viable heat sources - such as industrial excess heat, ambient air, or seawater that are suitable to utilize as heat source for the heat pump.

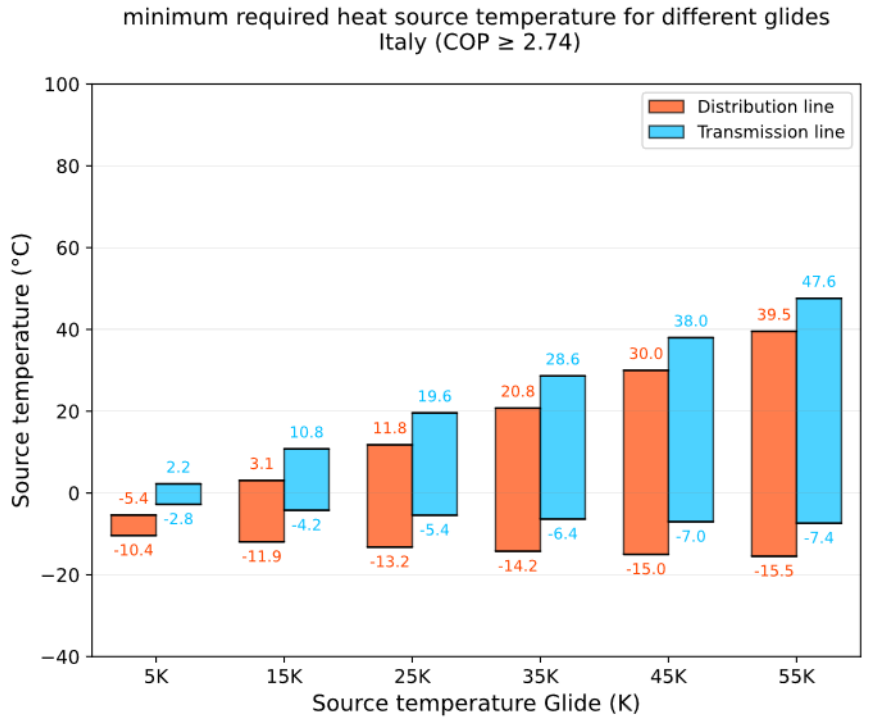


Figure 32: Minimum Required Heat Source Temperature

The high-temperature heat pump integrated within the DH network can either be centralized or decentralized, either on the Transmission network level (typically higher operating temperature) or distribution network level (typically lower operating temperature). Therefore, the minimum heat source temperature required by the heat pump integrated within the district heat network is estimated based on the equation in Section 2 and depicted in Figure 32.

The required minimum heat source temperature for a high-temperature heat pump integrated in the Italian district heating network is shown in Figure 32.

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With the minimum economic COP of 2.74, it is estimated that the temperature requirements for a low glide heat source is approximately 2 °C for the transmission network and approximately-5 °C for the distribution network. For a high glide heat source, the temperature requirement increases to approximately 50 °C for the transmission network and approximately 40 °C for the distribution network. The relatively low temperature requirements enhance the feasibility of utilizing low-grade heat sources such as ambient air or seawater. Utilization of high-grade industrial waste heat will result in higher economic savings and energy efficiency.

Based on the PETA map [1], the total recoverable industrial excess heat in Italy after maximum internal heat recovery has been estimated. For Italy, this results in a Level 1 estimate of approximately 70 PJ per year (2222 MW). Of this, approximately 25 PJ per year can be recovered above 55 °C (Level 2) and 18 PJ per year above 95 °C (Level 3).

The current share of district heating only covers 2 % of the total heat demand in the residential and service sector, corresponding to approximately 538 MW out of the total demand of 26,914 MW. With the direct utilization of industrial excess heat available above 95 °C (Level 3), approximately 573 MW can be recovered, which is sufficient to supply the current district heating demand of 538 MW. Considering the expected future expansion of district heating in Italy, a district heating share of approximately 20 % is assumed for the analysis of the decarbonization potential and LCoH calculations.

Figure 33, shows the decarbonization strategy for Italy under three scenarios defined in Section 2.1.

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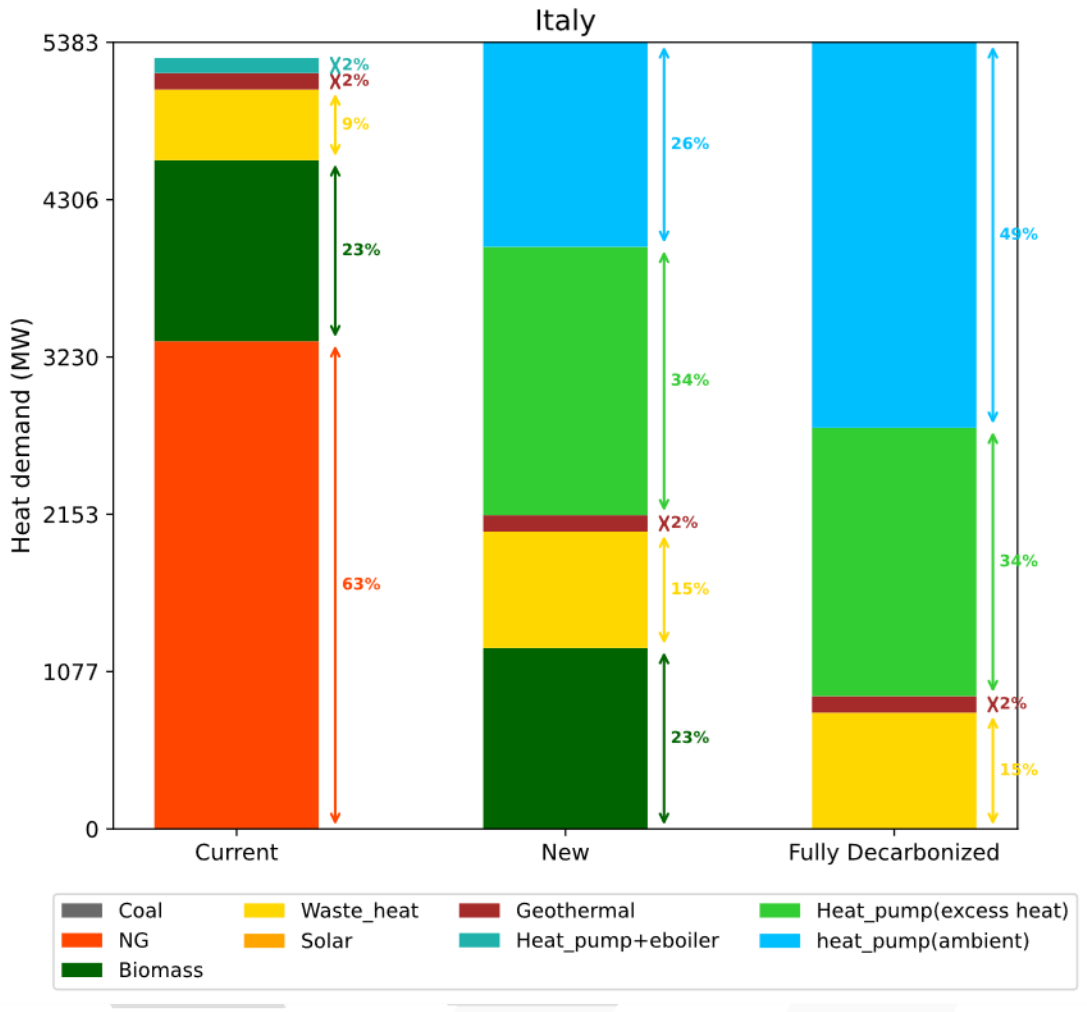


Figure 33: Decarbonization strategy for the transition of Italy's district heating generation

In the New Scenario, direct utilization of waste heat covers approximately 796 MW, corresponding to about 15 % of the heat demand. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 use approximately 1426 MW of excess heat as heat source and, with an average COP of 4.48, cover about 34 % of the heat demand.

As natural gas currently supplies around 63 % of district heat, these two sources together (about 49 % of the heat demand) are not sufficient to replace it entirely. Ambient-air heat pumps therefore cover approximately 26 % of the heat demand with an average COP of 3.21, while biomass is maintained at around 23 % and geothermal at around 2 %.

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In the Fully Decarbonized Scenario, ambient-air heat pumps must cover approximately 49 % of the heat demand, in addition to direct waste heat and excess heat pumps, to eliminate biomass and fully decarbonize the energy mix. These heat pumps achieve an average COP of 3.21, which is above the minimum economic COP of 2.74 for Italy.

b) Economic assessment

Figure 34, compares the LCoH across different heat supply technologies for full load operating hours of 8760 hours and for the three scenarios; Current, New, and Fully Decarbonized.

In the Current Scenario, natural gas and biomass are the main source of heat generation, with LCoH values around 61 €/MWh and 102 €/MWh, respectively. A small amount of waste heat is also applied, with a LCoH of around 4.3 €/MWh.

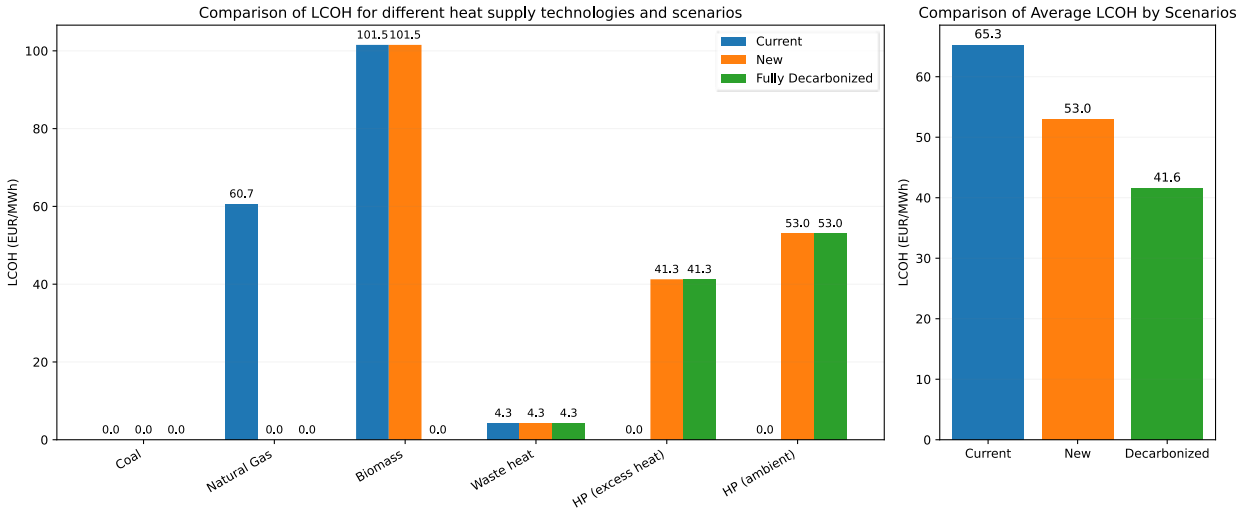


Figure 34: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for full load of 8760 operating hours

In the New Scenario, with the increased share of heat pump using industrial excess heat and ambient air, the use of coal and natural gas are phased out, while biomass remains at 102 €/MWh, and heat supply from heat pumps using excess heat and ambient air attain a LCoH of around 41 €/MWh and 53.5 €/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and biomass are eliminated, and the system relies solely on waste heat and heat pumps. The heat supply with waste heat

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has a very low LCoH at ~4.3 €/MWh. Heat pump using industrial excess heat attain a LCoH around 41 €/MWh and ambient air heat pumps 53.5 €/MWh.

Finally, the comparison of average LCoH shows a downward trend from 65 €/MWh in the Current Scenario to 53 €/MWh in the New Scenario and dropping to 41 €/MWh in the Fully Decarbonized Scenario. This highlights the shift to low-carbon and high-efficiency technologies which leads to significantly lower heating costs.

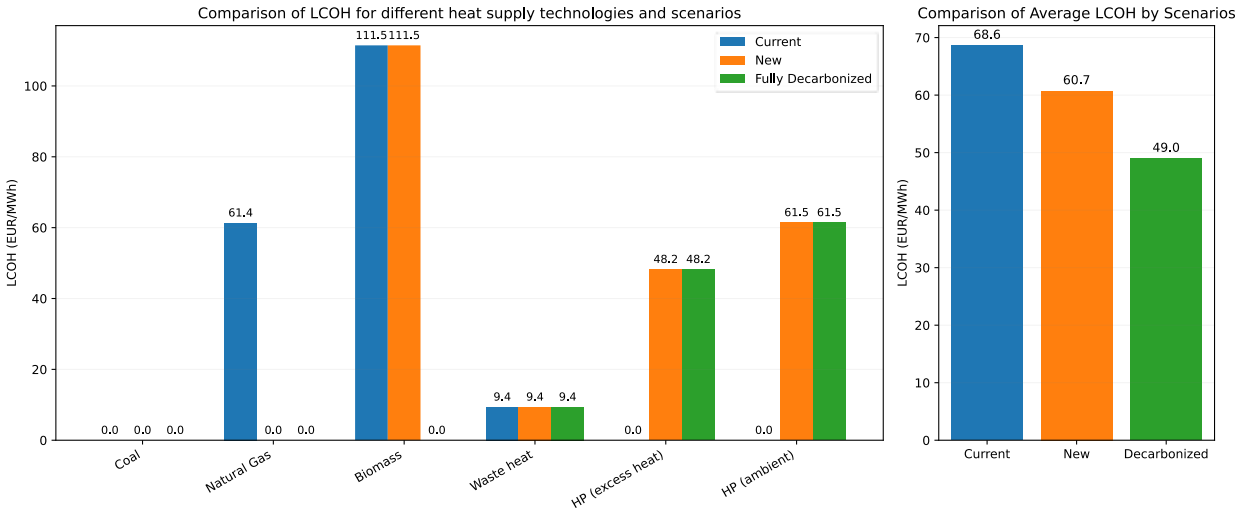


Figure 35: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for part load of 4000 operating hours

Similarly, Figure 35, compares the LCoH across different heat-supply technologies for 4000 operating hours, to address the part load operating behaviour of the technologies.

In the Current Scenario, the LCoH of natural gas and biomass are around 61 €/MWh and 112 €/MWh respectively.

In the New Scenario, with the increased share of heat pumps using industrial excess heat and ambient air, the use of coal and natural gas are phased out, while biomass remains at 112 €/MWh. Heat supply from heat pumps using excess heat and ambient air attain LCoH values of around 48 €/MWh and 62 €/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and biomass are eliminated, and the system relies solely on waste heat and heat pumps. The heat supply with waste heat has a very low LCoH at ~9 €/MWh. Heat pumps using industrial excess and ambient

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source heat pumps attain a LCoH like New Scenario of approximately 48 €/MWh and 62 €/MWh, respectively.

Finally, for 4000 operating hours per year, the average levelized cost of heat in the Current Scenario was 67 €/MWh. This value was reduced to 61 €/MWh in the New Scenario and 49 €/MWh in the Fully Decarbonized Scenario. Compared to the results presented in Figure 34, where the heat pumps operate throughout the entire year, the reduced number of operating hours results in increases in the levelized cost of heat of 6 %, 22 %, and 39 % for the Current, New, and Fully Decarbonized Scenarios, respectively.

4.9 Sweden



Sweden has the second highest share of district heating in the EU, covering approximately 58 % of the heat demand for the residential and service sectors, corresponding to approximately 3162 MW [16]. The total installed capacity of district heating was approximately 27.9 $GW_{thermal}$ in 2022 as shown in Table 31. Stockholm, Gothenburg, Linköping, and Malmö are the five largest district heating networks with heat demands of 913 MW, 398 MW, 73 MW, and 220 MW, respectively [19]. The forward and return temperature of the transmission and distribution networks are as shown in Table 32 [16]. The transmission network has a forward and return temperature of up to 100 °C and 50 °C, respectively, while the distribution network has a forward and return temperature of up to 90 °C and 40 °C, respectively.

Table 31: District Heating Installed Capacity Sweden

Installed capacity (GW_{th})	2018	2021	2022	2023
	-	-	27.9	-

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Table 32: Transmission and Distribution Network Temperatures

Temperature level	Transmission Network (°C)	Distribution Network (°C)
Forward temperature	100	90
Return temperature	50	40

The energy-mix in the generation of District heat over the period is shown in Table 33. Sweden is the only country which is already utilizing a high share of renewables and only 3 % district heating generation was from fossil fuels in the year 2023. Here, coal accounted for around 2 % and natural gas for approximately 1 %. The energy-mix is mainly dependent on biomass of around 63 %, direct waste heat utilization of around 27 %, and heat pumps and E-boiler of around 8 %.

The low network operating temperature and with the high share of industrial waste and excess heat within the current network, highlights the technical and economic feasibility to increase the share of heat pumps. Thus, eliminating the need for fossil fuel utilization in the generation of district heating.

Table 33: Energy Source Mix in the Generation of District Heat

Energy source	2018	2021	2022	2023
Coal	6 %	1.3 %	-	2 %
Natural gas	2 %	1.4 %	1.7 %	1 %
Oil	3 %	-	-	
Biomass	39 %	76 %	64 %	63 %
Waste heat	33 %	13.6 %	28 %	27 %
Solar	-	-	-	-
Geothermal	-	-	-	-
Heat pump & E-boiler	10 %	8 %	6 %	8 %
Other	7 %	-	-	-

4.9.1 Decarbonization Strategies

a) Assessment of Industrial excess heat

To integrate a heat pump within the district heat network the temperature and availability of heat source is a prerequisite. Therefore, the assessment starts with the estimation of minimum heat source temperature required by the high-temperature

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heat pump for feasible technical and economic integration. Thereby, identifying the viable heat sources - such as industrial excess heat, ambient air, or seawater that are suitable to utilize as heat source for the heat pump.

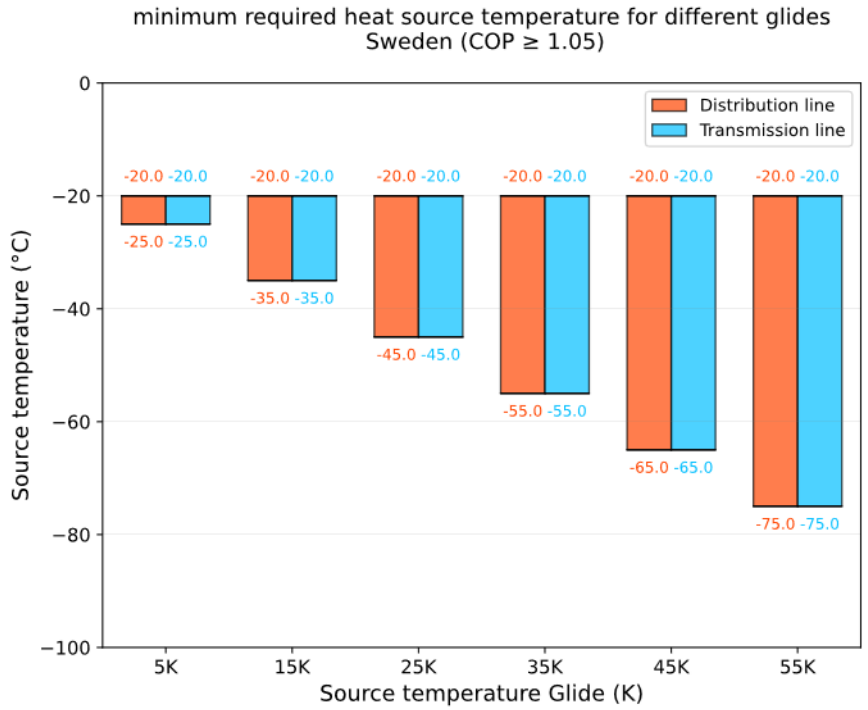


Figure 36: Minimum Required Heat Source Temperature

The required minimum heat source temperature for a high-temperature heat pump integrated in the Swedish district heating network is shown in Figure 36.

Like Finland, the price of natural gas and electricity are almost the same and which infers a low minimum economic COP. The minimum economic COP of Sweden is around 1.05.

For a high-temperature heat pump integrated in the Swedish district heating network, it is estimated that heat source temperatures below 0 °C are both technically and economically viable regardless of the heat source glide. Therefore, heat sources such as ambient air, seawater or low-temperature industrial excess heat can be used as potential heat sources.

Based on the PETA map [1], the total recoverable industrial excess heat in Sweden after maximum internal heat recovery has been estimated. For Sweden, this results in a Level 1 estimate of approximately 35 PJ per year (1110 MW). Of this, approximately 12 PJ

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per year can be recovered above 55 °C (Level 2) and 8 PJ per year above 95 °C (Level 3).

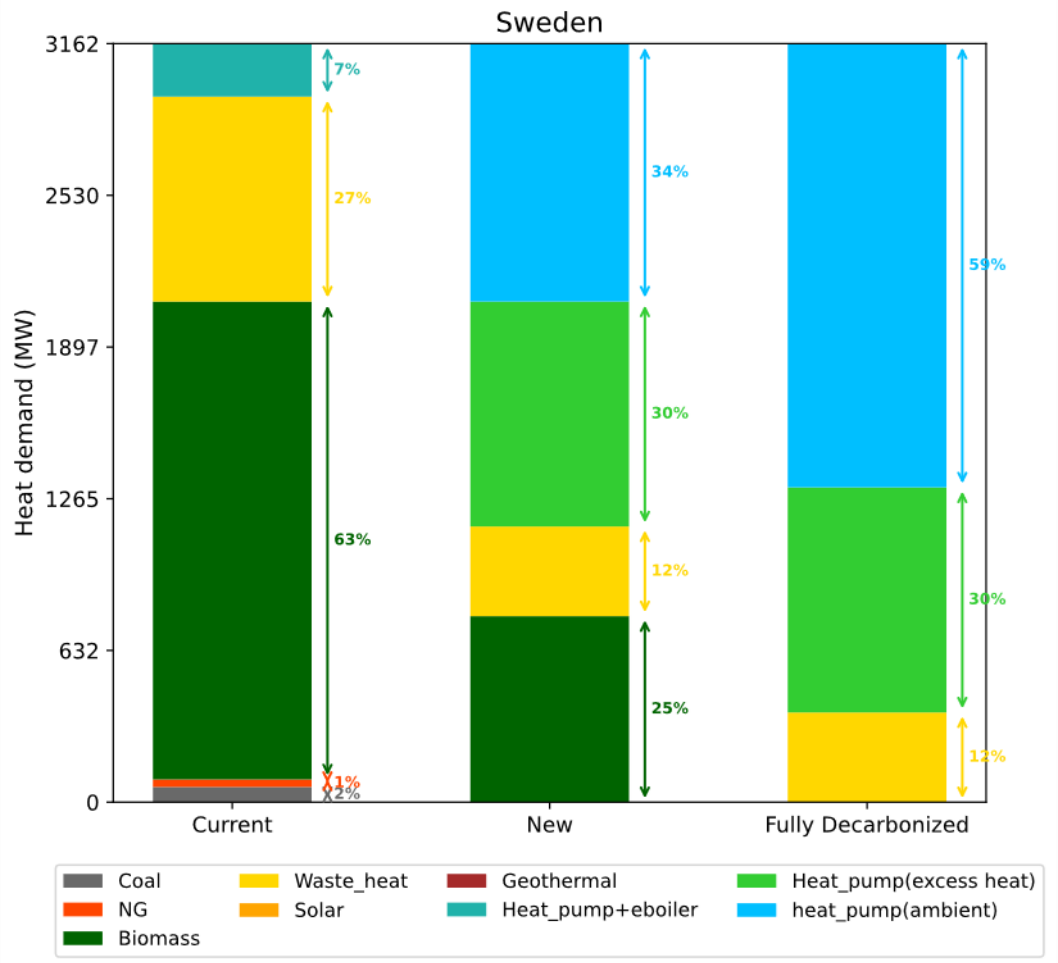


Figure 37: Decarbonization strategy for the transition of Sweden's district heating generation

Figure 37, shows the decarbonization strategy for Sweden under three scenarios defined in Section 2.1.

In the New Scenario, direct utilization of waste heat covers approximately 374 MW, corresponding to about 12 % of the heat demand. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 use approximately 735 MW of excess heat as heat source and, with an average COP of 4.64, cover about 30 % of the heat demand. Ambient-air heat pumps cover a further 34 %, which eliminates fossil fuels from the energy mix, while the share of biomass is reduced from 63 % to 25 %.

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In the Fully Decarbonized Scenario, ambient-air heat pumps must cover approximately 59 % of the heat demand, in addition to direct waste heat and excess heat pumps, to eliminate biomass and fully decarbonize the energy mix. These heat pumps can achieve an average COP of 3.26, well above the minimum economic COP of 1.05 for Sweden.

b) Economic assessment

Figure 38, compares the LCoH across different heat-supply technologies under three scenarios—Current, New, and Fully Decarbonized, and shows the average LCoH for each scenario. In the Current Scenario, fossil-based based heat supply such as coal and natural gas, has LCOH values of around 88.9 €/MWh and 81.6 €/MWh, respectively, while heat supply from biomass appears at a much higher cost of 100 €/MWh due to higher biomass prices.

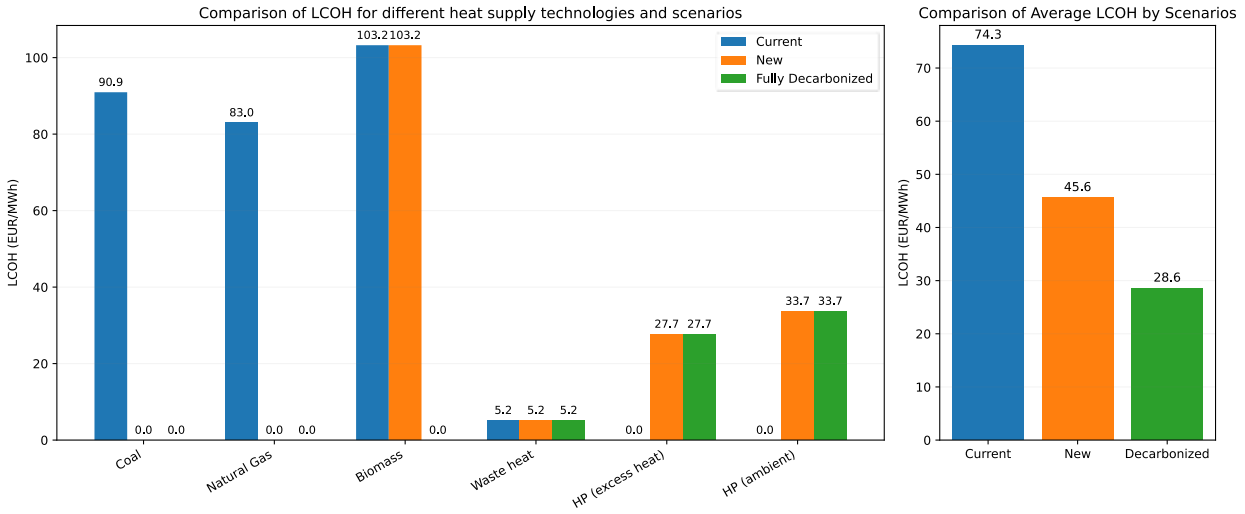


Figure 38: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for full load of 8760 operating hours

In the New Scenario, with the increased share of heat pump using industrial excess heat and ambient air, coal and natural gas are phased out, while biomass remains at 103 €/MWh. Heat supply from heat pumps using excess heat and ambient heat attain LCoH values of around 28 €/MWh and 34 €/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and biomass-based heat supply are eliminated, and the system relies on solely on waste heat and heat pumps. The heat supply with waste heat has a very low LCoH at ~5 €/MWh, while heat pumps using

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industrial excess heat attains a LCoH of around 28 €/MWh and ambient air heat pumps 34 €/MWh.

Finally, the comparison of average LCoH shows a clear downward trend from 74 €/MWh in the Current Scenario to 46 €/MWh in the New Scenario and dropping to 29 €/MWh in the Fully Decarbonized Scenario. This highlights the shift to low-carbon and high-efficiency technologies which leads to significantly lower heating costs.

Similarly, Figure 39, compares the LCoH across different heat-supply technologies for 4000 operating hours, to address the part load operating behaviour of the technologies.

In the Current Scenario, fossil-based heat supply such as coal and natural gas, has LCoH values of around 100 €/MWh and 84 €/MWh, respectively, while heat supply from biomass appears at a much higher cost of 115 €/MWh.

In the New Scenario, direct utilization of waste heat covers approximately 374 MW, corresponding to about 12 % of the heat demand. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 use approximately 735 MW of excess heat as heat source and, with an average COP of 4.64, cover about 30 % of the heat demand. Ambient-air heat pumps cover a further 34 %, which eliminates fossil fuels from the energy mix, while the share of biomass is reduced from 63 % to 25 %.

In the Fully Decarbonized Scenario, ambient-air heat pumps must cover approximately 59 % of the heat demand, in addition to direct waste heat and excess heat pumps, to eliminate biomass and fully decarbonize the energy mix. These heat pumps can achieve an average COP of 3.26, well above the minimum economic COP of 1.05 for Sweden.

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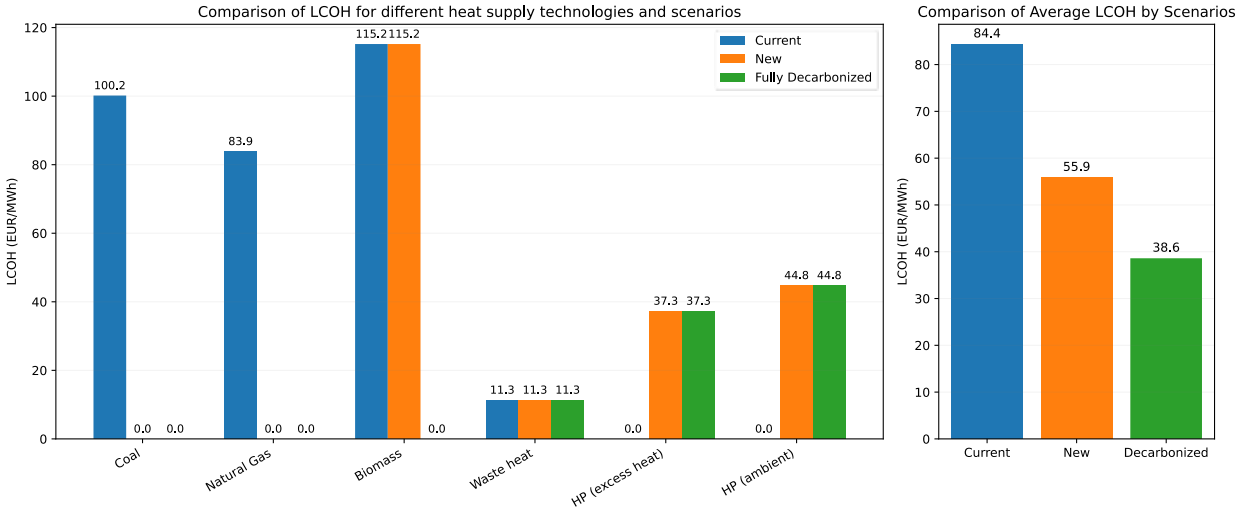


Figure 39: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for part load of 4000 operating hours

Finally, for 4000 operating hours per year, the average levelized cost of heat in the Current Scenario was 84 €/MWh. This value was reduced to 56 €/MWh in the New Scenario and 39 €/MWh in the Fully Decarbonized Scenario. Compared to the results presented in Figure 38, where the heat pumps operate throughout the entire year, the reduced number of operating hours results in increases in the levelized cost of heat of 6 %, 20 %, and 43 % for the Current, New, and Fully Decarbonized Scenarios, respectively.

4.10 Slovakia



Slovakia is one of the EU countries with least installed District heating capacity of approximately 11.97 $GW_{thermal}$ in 2023 [17], and with high share of District heat in the total heat demand of Residential and Service sectors of about 41 % approximately 625 MW

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[16]. Košice, Bratislava, Žilina, and Trnava are the high heat demand density network in Slovakia with heat demand of 43 MW, 94 MW, 26 MW, and 19 MW respectively according to PETA [19]. The Forward and Return temperature of the Transmission and Distribution network is shown in Table 35, estimated from Low2HighDH [28]. The Transmission network with maximum Forward and Return temperature of up to 130 °C and 60 °C respectively, and the distribution network with maximum Forward and Return temperature of up to 120 °C and 50 °C respectively.

Table 34: District Heating Installed Capacity Slovakia

Installed capacity (GW_{th})	2018	2021	2022	2023
	15	11.97	11.97	11.97

Table 35: Transmission and Distribution Network Temperatures

Temperature level	Transmission Network (°C)	Distribution Network (°C)
Forward temperature	130	120
Return temperature	60	50

The energy-mix in the Slovakian district heating networks is shown in Table 36. Similarly to Poland, Germany, Czechia and Italy, the energy-mix for district heating generation in Slovakia, is mainly comprised of fossil fuels of which coal accounts for approximately 25 % and natural gas for around 50 %. Further, biomass accounts for approximately 25 %.

As the majority of district heating generation in Slovakia depends on fossil fuels, an intensive and high share of renewables are required for the decarbonization of district heating generation. This may be achieved by increasing the share of biomass, direct utilization of waste heat, high-temperature heat pumps, solar thermal, geothermal etc. Waste heat integration offers two main pathways: direct waste heat utilization and the integration of excess heat as a heat source for high-temperature heat pumps, this is elaborated in the following sections.

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Table 36: Energy Source Mix in the Generation of District Heat

Energy source	2018	2021	2022	2023
Coal	26 %	23 %	23.4 %	25 %
Natural gas	54 %	55.5 %	58.5 %	50 %
Oil	11 %	-	-	-
Biomass	9 %	21.5 %	18 %	25 %
Waste heat	-	-	-	-
Solar	-	-	-	-
Geothermal	-	-	-	-
Heat pump & E-boiler	-	-	-	-
Other	-	-	-	-

4.10.1 Decarbonization Strategies

a) Assessment of Industrial excess heat

A high-temperature heat pump integrated within the district heating network; the temperature and availability of heat source are necessary. Therefore, the assessment begins with the estimation of minimum heat source temperature required by the high-temperature heat pump for feasible technical and economic integration. Thereby identifying the viable heat sources - such as industrial excess heat, ambient air, or seawater that are suitable to utilize as heat source for the heat pump.

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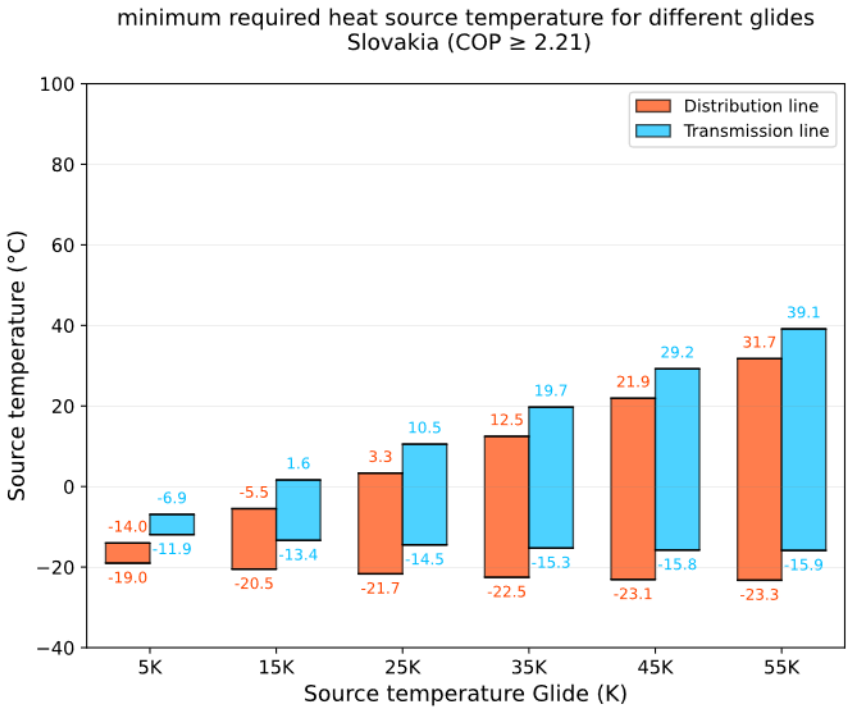


Figure 40: Minimum Required Heat Source Temperature

The required minimum heat source temperature for high-temperature heat pumps integrated in the Slovakian district heating network is shown in Figure 40.

With a minimum economic COP of 2.21, a heat pump integrated within the Slovakian district heating networks may be a viable solution even with heat source temperatures below 0 °C. Thus, allowing the utilization of ambient heat sources such air or water.

For a low glide heat source, the required minimum heat source temperature is approximately -7 °C for the transmission network and approximately -15 °C distribution network. For a high glide heat source, the temperature requirements are increase to 40 °C transmission network and 32 °C for the distribution network.

From the results it is estimated that the Slovakian DH network can be decarbonized by increasing the share of renewables, particularly high-temperature heat pumps supplied by low-grade heat sources, including ambient air or seawater, while still ensuring technically and economically viable integration.

Based on the PETA map [1], the total recoverable industrial excess heat in Slovakia after maximum internal heat recovery has been estimated. For Slovakia, this results in a Level 1 estimate of approximately 9 PJ per year (289 MW). Of this, approximately 4.5 PJ

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per year (142 MW) can be recovered above 55 °C (Level 2) and 3.5 PJ per year (111 MW) above 95 °C (Level 3).

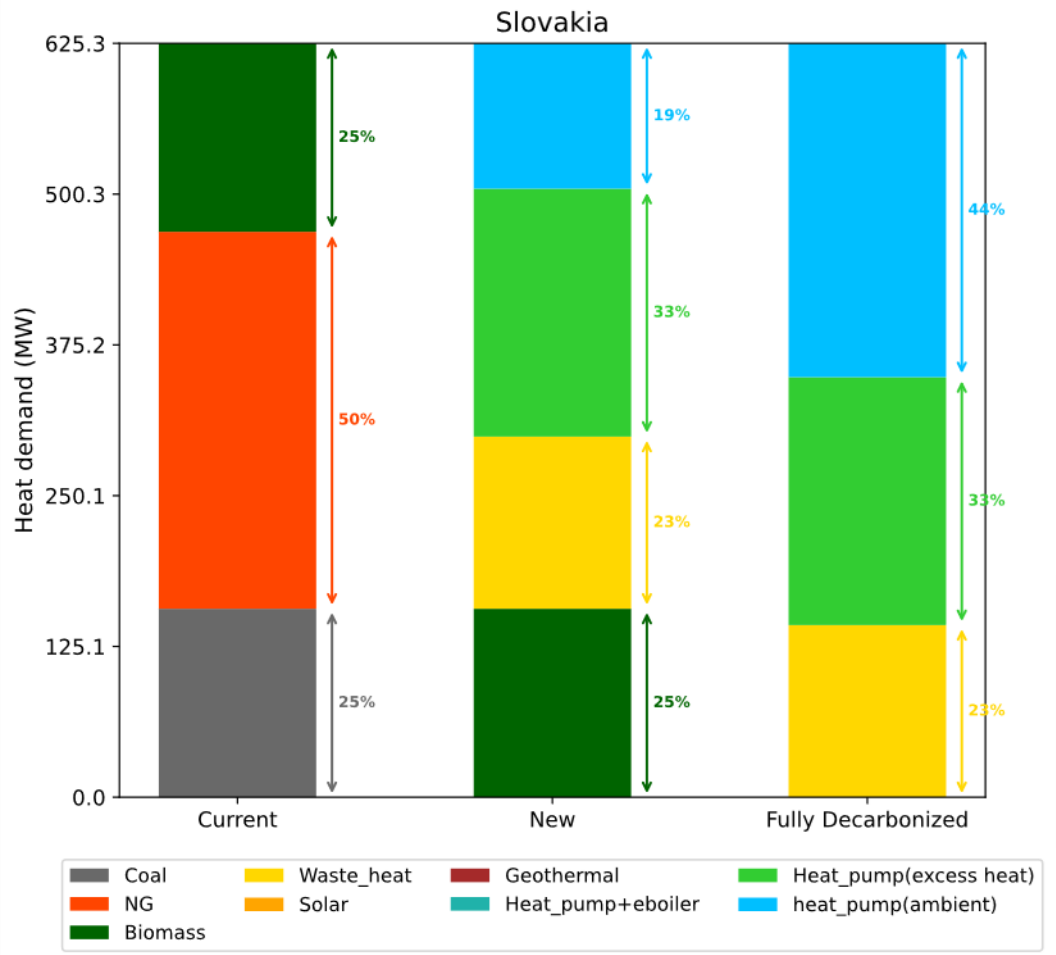


Figure 41: Decarbonization strategy for the transition of Slovakia's district heating generation

Figure 41, shows the decarbonization strategy for Slovakia under three scenarios defined in Section 2.1.

In the New Scenario, direct utilization of waste heat covers approximately 142 MW, corresponding to about 23 % of the heat demand. Heat pumps upgrading industrial excess heat from Level 2 to Level 1 use approximately 145 MW of excess heat as heat source and, with an average COP of 3.44, cover about 33 % of the heat demand.

As coal (25 %) and natural gas (50 %) currently supply 75 % of district heat, these two sources together (about 56 % of the heat demand) are not sufficient to replace all

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fossil fuels. Ambient-air heat pumps therefore cover approximately 19 % of the heat demand with an average COP of 2.73, while biomass is maintained at around 25 %.

In the Fully Decarbonized Scenario, ambient-air heat pumps must cover approximately 44 % of the heat demand, in addition to direct waste heat and excess heat pumps, to eliminate biomass and fully decarbonize the energy mix. These heat pumps can achieve an average COP of 2.73, which is above the minimum economic COP of 2.21 for Slovakia.

In the Fully Decarbonized Scenario, in addition to the direct waste heat utilization and industrial excess heat heat pumps, approximately 44 % of the heat demand must be met by ambient air heat pumps to fully eliminate biomass and decarbonize the energy mix. Even with ambient heat sources, a heat pump COP of 2.73 can be achieved.

b) Economic assessment

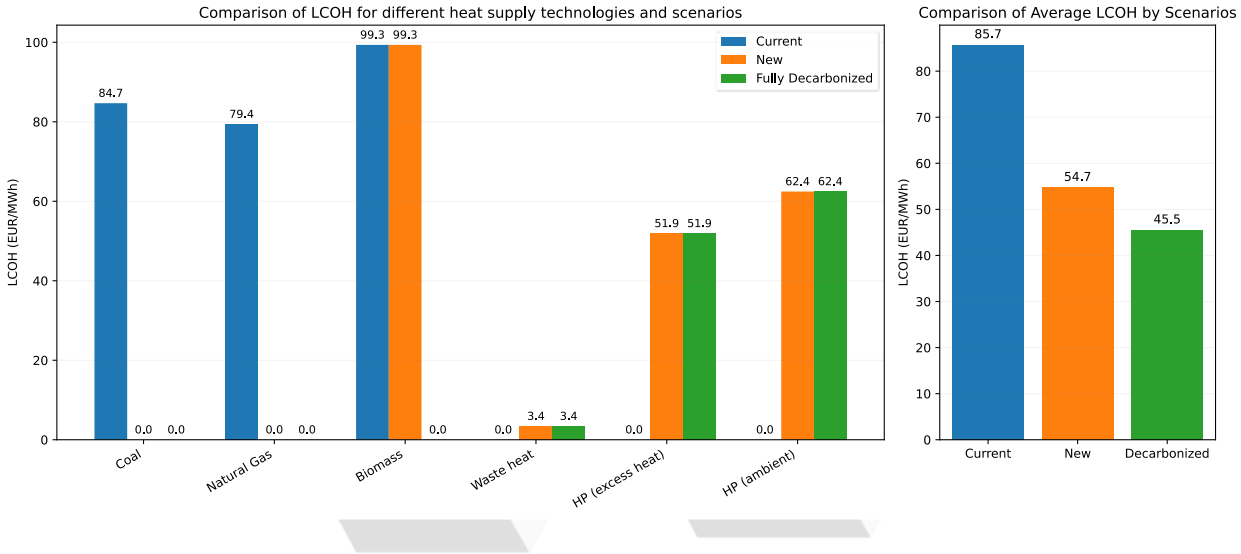


Figure 42: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for full load of 8760 operating hours

Figure 42, compares the LCoH across different heat supply technologies for full load operating hours of 8760 hours and for the three scenarios; Current, New, and Fully Decarbonized.

In the Current Scenario, fossil-based based heat supply such as coal and natural gas, has LCOH values of around 85 €/MWh and 80 €/MWh, respectively, while heat supply

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from biomass appears at a much higher cost of 99 €/MWh due to higher biomass prices.

Finally, the comparison of average LCoH shows a clear downward trend from 86 €/MWh in the Current Scenario to 55 €/MWh in the New Scenario and dropping to 46 €/MWh in the Fully Decarbonized Scenario. This highlights the shift to low-carbon and high-efficiency technologies which leads to significantly lower heating costs.

Similarly, Figure 43, compares the LCoH across different heat-supply technologies for 4000 operating hours, to address the part load operating behaviour of the technologies.

In the Current Scenario, fossil-based heat supply such as coal and natural gas, has LCoH values of around 91 €/MWh and 80 €/MWh, respectively, while heat supply from biomass appears at a much higher cost of approximately 107 €/MWh.

In the New Scenario, with the increased share of heat pumps using industrial excess heat and ambient air, the use of coal and natural gas are phased out, while biomass remains at 107 €/MWh. Heat supply from heat pumps using excess heat and ambient air attain a LCoH of around 56 €/MWh and 68 €/MWh, respectively.

In the Fully Decarbonized Scenario, fossil fuels and biomass-based heat supply are eliminated, and the system relies solely on waste heat and heat pumps. The heat supply from waste heat has a very low LCoH at ~7.1 €/MWh, while heat pump utilizing industrial excess heat attains a LCoH of around 56 €/MWh and ambient air heat pumps 68 €/MWh.

Finally, for 4000 operating hours per year, the average levelized cost of heat in the Current Scenario was 89 €/MWh. This value was reduced to 60 €/MWh in the New Scenario and 61 €/MWh in the Fully Decarbonized Scenario. Compared to the results presented in Figure 42, where the heat pumps operate throughout the entire year, the reduced number of operating hours results in increases in the levelized cost of heat of 3 %, 8 %, and 13 % for the Current, New, and Fully Decarbonized Scenarios, respectively.

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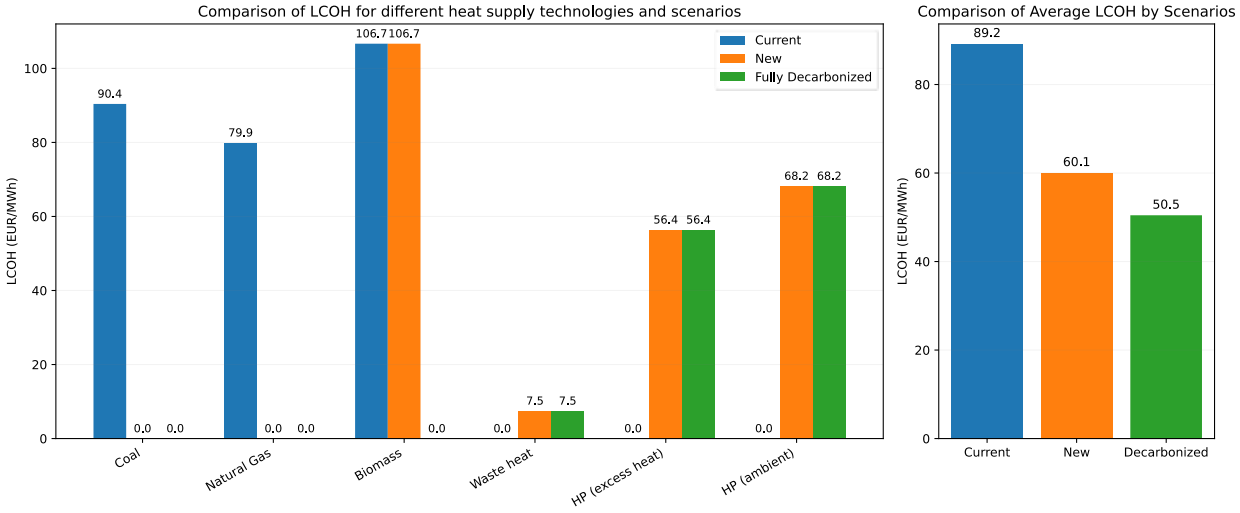


Figure 43: Comparison of LCoH Across Heat Supply Technologies and Decarbonization Scenarios for part load of 4000 operating hours

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5. CONCLUSION

This study has assessed the opportunities for integrating high-temperature heat pumps and industrial excess heat into district heating systems across ten European countries with widely varying energy mixes, heat demands, and network characteristics. The results demonstrate that substantial decarbonization of district heating can be achieved through the systematic recovery and upgrading of industrial excess heat, complemented by ambient-source heat pumps where necessary.

A key finding is that the viability of heat pump integration is highly dependent on both network operating temperatures and energy prices. Countries with lower district heating temperatures generally exhibit lower minimum heat source temperature requirements and higher achievable heat pump efficiencies. Nevertheless, even countries operating higher-temperature district heating systems can benefit significantly from industrial excess heat integration when sufficient source temperatures are available. This confirms that HTHPs can serve as an effective bridge between existing high-temperature district heating infrastructure and future low-carbon heating systems.

The analysis further highlights the strategic importance of industrial excess heat. Large volumes of recoverable heat are available throughout Europe, particularly from chemical production, refineries, metallurgy, and energy-intensive manufacturing sectors. Much of this heat is currently rejected to the environment despite being technically suitable for district heating applications. The results indicate that direct utilization of higher-temperature excess heat should be prioritized wherever possible due to its exceptionally low cost, while lower-grade excess heat can be economically upgraded by HTHPs.

From an economic perspective, the transition away from fossil fuels is not associated with increased heat supply costs. On the contrary, the majority of evaluated countries demonstrate significant reductions in average levelized cost of heat under the decarbonization scenarios. Heat supplied from industrial excess heat and heat pumps is generally found to be more cost-competitive than heat generated from biomass and, in many cases, fossil fuels. This finding suggests that industrial heat recovery can create a rare alignment between economic and environmental objectives.

The study also demonstrates that no single decarbonization pathway is universally applicable. Countries such as France and Austria possess sufficient industrial excess

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heat resources to achieve near-complete decarbonization with limited reliance on ambient-source heat pumps, whereas countries such as Denmark, Finland, Sweden, Poland, Czechia, and Slovakia require a combination of industrial excess heat and large-scale ambient heat recovery. Consequently, future district heating strategies should be tailored to national and regional resource availability rather than relying on a uniform technology portfolio.

In conclusion, high-temperature heat pumps offer a robust, flexible, and economically attractive solution for accelerating the decarbonization of European district heating systems. The technology enables effective utilization of industrial excess heat resources, reduces reliance on fossil fuels and biomass, and supports the transition toward electrified energy systems. Continued deployment of HTHPs, together with supportive regulatory frameworks, industrial-sector cooperation, and investments in district heating infrastructure, will be critical for unlocking the full potential of industrial heat recovery and achieving Europe's long-term climate objectives.

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