

Balancing heat saving and supply in local energy planning: Insights from 1970-1989 buildings in three European countries

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ABSTRACT

This study investigates the cost balance between heat energy savings through building envelope retrofits and supply from low-carbon decentralised and centralised technologies in a generic urban district, composed of residential and non-residential buildings from the 1970–1989 construction period. For generalisability, the district is analysed in three European countries (Bulgaria, Germany, Finland), each with distinct weather conditions and price levels. Using bottom-up energy modelling and adopting a societal perspective that includes external costs, the study finds the cost-effectiveness of retrofits to be context-specific. In Bulgaria, retrofits prove largely cost-effective, whereas in Germany and Finland, high labour and material costs pose challenges. Heat pumps, whether decentralised in buildings or centralised in district heating systems, emerge as key options for heat supply, even in cold climates. The study underscores the importance of integrated energy planning in line with the ‘energy efficiency first’ principle and corresponding incentive structures to promote sustainable urban energy systems.

1. Introduction

1.1. Background

Urban areas play a critical role in the European Union’s (EU) transition towards a net-zero emissions energy system. About 75% of the EU’s population currently lives in urban areas [1], a figure expected to rise to 84% by 2050 [2]. Through local energy planning, municipal decision-makers can contribute to fossil-free urban energy systems, job creation, and other energy-related objectives [3–5].

In this context, residential and non-residential buildings are key, given their life cycles of 40–100 years [6] and their share of 40% in EU-wide final energy consumption [7]. Significant thermal energy saving potential exists for building envelope upgrades - especially for existing buildings, of which at least 75% are expected to still exist by 2050 [8]. Resulting heat savings can reduce the size and associated investment required for both centralised district heating (DH) and decentralised heating solutions, as well as related infrastructures for heat, electricity, and gas [9,10]. Hence, combinations of measures on the building envelope and technical systems can create synergies that lead to better outcomes regarding costs and energy performance than

single measures [11].

With the ‘energy efficiency first’ (EE1st) principle laid down in the Governance Regulation [12], the EU aims to systematically prioritise energy efficiency solutions (e.g., building retrofits) whenever these cost less or provide more value to society than energy supply (e.g., DH system expansion) in meeting consumers’ energy service needs. The principle can help avoid lock-in to long-lived energy infrastructures, ensure that energy service needs are met using the least-cost alternatives available, and thus contribute to a cost-efficient decarbonisation of the EU [13]. As such, the concept of EE1st is closely related to that of smart energy systems [14,15], as both concepts aim to combine and coordinate technological and behavioural solutions to achieve an optimal solution for the whole energy system.

1.2. State of research

As urban planners become more engaged in energy planning, they require robust modelling tools to support local energy strategy development and decision-making. The research literature features over 100 modelling tools for urban-to regional-scale energy system analysis [16], as described in a variety of review articles [17–23]. These tools differ in

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terms of purpose, technologies and energy end-uses considered, and levels of temporal and spatial detail.

A research line particularly relevant in the context of the EE1st principle deals with the techno-economic balance of energy savings and energy supply options [9,10,24–36]. For example, analysing the city of Brasov (Romania), Büchele et al. [27] show that heat savings of 58–78% compared to existing levels are more cost-effective than all assessed heat supply options. Similarly, for the case of Copenhagen (Denmark), Harrestrup and Svendsen [29] find that it is slightly cheaper to invest in thermal retrofits that reduce heat demand by 65% before deploying new renewable DH supply. These studies generally indicate that reductions in building energy demand up to a certain level could involve lower overall cost than the expansion of energy supply options alone. This underscores the relevance of integrated urban energy planning in line with both the EE1st principle and smart energy systems.

However, some research gaps remain. Many of the above studies apply only to a selected context with specific climate conditions, energy resource potentials, and price levels [24–31]. In turn, relatively few studies apply the same approach to multiple contexts [9,10,32–36], highlighting the need for systematic comparative analysis. Moreover, in terms of heating options, some of the studies focus exclusively on either centralised DH systems [25,26,29,31] or decentralised building-integrated solutions [30,33], requiring integrated analysis to include all potentially cost-effective options. Finally, most studies focus on the private internal costs borne by building owners or utility companies [10,24–27,29,30,32–35]. Apart from occasional adjustments to discount rates, they frequently overlook the societal perspective [37], also known as macroeconomic [11], that encompasses external costs such as air pollution. Incorporating the full societal implications of energy supply and savings options is fundamental to the EE1st concept, as it forms a normative benchmark for informed energy planning and policy-making [13].

1.3. Research objectives

Understanding the synergies between heat savings and supply in urban areas is crucial to determine sustainable, technically robust, and economically viable system configurations. This study aims to inform public policy through the application of spatially resolved building energy modelling. The analysis focuses on identifying potentially cost-efficient combinations of (i) building envelope renovation packages, (ii) decentralised heat supply, and (iii) centralised DH options.

For this purpose, a hypothetical case study is devised, featuring a generic urban district composed of residential, commercial, and educational buildings from the 1970–1989 construction period in need of major renovation - concerning both building envelopes and technical heating systems.¹ This situation prompts a benevolent urban planner in the year 2020 to determine which options (i-ii) should be prioritised. In evaluating these options, the study adopts a societal perspective, considering society's time preference and explicitly including external costs from direct greenhouse gas (GHG) and air pollution emissions, to align with broader socio-environmental interests.²

To account for the geophysical and economic heterogeneity across the EU, the generic urban district is analysed for country-specific conditions in Bulgaria (BG), Germany (DE), and Finland (FI). Differences

¹ For the reference year 2020, the choice of the 1970–1989 period was justified by the typical 30–50 year renovation cycle of buildings [11]. Additionally, this construction period represents around 28% of the EU dwelling stock [38].

² GHG and air pollution emissions are not only classic externalities [39] but also significant multiple impacts in the energy efficiency discussion [37,40]. For the EU building sector in 2030, their monetary value has been estimated at 0.11 times the value of energy cost savings for GHG and 0.25 times for air pollution emissions [41].

thus result from climate conditions, current building energy performance, and price levels.³ Given the hypothetical setting, the study addresses the question of how much the energy for space heating should be reduced through building retrofits and how it should be supplied in a building stock from the 1970–1989 construction period. In a sensitivity analysis, particular attention is paid to critical assumptions, such as the effect of supply temperatures on heat pump performance.

This study is structured as follows. Section 2 describes the methodology. Section 3 provides the numerical results. Section 4 discusses the methodological limitations and policy implications of the study. Finally, Section 5 concludes the study and suggests future research directions.

2. Methodology

The methodology adopted in this study is visualised in Fig. 1, comprised of four steps. First, a generic urban district is defined (Section 2.1), which is analysed across the countries BG, DE, and FI. Second, the energy need for heating is calculated for each building within the urban district, according to three renovation packages (Section 2.2). Third, the costs of these renovation packages, as well as the costs of both decentralised and centralised heat supply options are determined (Section 2.3). Finally, cost-efficient combinations of these options are calculated (Section 3).

2.1. Definition of generic urban district

The generic urban district is characterised as a municipally owned city district of 15 ha, built in the 1970–1989 construction period and inspired by the real district 'Citypark' in Karlsruhe, Germany.⁴ It comprises 125 buildings ranging from 1 to 7 storeys, with a peak occupancy of around 11,000 people. As shown in Table 1, eight building use types are assumed in the district.

The City Energy Analyst (CEA) model⁵ [45,46] is used to generate a digital elevation model of the building topography in the generic urban district (Fig. 2). The resulting building geometry data (footprint area, height, orientation) serves as an input for calculation of heating energy needs (Section 2.2). Based on OpenStreetMap [47], the CEA model also endogenously provides data on road lengths, which are relevant for the estimation of feasible district heating networks (Section 2.3).

2.2. Renovation packages and energy need for heating

The balance between building renovation and heating systems is examined by defining three renovation packages with varying energy performance requirements⁶

- **EXISTING:** No thermal retrofits are applied. Buildings undergo usual refurbishment to maintain aesthetics, functionality, and safety, but without affecting thermal energy performance.

³ To illustrate these aspects, average heating degree days (2010–2020) range from 2432 (BG) to 5390 (FI) [42]. Average useful energy demand for space heating in residential buildings ($kWh/(m^2yr)$) ranges from 59 (BG) to 196 (FI) [43]. The consumer price level index for energy ($EU_{27} = 100$) is between 56 (BG) and 120 (DE) [44].

⁴ Location: 49°00'08.3"N 8°25'02.5"E.

⁵ CEA is a Python-based open-source model framework for the analysis and optimisation of energy systems in neighbourhoods and city districts [45]. This study uses CEA version 3.31.

⁶ As per [9,48], 'retrofits' are here understood as the process of enhancing building energy performance, e.g., through insulation. 'Refurbishments', in turn, involve maintaining or upgrading building aesthetics, functionality, and safety without targeting energy performance. Lastly, 'renovation' comprises both retrofits and refurbishments.

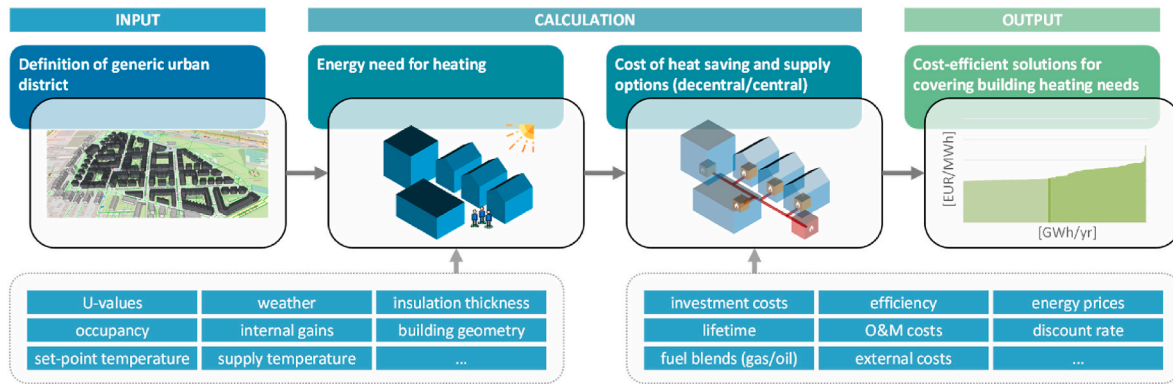


Fig. 1. Methodology for determining cost-efficient combinations of building renovation measures and heat supply options.

Table 1

Characterisation of generic urban district by building use type.

Use type	Conditioned floor area		Peak occupancy	
	[m ²]	[%]	[people]	[%]
Apartment	181,716	79.6%	5681	51.3%
Grocery store	1168	0.5%	41	0.4%
Hotel	1761	0.8%	102	0.9%
Library	6584	2.9%	1536	13.9%
Office	30,884	13.5%	2057	18.6%
Restaurant	2282	1.0%	133	1.2%
Retail shop	979	0.4%	27	0.2%
School	2988	1.3%	1494	13.5%
Total	228,361	100.0%	11,071	100.00%

- **STANDARD:** Light retrofit packages are applied to roofs, windows, walls, and floors, resulting in effective energy savings and reduced need for heat supply.
- **ADVANCED:** Deep retrofit packages, reflecting the best available options, are implemented to significantly improve building energy performance.

The thermo-physical properties of the individual buildings are based on the reference buildings of the TABULA building typologies [49–51], selecting multi-family buildings from around the 1970–1989 period. Table 2 presents the thermal heat transfer coefficients (U-value, W/(m²·K)) and the added insulation thickness (cm) for each renovation package. The specific costs are described in Section 2.3.

To calculate the energy need for heating [11] associated with the defined renovation packages, the CEA model is applied to each of the

125 buildings defined in Section 2.1. As detailed in Refs. [46,52], the model computes heating needs using an hourly single-zone resistance-capacitance model based on EN ISO 13790:2008 [53]. This essentially takes into account (a) heat losses from ventilation and transmission, and (b) heat gains from occupancy, solar radiation, and internal loads.

For this purpose, the model determines hourly occupancy schedules for the building use types listed in Table 2, utilising a dedicated occupant presence model described in Ref. [54]. This results in hourly ventilation rates, along with consumption values for appliances, lighting, and other energy services that affect internal gains, as summarised in Table A 1. Solar heat gains are estimated in CEA based on hourly solar irradiation, topographic obstructions by surrounding buildings and atmospheric effects [52]. Weather files representing a typical meteorological year (2007–2021) for the locations of Sofia (BG), Berlin (DE), and Helsinki (FI) are obtained in EnergyPlus Weather (.epw) format from Ref. [55].

Boundary conditions across countries and renovation packages are given in Table A 2. Specifically, the set-point temperature in all buildings is set to 20 °C [56]. Heating temperatures affect the performance of heat pumps (Section 2.3). In EXISTING buildings, radiators with nominal supply/return temperatures of 70 °C/55 °C are assumed [57]. The original radiators are preserved in each renovation package. Due to lower heat loads and given typically oversized radiators in 1970–1989 buildings [56,57], nominal temperatures in STANDARD and ADVANCED renovations are reduced to 60 °C/50 °C and 55 °C/45 °C, respectively, without compromising thermal comfort [57,58]. Floor heating installation is not incorporated, given its potentially prohibitive renovation costs [59].

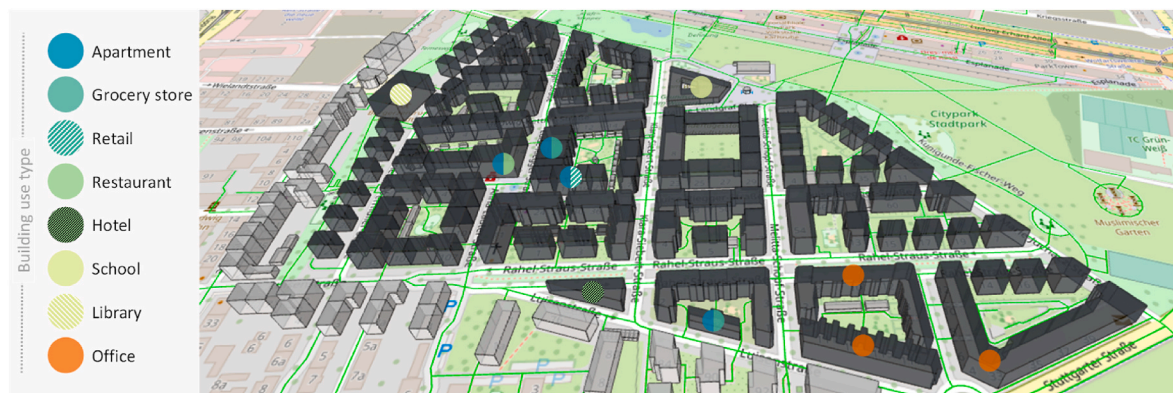


Fig. 2. Digital elevation model of the urban district by building use type. Unless otherwise indicated, all shaded buildings are multi-family apartment buildings.

Table 2
Building characteristics by country, package and element.

Element by U-value [W/m^2K] Insulation added [cm] Specific investment costs [EUR_{2020}/m^2]					
Country	Package	Roof	Wall	Floor	Window
Bulgaria	EXISTING	0.59 W/m^2K - -	0.93 W/m^2K - -	1.29 W/m^2K - -	2.63 W/m^2K - -
	STANDARD	0.26 W/m^2K 8 cm 29.18 EUR/m^2	0.31 W/m^2K 8 cm 38.06 EUR/m^2	0.38 W/m^2K 7 cm 17.52 EUR/m^2	1.40 W/m^2K - 79.80 EUR/m^2
	ADVANCED	0.26 W/m^2K 8 cm 29.18 EUR/m^2	0.31 W/m^2K 8 cm 38.06 EUR/m^2	0.27 W/m^2K 10 cm 19.14 EUR/m^2	0.80 W/m^2K - 109.29 EUR/m^2
Germany	EXISTING	0.43 W/m^2K 6 cm -	0.80 W/m^2K - -	0.65 W/m^2K - -	3.00 W/m^2K - -
	STANDARD	0.17 W/m^2K 12 cm 57.40 EUR/m^2	0.21 W/m^2K 12 cm 81.15 EUR/m^2	0.26 W/m^2K 8 cm 33.98 EUR/m^2	1.30 W/m^2K - 159.41 EUR/m^2
	ADVANCED	0.09 W/m^2K 30 cm 68.63 EUR/m^2	0.12 W/m^2K 24 cm 109.70 EUR/m^2	0.20 W/m^2K 12 cm 38.04 EUR/m^2	0.80 W/m^2K - 205.65 EUR/m^2
Finland	EXISTING	0.17 W/m^2K - -	0.33 W/m^2K - -	0.27 W/m^2K - -	2.04 W/m^2K - -
	STANDARD	0.09 W/m^2K 20 cm 58.52 EUR/m^2	0.21 W/m^2K 5 cm 60.49 EUR/m^2	0.21 W/m^2K 4 cm 28.06 EUR/m^2	0.90 W/m^2K - 184.23 EUR/m^2
	ADVANCED	0.05 W/m^2K 50 cm 76.08 EUR/m^2	0.08 W/m^2K 30 cm 116.30 EUR/m^2	0.20 W/m^2K 45 cm 67.14 EUR/m^2	0.76 W/m^2K - 196.37 EUR/m^2

U-values and insulation thickness based on [49–51], using Sweden as proxy for Finland | Specific investment costs based on linear functions in Table A 3, expressed per m^2 of component area; including materials, labour and professional fees; excluding general refurbishment costs (scaffolding, paint works, etc.) (Footnote 6).

2.3. Cost calculation

This section outlines the cost metrics for building renovation (Section 2.3.1), decentralised (2.3.2), and centralised heat supply (2.3.3), as well as related energy (2.3.4) and external costs (2.3.5). The analysis explicitly employs a societal perspective [13,37]. Following standard cost-benefit analysis [60–62], this evaluation perspective features a low discount rate here set at 2 %/yr, excludes taxes and subsidies as financial transfers within society, incorporates external costs in the form of climate and air pollution damages, and expresses present values in real terms (EUR_{2020}), excluding inflation.

Apart from the building structures, the study adopts a greenfield approach [23], which disregards any existing assets such as thermal networks. It also assumes that building renovation takes place all at once, rather than in stages [63]. This corresponds to the narrative in Section 1.3 that at the time of analysis, both building envelopes and technical heating systems require significant renovation.

2.3.1. Building renovation

The specific costs of building renovation packages C_{ren} for a given country and building are calculated using Equation (1), where α is the annuity factor (1/yr) for a building element m , A is the element area (m^2), I represents the specific initial investment costs (EUR/m^2),⁷ and ΔQ denotes the useful energy savings compared to the EXISTING building state (MWh/yr). The discount rate is symbolised by δ , and the building element lifetime is indicated by n .

$$C_{ren} = \sum_m (\alpha_m \bullet A_m \bullet I_m) / \Delta Q \quad [EUR_{2020}/MWh]$$

where

$$\alpha_m = \frac{\delta}{1 - (1 + \delta)^{-n_m}} \quad [1/yr]$$

The cost calculation follows this approach.

Equation 1

1. Linear cost function parameters are obtained from Refs. [65,66] for DE in 2017 (Table A 3).⁸ For envelopes, the specific investment cost (EUR/m^2) is a function of added insulation (cm); for windows, the cost is a function of the U-value ($W/(m^2 \cdot K)$). The costs represent the sum of material costs, labour costs, and professional fees, excluding value added tax and miscellaneous charges.
2. Two adjustments are made to the data: (a) the values are transferred to BG and FI in 2017 (EUR_{2017}) using Eurostat's price level indices for construction [68]; (b) the country-specific values are then adjusted to EUR_{2020} levels using construction cost indices [69].

The resulting specific investment costs by building element are given in Table 2. In line with the 'improvement' approach in Ref. [70], these values represent the additional *retrofit* costs to improve a building's thermal performance, excluding *refurbishment* costs (see Footnote ⁶) necessary for maintaining aesthetics and functionality (scaffolding, paint works, etc.). As per EN 15459 [71], technical lifetime is set at 50 years for all insulation measures and 30 years for windows.

2.3.2. Decentralised heat supply

The specific costs for decentralised heating systems (C_{dec}) are calculated using Equation (2), dividing the present value of all expenses by the present value of energy needs for space heating (Q_H) and water heating (Q_W). I represents the initial investment costs, C_{ene} denotes energy costs (including auxiliary electricity needs), $C_{o\&m}$ refers to non-fuel-related operation and maintenance costs (inspections, cleaning, etc.), and C_{ext} stands for external costs (see Section 2.3.5). Additionally, t is the annual time step, n indicates the technology lifetime, α is the annuity factor (see Equation (1)), ρ is the energy price, and η represents the conversion efficiency.

$$C_{dec} = \left(I + \sum_{t=1}^n \frac{C_{ene,t} + C_{o\&m,t} + C_{ext,t}}{(1 + \delta)^t} \right) / \left(\frac{Q_H + Q_W}{\alpha} \right) \quad [EUR_{2020}/MWh]$$

where

$$C_{ene,t} = \rho_t \bullet \frac{Q_H + Q_W}{\eta} \quad [EUR_{2020}]$$

Equation 2

⁷ Following Commission Delegated Regulation (EU) No 244/2012 [64], this study uses the term 'initial investment costs', although it is regarded as incorrect in accounting terms, as costs represent recurrent outlays, while investments (or capital expenditures) are non-recurrent capital outlays for future returns [61].

⁸ As discussed in Ref. [65], alternative national sources for renovation costs do exist [e.g., [67]] but tend to lack internal consistency. Therefore, the study adopts a common approach based on Germany's values.

Six decentralised technologies are considered: air-water heat pumps, biomass boilers (wood pellet and wood chip variants), gas boilers, ground-water heat pumps, and oil boilers. As reported in Section 2.3.4, boilers are analysed in terms of different fuel blends for gas (natural gas, biomethane, hydrogen, synthetic methane) and oil (fuel oil, biooil, synthetic fuel).

The technology data is largely based on the Danish Energy Agency's technology catalogue [72]. It provides several observed technology variants from which linear functions for investment costs, efficiency and other variables can be derived. These functions are applied to each of the 125 buildings per renovation package, with nominal thermal capacity (kW_{th}) as the independent variable.

By default, all costs are given for Denmark in the year 2020, differentiated by equipment and installation. To transfer these costs to the case study countries, equipment costs are adjusted based on Eurostat's price level index for machinery [73]. Likewise, installation costs are adjusted based on Eurostat's labour cost levels [74]. Table 3 displays the resulting ranges for efficiency and other variables, while the complete parameters are provided in Table A 4–Table A 6.

The coefficient of performance (COP) of heat pumps (HP) at each hour h largely depends on source temperature T_{source} and sink temperature T_{sink} . These temperatures vary over the year, influenced by climate and the nominal heat supply temperatures (Section 2.2). As per [72], heat pumps are typically designed to deliver sufficient heat output Q at T_{source} above -7°C (266 K) and T_{sink} below 55°C (328 K). Below -7°C , the heat pump would not provide adequate heat. Therefore, heat pumps are modelled as bivalent systems with a backup (BU) electric heater having an efficiency η_{BU} of 100%.

Based on the principles of the Carnot cycle and the exergetic efficiency of heat pumps φ_{HP} [46], the hourly COP is derived bottom-up from the CEA model's hourly heating curves for each building, country and renovation package (Equation (3)). This process distinguishes between space and water heating due to their different temperature profiles.

$$\text{COP}_{HP,h} = \left(1 - \frac{T_{source,h}}{T_{sink,HP,h}}\right)^{-1} \cdot \varphi_{HP} \quad [-] \quad \text{Equation 3}$$

The annual performance entered as η in Equation (2) is expressed as the seasonal performance factor (SPF) [75] (Equation (4)), i.e., including the energetic performance of the backup unit. For accuracy, φ_{HP} is calibrated to the simulated SPF s for multi-family buildings in DE [75], yielding values of 0.37 for air-water and 0.41 for ground-water heat pumps.

$$\text{SPF} = \sum_h (Q_{HP,h} + Q_{BU,h}) / \sum_h \left(\frac{Q_{HP,h}}{\text{COP}_{HP,h}} + \frac{Q_{BU,h}}{\eta_{BU}} \right) \quad [-] \quad \text{Equation 4}$$

As reported in Table 3 and Table A 6, resulting mean SPF s, weighted by space and water heating needs, are in the range 2.45–3.34 for air-water and 3.19–3.88 for ground-water heat pump systems. The backup electric heater provides 1–10% of annual heat demand, depending on the country and renovation state.

Table 3
Techno-economic data for decentralised heat supply technologies.

Technology	Efficiency [-]	Investment fix [$EUR_{2020}/unit$]	Investment variable [EUR_{2020}/kW_{th}]	Lifetime [yr]	O&M fix [$EUR_{2020}/kW_{th}/yr$]
Air-water heat pump	2.45–3.34 ^c	6264–8985	353.6–452.8	16–25	148.3–257.9
Biomass boiler	0.76–0.92	6776–8925	121.9–159.4	15–25	192.7–335.1
District heating substation ^a	0.95–1.00	1798–2861	21.8–30.2	20–30	19.0–33.0
Gas boiler	0.95–1.03	1441–2152	46.1–59.7	18–30	81.7–142.0
Ground-water heat pump ^b	3.19–3.88 ^c	8957–15,105	324.9–523.6	18–40	116.1–201.9
Oil boiler	0.92–0.95	2737–3732	49.1–63.8	15–25	63.4–110.3

Aggregate ranges (min-max), see Table A 4–Table A 6 for details | ^a Indirect substation with heat exchanger [72] | ^b Shallow depth vertical collectors, assuming +30% investment cost compared to horizontal collectors solution [72] | ^c Seasonal performance factor for bivalent heat pump system with backup electric heater, see Equation 4.

2.3.3. Centralised heat supply

The costs for centralised district heating solutions are determined analogously to the decentralised solutions (Equation (2)). The main difference is that the system elements (i.e., generation, pipes, water circulation pumps, substations) are valued separately and then aggregated.

Generation technologies include heat pumps (air source, deep geothermal), electrode boilers, gas boilers, and biomass boilers (wood chips, wood pellets, straw). Combined heat and power and seasonal heat storage technologies are not considered due to complex power system interactions requiring broader system boundaries. Based on [76], investment costs and other inputs are represented as linear functions, where the independent variable is the nominal thermal capacity (MW_{th}). Table A 7–Table A 8 provide the function parameters and Table 4 summarises this data.

Centralised heat pumps are typically designed for base load. Therefore, they are modelled as bivalent systems combined with either electric, gas or biomass peak boilers. As per [76], the heat pumps are set to meet 85% of annual heat demand (MWh_{th}), which corresponds to 29–37% of the nominal thermal load (MW_{th} , see Fig. 6), resulting in lower costs compared to a monovalent setup. The performance of centralised air source heat pumps follows the same approach based on hourly heating curves as for decentralised systems (Section 2.3.3). Efficiency data for geothermal heat pumps is based on [76].

Indirect substations are considered as building connections, with costs reported in Section 2.3.2. The DH network layout, pipe diameters, and heat losses are endogenously determined in CEA. This involves a mixed-integer linear optimisation combined with a minimum spanning tree algorithm to determine the least-cost layout, subject to water pressure and velocity constraints, as detailed in Ref. [46]. Pipe costs are disaggregated by pipe diameters, listed in Table A 10. Costs are based on [45,77], using labour [74] and machinery price level indices [73,78] to infer default values to EUR_{2020} price levels in BG, DE, FI. Pipe lifetime is set at 40 years [77]. Specific investment costs for circulation pumps (EUR/MW_{ei}) are based on [77], using the same price adjustments as for substations.

2.3.4. Energy costs

Energy carrier costs are considered along two dimensions: (a) *supply scenarios* (business-as-usual, BAU vs. net-zero emissions by 2050, NET-ZERO), and (b) to account for uncertainty in energy prices, LOW and HIGH *price pathways* within these scenarios. For gas and oil, the fact that final users obtain them as mixes or blends (e.g., grid-based gas may consist of natural gas, biomethane, hydrogen, etc.) is taken into account. Consequently, fuel mixes are defined for the period 2020–2050 (Table A 11), based on [79].

Detailed prices are given in Table A 12–Table A 13 for energy and network charges, respectively. Table 5 provides a summary across countries (BG, DE, FI), supply scenarios (BAU, NET-ZERO), and price pathways (LOW, HIGH). Data is compiled from the IEA World Energy Outlook 2022 [80], the EU Reference Scenario 2020 [81], the European Commission's Clean Planet for all study [82], Eurostat [83,84], and dedicated studies for bioenergy [85,86] and synthetic fuels [87,88].

Table 4

Techno-economic data for centralised heat supply technologies.

Technology	Efficiency [–]	Investment [kEUR ₂₀₂₀ /MW _{th}]	Lifetime [yr]	O&M fix [kEUR ₂₀₂₀ /MW _{th} /yr]	O&M variable [EUR ₂₀₂₀ /MW _{th}]
Air source heat pump	3.65–4.53 ^b	490–1139	15–40	0.5–2.7	0.77–2.43
Electrode boiler	0.98–0.99	17–163	20–20	0.5–1.0	0.20–0.45
Gas boiler	0.93–1.05	23–230	25–25	0.5–2.3	0.26–1.80
Geothermal heat pump ^a	4.17–5.45 ^b	1164–3845	25–30	11.5–20.3	2.52–5.21
Straw boiler	0.88–1.04	382–977	20–35	22.2–53.8	0.25–0.79
Wood chip boiler	0.89–1.15	341–745	20–35	14.2–34.0	0.42–1.55
Wood pellet boiler	0.90–1.02	366–775	20–35	14.3–34.2	0.21–0.62

Aggregate ranges (min-max), see Table A 7–Table A 9 for details | ^a Compression heat pump with heat extraction from 1200 m depth | ^b Seasonal coefficient of performance for 85% share in annual heat demand, excluding efficiency of peak boiler.

Table 5Energy prices by energy carrier (EUR₂₀₂₀/MWh).

Energy carrier type	Energy carrier	Energy		Network
		2020	2050	2020–2050
Biomass	Straw	21.55–27.66	23.18–37.02	2.75–3.94
	Wood chips	23.88–30.65	25.70–41.03	
	Wood pellets	31.50–40.43	30.07–48.02	
Electricity	Electricity	49.93–64.14	50.24–104.80	25.90–54.90
	Biomethane	56.40–75.90	63.97–98.76	
	Hydrogen	170.72–172.57	63.80–118.67	
Gas	Natural gas	16.70–25.20	6.68–24.40	13.20–20.10
	Synthetic methane	208.82–211.08	86.85–148.56	
	Oil	70.50–94.88	79.96–123.45	
Oil	Biooil	54.09–76.16	18.81–104.85	3.44–7.61
	Oil	54.09–76.16	18.81–104.85	
	Synthetic fuel	220.26–222.64	95.07–158.28	

Aggregate ranges across countries (BG, DE, FI), supply scenarios (BAU, NETZERO), price pathways (LOW, HIGH), see Table A 12–Table A 13 for details | Prices excluding taxes/fees/levies and external costs.

These values are net of taxes, levies and external costs and are expressed in EUR₂₀₂₀ using Eurostat's consumer price index [89]. For electricity in 2020, an allowance price of 24.5 EUR/tCO₂ under the EU Emissions Trading System [90] is subtracted to avoid double-counting of climate damage costs (Section 2.3.5).

2.3.5. External costs

The external costs of heat supply are determined for air pollution and greenhouse gas emissions. These costs are based on a damage cost approach, which involves estimating the monetary value of the damages caused by specific pollutants on specific receptors [91,92]. The pollutants considered include carbon dioxide equivalents (CO₂eq), ammonia (NH₃), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), particulate matter (PM), and sulphur dioxide (SO₂). Receptors include climate, human health, biodiversity, crops, and building materials (e.g. degradation of concrete structures). The emission scope involves direct emissions within the urban district, plus upstream emissions from grid-based electricity, corresponding to the 'geographic-plus' definition in Refs. [20,93].⁹

As stated in Equation (5), external costs for a given country and heating technology at annual time step t are determined as the product of the emission factor ε [t/MWh_{th}], the value factor σ [EUR/t], and the energy use for space and water heating (see Equation (2)) for all pollutants i and receptors j .

$$C_{ext,t} = \sum_{i=1} \sum_{j=1} \left(\varepsilon_{i,t} \cdot \sigma_{i,j,t} \cdot \frac{Q_H + Q_W}{\eta} \right) \quad [\text{EUR}_{2020}] \quad \text{Equation 5}$$

Emission factors ε for different fuels (e.g., natural gas) are based on [94,95] (Table A 14). The greenhouse gas intensity of grid-based

⁹ Not considered are Scope 3 emissions, including 'grey' energy for the production of building elements [11].

electricity is derived from Refs. [81,96] for the BAU price scenario, while the NETZERO scenario supposes a 95% reduction by 2050 compared to 2020 levels. The air pollution intensity of electricity is calculated by dividing total air pollution emissions [97] by final consumption [7]. For 2050, this intensity is assumed to improve in the same way as the greenhouse gas intensity (Table A 15).

Value factors σ by air pollutant and receptor are obtained for DE from Ref. [92] (Table A 16). Unit value transfer [91] is applied for BG and FI, using an income elasticity of 0.8 in terms of PPP-adjusted GDP per capita [98]. Based on recent evidence [99], a social cost of carbon of 167 EUR₂₀₂₀ (185 USD₂₀₂₀) per tonne of CO₂-equivalent is applied at a discount rate of 2% (Table A 17). Table 6 summarises the resulting cost rates in EUR per MWh of final energy, i.e., the cross product of ε and σ .

3. Results

The following sections present building energy performance (3.1), costs of decentralised (3.2) and centralised heating options (3.3), overall cost-efficient solutions (3.4), and a sensitivity analysis (3.5).

3.1. Building energy performance and renovation cost

As shown in Fig. 3, the distribution of the specific energy performance for space heating (kWh_{th}/(m²yr)) varies according to the renovation packages implemented across the 125 buildings (Sections 2.1–2.2). STANDARD and ADVANCED retrofits effectively reduce the buildings' thermal conductivity and, consequently, the energy need for heating. Median reductions are 61% (BG), 73% (DE), and 52% (FI) when comparing ADVANCED and EXISTING states. The lower outliers are mainly offices with high internal gains, while the upper outliers are detached apartment and school buildings. Median energy needs for sanitary hot water (data not shown) are between 19 and 21 kWh_{th}/(m²yr).

Fig. 4 presents cost-potential curves of the useful energy savings for space heating. Cumulative saving potentials compared to the EXISTING package vary between 35% and 72%. Per MWh saved, STANDARD retrofits are cheaper than ADVANCED retrofits, but achieve lower energy savings. Within each country and package, cost differences result from occupancy and internal gains (Section 2.2), as well as the ratio of building envelope area to conditioned floor area. 87–88% of energy savings potentials come from apartments, 7–8% from offices, and the rest from other use types (data not shown).

Table 6External cost rates (EUR₂₀₂₀/MWh) by energy carrier type and emission type.

Energy carrier type	Air pollution		Greenhouse gases	
	2020	2050	2020	2050
Biomass	2.24–7.75	2.24–7.75	0.06–0.07	0.06–0.07
Electricity	2.95–8.99	0.15–1.70	10.66–60.27	0.53–11.93
Gas	0.82–1.57	1.22–3.77	33.21	4.27–24.13
Oil	1.73–3.29	4.45–19.89	44.24	2.35–31.17

Aggregate ranges across countries (BG, DE, FI) and supply scenarios (BAU, NETZERO). See Table A 14–Table A 17 for details.

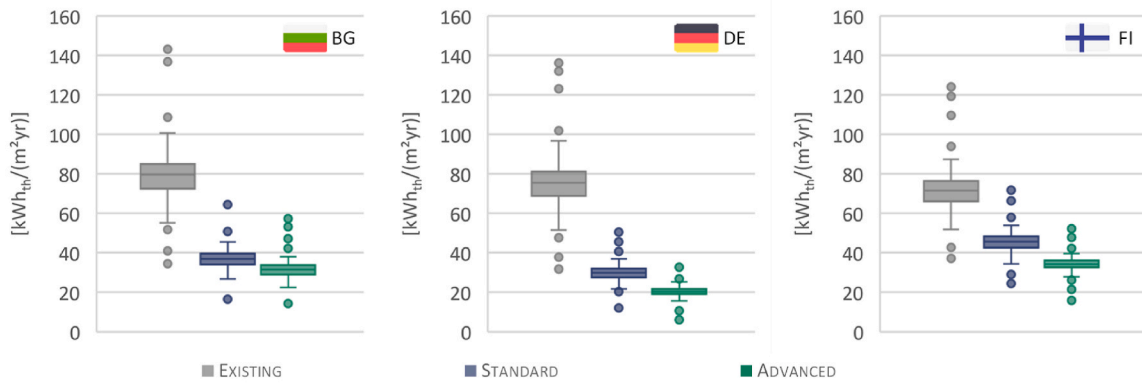


Fig. 3. Specific energy performance for space heating by country and renovation package $n = 125$ buildings by package, see Section 2.1-2.2 | m^2 of conditioned floor area.

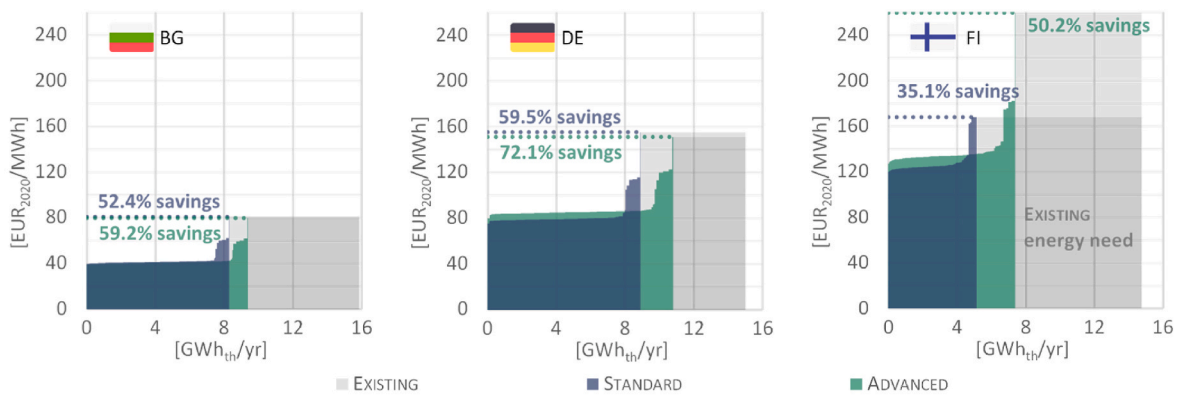


Fig. 4. Cost-potential curve of useful energy savings in space heating by renovation package.

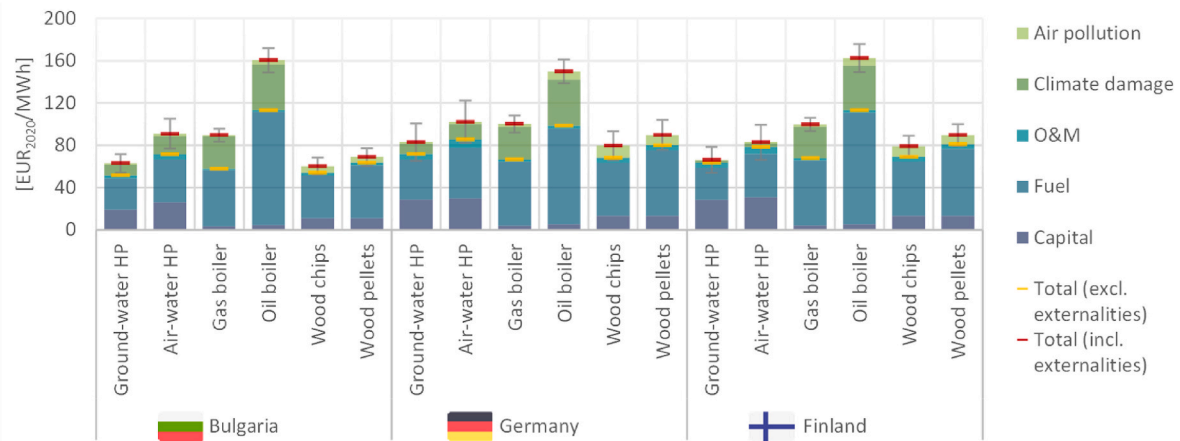


Fig. 5. Mean specific costs for decentralised heating systems by cost type 1,500 variants by country and technology (= 2 supply scenarios \times 2 price pathways \times 3 renovation packages \times 125 buildings).

To understand what drives differences across countries, Table 7 decomposes the numbers from Fig. 4 for the contrasting cases of FI and BG under the ADVANCED package. Three effects are considered.

- Climate conditions (1) moderately impact outcomes: warmer climates in BG yield less space heating savings and higher specific renovation costs compared to FI.
- U-values (2) strongly affect outcomes: according to Table 2, EXISTING buildings in BG have higher U-values and more ambitious retrofit options than in FI, enabling greater relative energy savings.
- Renovation cost levels (3) have the most substantial impact: lower labour and material costs make renovations more affordable in BG than in FI.

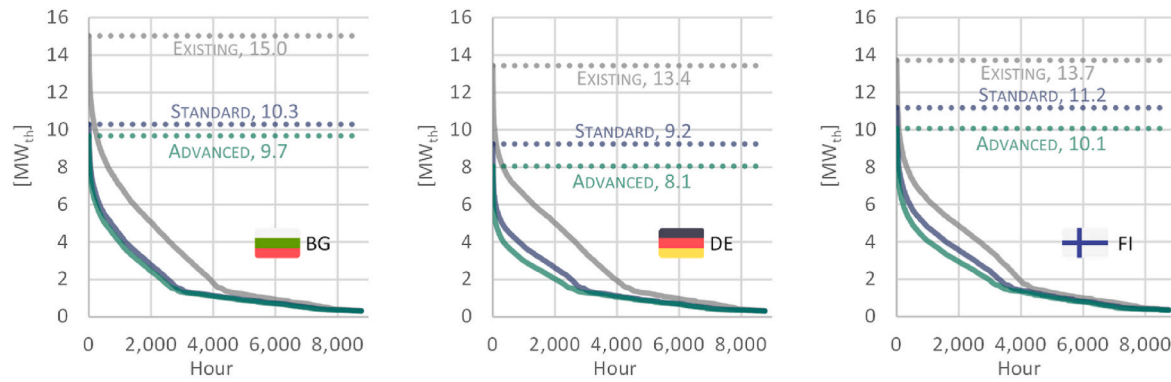


Fig. 6. Thermal load duration curve for centralised district heating supply by renovation package Including heat distribution losses as determined in the CEA model [46].

Table 7

Decomposition of building energy savings and renovation costs for the **ADVANCED** package in Finland (FI) and Bulgaria (BG).

Effect by country			Total savings in useful energy for space heating [MWh_{th}/yr] ^d	Weighted average building renovation costs [EUR_{2020}/MWh_{th}] ^d
(1) Weather ^a	(2) U-values ^b	(3) Renovation cost level ^c		
FI	FI	FI	7404	139.80
BG	FI	FI	5961	173.65
BG	BG	FI	9387	110.27
BG	BG	BG	9387	43.03

^a Based on [55], see Section 2.2.

^b Based on [51], see Table 2.

^c Based on [68], see Section 2.3.1.

^d See Fig. 4.

3.2. Decentralised supply costs

Fig. 5 shows the mean average specific costs for decentralised supply. For each country and technology, this covers 1500 variants from two supply scenarios (BAU, NetZERO), two price pathways (LOW, HIGH), three renovation packages (EXISTING, STANDARD, ADVANCED), and 125 buildings.

Mean least-cost options in both BG and DE are wood chip boilers (60 and 80 EUR/MWh, respectively), and ground source heat pumps in FI (66 EUR/MWh). When adding external costs to capital, fuel, and O&M costs, biomass costs increase by 9–17%, heat pumps by 4–28%, gas by 48–55%, and oil by 42–52%. The standard deviation is high for heat pumps due to improving energetic performance after retrofits (Section 2.3.2). Despite higher total investments, specific capital costs for ground source heat pumps tend to be lower than for air source heat pumps, attributable to longer lifetimes (Table 3).

3.3. Centralised supply costs

Fig. 6 shows the thermal load duration curve for centralised DH supply. When comparing the ADVANCED and EXISTING packages, peak load is reduced by 36% (BG), 40% (DE), and 27% (FI). For a calculated total network length of 5040 m, linear heat densities (MWh_{th}/m) decrease from 5.10 to 2.90 (BG), 4.91 to 2.40 (DE), and 4.90 to 3.21 (FI) between EXISTING and ADVANCED packages (data not shown).

Fig. 7a provides the mean average specific costs for centralised DH options across supply scenarios, price pathways, and renovation packages. Heat pumps are displayed in combination with peak boiler variants (see Section 2.3.3). Mean least-cost centralised solutions are monovalent wood chip boilers in BG (81 EUR/MWh), and air source heat pump systems in both DE and FI (124 and 103 EUR/MWh, respectively). Monovalent electrode boilers are generally the most expensive. As

shown in Fig. 7b, costs are dominated by generation, with specific pipe costs between 8.4 (BG) and 18.0 (DE) EUR/MWh. Costs for substations and pumps are negligible, accounting for 1–3% of overall specific costs.

3.4. Cost-efficient solutions

A three-step heuristic optimisation is employed to balance energy demand reduction via building retrofits and supply via decentralised or centralised heat technologies. First, the least-cost mix of renovation packages (Table 2) and decentralised options (Table 3) is selected. Second, the least-cost combinations of renovation and centralised supply options (Table 4) are determined. Finally, for each country, the lowest cost solution (decentral/central) is selected.

The costs of supply options are derived from mean specific costs across supply scenarios (BAU, NetZERO) and price pathways (LOW, HIGH) (Sections 3.2–3.3). Two sets of least-cost solutions are determined. The first set (a) includes all heat supply technologies available. The second set (b) excludes biomass combustion, due to sustainability issues (e.g., deforestation), and ground source heat pumps, due to disruptive ground works in densely populated urban areas.

The results are presented in Fig. 8 and Table 8. For set (a), 91% of the technical potential for retrofitting is utilised in BG, reducing annual costs by 8%. In contrast, no cost-effective retrofit measures are identified in DE and FI. Decentralised heating options are chosen in all three countries with a mix of wood chip boilers and ground-water heat pumps. These options are 20–27% cheaper than the least-cost centralised solution. Notably, ground-water heat pumps are also selected in FI's cold climate, attributable to both low electricity prices and low external costs.

In set (b), significant differences emerge. Besides BG, cost-effective building retrofits are observed in DE, exploiting 75% of the technical potential and reducing total costs by 20% and 8% in BG and DE, respectively. In BG, centralised DH supply, based on an air-source heat pump and a backup gas boiler, is chosen, with minor cost savings of 2% compared to the decentralised solution. In DE and FI, decentralised air source heat pumps emerge as the major supply option.

3.5. Sensitivity analysis

In order to evaluate the robustness of the results, a sensitivity analysis was conducted for technology set (b) in Table 8. Table 9 displays the outcomes of this analysis, focusing on three independent variables.

- the discount rate (1.5%, 2.0%, 2.5%, 3.0%), representing societal time preference and ethical considerations regarding the well-being of future generations;
- energy supply scenarios (BAU vs. NetZERO) and price pathways (LOW vs. HIGH) (Section 2.3.4);

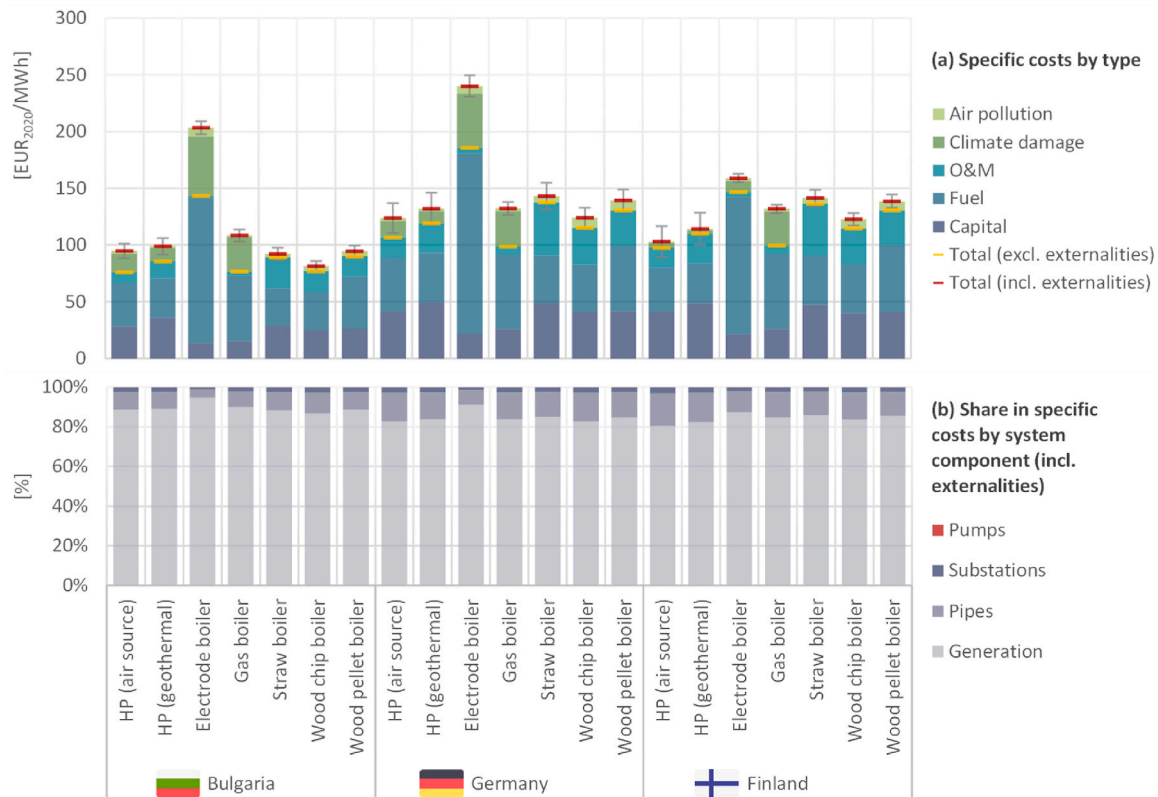


Fig. 7. Mean specific costs for centralised district heating systems

12 base variants by country and technology (= 2 supply scenarios \times 2 price pathways \times 3 renovation packages); 60 variants for heat pumps (= 12 base variants \times 5 backup boiler options).

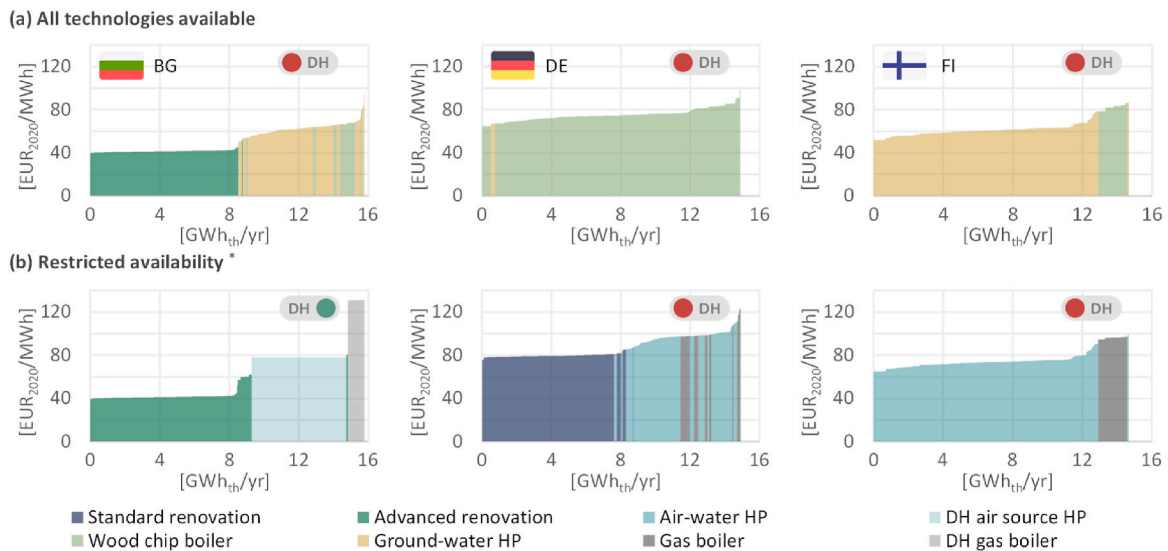


Fig. 8. Specific costs and share in useful energy demand of least-cost solutions

* No biomass; no ground source or geothermal heat pumps | Specific costs (EUR/MWh) as per Equation (1) and Equation (2), including external costs (climate, air pollution).

- nominal heat supply/return temperatures, crucial for the efficient operation of heat pumps. The default 'DYNAMIC' case considers temperature reductions for STANDARD and ADVANCED packages to 60/50 °C and 55/45 °C (Section 2.2), while 'STATIC' maintains 70/50 °C as from the EXISTING package.

Across the tested variants, air source heat pumps remain a fairly robust choice for heat supply. The discount rate affects not only default costs but also the long-term horizon of external climate damage, as represented by the social cost of carbon [99] (Table A 17). A higher discount rate lowers the present value of future damages, making gas boilers more cost-effective. Supply scenarios and price pathways have

Table 8
Detailed performance of least-cost solutions.

Set ^a	Category	Performance indicator	Unit	Country		
				Bulgaria	Germany	Finland
(a) All technologies available	Total costs	Total discounted average costs	[EUR ₂₀₂₀ /yr]	1,067,615	1,446,579	1,221,120
		Specific discounted average costs	[EUR ₂₀₂₀ /MWh _{th}]	50.58	74.65	62.49
	Cost-effective savings through building retrofits ^b	Energy savings	[MWh _{th} /yr]	8498	–	–
		Energy savings	[%]	53.6%	–	–
		Technical potential	[%]	90.5%	–	–
		Cost savings	[EUR ₂₀₂₀ /yr]	87,896	–	–
	Heat supply	Cost savings	[%]	7.6%	–	–
		Supply type	[–]	Decentral	Decentral	Decentral
		Major technology	[–]	Ground source heat pump	Wood chips boiler	Ground source heat pump
		Share in heat supply	[%]	74.0%	98.9%	87.2%
		Cost savings vs. supply alternative (central/decentral)	[%]	19.6%	23.7%	26.6%
(b) Restricted availability	Total costs	Total discounted average costs	[EUR ₂₀₂₀ /yr]	1,327,191	1,727,459	1,473,722
		Specific discounted average costs	[EUR ₂₀₂₀ /MWh _{th}]	60.39	87.11	75.42
	Cost-effective savings through building retrofits ^b	Energy savings	[MWh _{th} /yr]	9387	8042	–
		Energy savings	[%]	59.2%	53.6%	–
		Technical potential	[%]	100.0%	74.4%	–
		Cost savings	[EUR ₂₀₂₀ /yr]	332,424	140,517	–
	Heat supply	Cost savings	[%]	20.0%	7.5%	–
		Supply type	[–]	Central	Decentral	Decentral
		Major technology	[–]	Air source heat pump	Air source heat pump	Air source heat pump
		Share in heat supply	[%]	85.0%	72.8%	87.2%
		Cost savings vs. supply alternative (central/decentral)	[%]	2.3%	8.9%	11.5%

^a Restricted availability: no biomass combustion, no ground source/geothermal heat pumps.

^b Compared to EXISTING renovation package (Section 2.2); energy savings in terms of useful energy for space heating.

minimal effect on outcomes, which is attributed to the interlinked nature of these dimensions and discounting. Notably, the efficiency of heat pumps is significantly influenced by supply/return temperatures, becoming less cost-effective if not operated at low temperatures after renovation.

4. Discussion

The results highlight that the optimal balance between heat savings and supply varies contextually, influenced by technology availability, cost levels, and discount rates. Under certain conditions, building retrofits significantly lower costs; however, when labour and material costs are high, installing new heat supply without prior retrofitting may be more economically viable. Heat pumps, either decentralised or centralised, emerged as key options, even for non-retrofitted buildings in cold climates.

The findings align with existing literature: observed cost-effective heat energy savings of 0–60% versus current levels are consistent with EU estimates of 20–47% [9,79] and local figures of 20–78% [25–29,36]. The study supports the assertion that centralised DH may not consistently be more cost-effective than low-carbon decentralised options, with DH's optimal EU market shares in the literature at 5–45% [100]. The importance of low-temperature heating is underlined, resonating with [56,59]. This section discusses the study's policy implications (Section 4.1) and limitations (Section 4.2).

4.1. Policy implications

The proposed recast of the EU Energy Efficiency Directive (EED) [101] emphasises the energy efficiency first (EE1st) principle, requiring decision-makers to determine solutions that yield cost-efficient outcomes for both individuals and society. Local authorities can address this principle through planning, zoning, financial incentives, and - as assumed in this study - the adoption of energy-efficient and low-carbon solutions in publicly owned buildings and energy infrastructures [102].

This study illustrates the value of urban energy systems modelling as

a decision support tool for identifying least-cost combinations of technical solutions. In this sense, Article 23 (6) of the proposed EED recast [101] would require Member States to carry out integrated heating and cooling planning for municipalities with a population exceeding 45,000. Denmark's experience [103] underscores the effectiveness of such planning to exclude options that are not economically viable, technologically feasible, and environmentally sustainable, while reducing risk for both suppliers and consumers.

However, major aspects of energy policy in the EU fall under the purview of regional or national governments, limiting the scope of action for local authorities [102,103]. In particular, national authorities face the challenge to create an enabling framework for decision-makers to adopt sustainable energy practices and technologies that benefit both their own interests and society as a whole.

Internalising external costs is the traditional economic approach to aligning private interests with societal goals [39]. The results in Section 3.2 show that, on top of technology and energy expenses, gas boilers generate societal costs of 48–55%. In response, the recast EU Emissions Trading System (ETS) Directive [104] establishes a new ETS scheme covering the building and road transport sectors. This could incentivise private decision-makers to adopt efficient, low-carbon options like heat pumps.

To expedite building retrofits, the EU Energy Performance of Buildings Directive (EPBD) requires Member States to set minimum energy performance standards (MEPS) for new and existing buildings undergoing major renovation. The proposed EPBD recast aims to intensify these provisions, specifically targeting the worst-performing buildings [105,106]. As shown in this study, establishing MEPS necessitates a careful balance between decarbonising heat supply and reducing building heating needs, to ensure “cost-optimal levels of minimum energy performance requirements” [105].

In sum, combining sound economic evaluation in local energy planning with comprehensive incentive structures is a promising strategy for fostering sustainable, resilient, and cost-efficient community energy systems in accordance with the EE1st principle.

Table 9
Sensitivity analysis on cost-efficient solutions.

Independent variable	Variant	Dependent variables: ^a Utilisation of technical potential for building retrofits [%] Share of major decentral (△) or central (●) supply technology in heat supply [%]		
		Bulgaria	Germany	Finland
Discount rate	1.5%	100.0% ● Air source HP (85%)	82.4% △ Air source HP (87%)	- △ Air source HP (90%)
	2.0% ^b	100.0% ● Air source HP (85%)	74.4% △ Air source HP (73%)	- △ Air source HP (87%)
	2.5%	99.2% △ Gas boiler (99%)	0.8% △ Gas boiler (99%)	- △ Air source HP (87%)
	3.0%	91.8% △ Gas boiler (100%)	- △ Gas boiler (100%)	- △ Air source HP (87%)
	Average (BAU, NetZERO, LOW, HIGH) ^b	100.0% ● Air source HP (85%)	74.4% △ Air source HP (73%)	- △ Air source HP (87%)
	BAU LOW	100.0% ● Air source HP (85%)	74.4% △ Air source HP (55%)	- △ Air source HP (87%)
	BAU HIGH	100.0% ● Air source HP (85%)	74.4% △ Air source HP (70%)	- △ Air source HP (87%)
	NetZERO LOW	100.0% ● Air source HP (85%)	74.6% △ Air source HP (75%)	- △ Air source HP (87%)
	NetZERO HIGH	100.0% ● Air source HP (85%)	74.4% △ Air source HP (74%)	- △ Air source HP (87%)
	Dynamic	100.0% ● Air source HP (85%)	74.4% △ Air source HP (73%)	- △ Air source HP (87%)
Heat pump supply/return temperatures ^d	Static	99.9% △ Gas boiler (99%)	72.3% △ Gas boiler (94%)	- △ Air source HP (87%)

^a See Table 8.

^b Default variant in Section 3.4, using technology set (b).

^c See Section 2.3.4.

^d See Sections 2.2–2.3.

4.2. Limitations

This study is subject to several limitations. First, in terms of technical detail, the analysis does not consider rooftop photovoltaic or solar thermal installations [107], nor does it endogenously represent increased power network costs in response to heat pump adoption [26]. It also disregards industrial excess heat potentials or seasonal energy storage in DH systems, potentially overestimating the cost of centralised heat supply [59,108]. Moreover, the analysis uses yearly average electricity prices, which does not reflect the possibility of optimising heat pump operation during low-price periods using demand response strategies [16,28].

Second, the study's hypothetical setup consists of a single urban district comprising generic reference buildings from the 1970–1989 construction period. In reality, the existing building stock in Europe is highly heterogeneous in terms of building types, construction periods, and renovation states [8,38]. Consequently, the study's findings cannot easily be scaled to a national level.

Third, the analysis adopts a societal perspective, including external costs and excluding transfer payments while applying a low discount rate. This represents the viewpoint of benevolent municipal authorities who are shareholders in local energy utilities and public property owners [102,109]. However, to understand the specific effects for building owners, tenants, property developers, and heat utilities, a

financial analysis [61,110] reflecting actual cash flow transactions, including all relevant taxes and subsidies, would be necessary. Any discrepancy between societal and financial calculations would indicate that the policy framework, including taxation levels, favours suboptimal solutions [28,109].

Fourth, the analysis does not consider the practical feasibility of the proposed solutions. For instance, due to budget constraints, a staged building renovation approach could be more preferable [63,111]. Technical constraints may include the availability of large-scale heat pumps for multi-family buildings, which often require custom solutions, unlike those in single-family buildings [72]. Moreover, different countries have varying levels of experience with certain heat technologies, like the relatively mature heat pump market in Finland [112], which could influence practical implementation.

Finally, this study includes direct air pollution and climate change impacts as significant external costs. However, it does not fully capture all relevant externalities, such as noise pollution, which may be an issue for air source heat pumps [72]. Moreover, the study could be broadened to include so-called multiple impacts [37,113], such as enhanced thermal comfort resulting from building retrofits, local job creation opportunities, and energy security considerations. Including these factors in the analysis could make the case for certain options, such as building retrofits, more attractive [41,114].

5. Conclusion

In this research, the potential for energy savings through building envelope retrofits and the role of decentralised and centralised heat supply technologies were investigated from a societal perspective, factoring in the external costs of greenhouse gas and air pollution emissions. This analysis encompassed a generic urban district in Bulgaria, Germany, and Finland, constructed during the 1970–1989 period. A heuristic optimisation approach was used to identify the least-cost combinations of these options.

The results suggest that the cost-effectiveness of retrofits is highly context-specific. In Bulgaria, deep retrofits are largely cost-effective. When excluding biomass combustion and ground source heat pumps due to sustainability and disruption concerns, respectively, renovation can yield up to 20% in annual cost savings and a 59% reduction in heat demand compared to existing levels. Conversely, in Germany and Finland, higher labour and material costs alter the economic balance: for instance, in Germany, retrofits may result in up to 8% cost savings with a 54% reduction in heating needs. Despite these varying conditions, both decentralised and centralised heat pumps emerged as key heat supply options, even for non-retrofitted buildings in the cold climates of Finland.

The study suggests that centralised district heating solutions may not consistently be more cost-effective than low-carbon decentralised options. However, it acknowledges the potential for cost reductions through model refinements, such as the integration of industrial excess heat potentials. Sensitivity analysis underlines the robustness of the overall findings, highlighting the significant impact of discount rates and the importance of low supply temperatures for efficient heat pump operation.

Policy implications include the need for balanced urban energy planning that integrates both energy-saving and supply measures. Effective local planning, coupled with supportive national policies, can facilitate the uptake of efficient low-carbon solutions. Future research should aim to integrate more technical model details and explore multiple impacts beyond classic externalities to provide a more comprehensive assessment of the heating transition in the building sector.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix. Techno-economic input data

Building renovation.

Table A 1

Internal loads by building use type

Parameter	Unit	Building use type							
		Apartment	Grocery	Hotel	Library	Office	Restaurant	Retail	School
Occupancy density	m^2/p	30.0	8.0	15.0	5.0	14.0	2.0	8.0	3.0
Peak sensible heat load of occupants	W/p	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Peak spec electrical load Appliances	W/m^2	8.0	2.0	8.0	2.0	7.0	2.0	2.0	4.0
Peak specific electrical load Lighting	W/m^2	2.7	21.3	2.7	6.9	15.9	6.9	33.3	14.0
Peak specific electrical load Cooling rooms	W/m^2	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0
Peak specific electrical load Server rooms	W/m^2	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Peak specific daily fresh water consumption	$l/d/p$	140.0	30.0	160.0	0.0	60.0	45.0	30.0	30.0
Peak specific daily hot water consumption	$l/d/p$	35.0	2.0	40.0	0.0	3.0	15.0	2.0	2.0

Source [45] | p person; l litre; d day

Table A 2

Boundary conditions for calculation of building energy need for heating in the CEA model

Category	Parameter	Setting
Building materials and envelope	Construction type	Internal heat capacity per unit of air conditioned area $C_m = 16500 [J/Km^2]$
	Airtightness	Air exchanges per hour at 50 Pa pressure $n_{50} = 3 [1/h]$
	Solar shading	Shading coefficient $r_{fsh} = 0.08$
	Glazed area to façade area ratio	0.2 (North), 0.15 (East), 0.2 (South), 0.15 (West)
Space heating	Set-point temperature	$T_{set} = 20^\circ C$
Water heating	Nominal supply temperature	High temperature water with $T_w = 60^\circ C$
Ventilation	Ventilation type	Window ventilation with night flush

Source [45,51]

Table A 3

Linear function parameters for specific investment costs of building renovation measures in Germany

Component	Renovation type ^a	Cost function parameters in form $f(x) = n + m \cdot x$ [EUR ₂₀₁₇ /m ² _{component}]			
		Variable [x]	Constant [n]	Additional cost [m]	Other costs ^b
Roof	Refurbishment	Insulation thickness [cm]	118.00 [EUR/m ²]	–	16.7%
	Retrofit		174.00 [EUR/m ²]	0.70 [EUR/(cm·m ²)]	
Floor	Refurbishment		0.00 [EUR/m ²]	–	
	Retrofit		29.00 [EUR/m ²]	1.14 [EUR/(cm·m ²)]	
Wall	Refurbishment		37.00 [EUR/m ²]	–	
	Retrofit		96.00 [EUR/m ²]	2.67 [EUR/(cm·m ²)]	
Window	Refurbishment	U-value [W/m ² K]	201.00 [EUR/m ²]	–	22.5%
	Retrofit		538.28 [EUR/m ²]	–111.54 [EUR/(W/m ² K)·m ²]	

Source [65,66] | ^a Refurbishment: maintenance of building aesthetics/safety, without addressing energy performance; retrofit: improvement of building energy performance, see Footnote 6 | ^b Share of miscellaneous taxes and charges not related to materials, labour or professional fees

Decentralised heat supply.

Table A 4

Technical parameters for decentralised heat supply technologies

Technology	Linear function expressed as $f(x) = n + m \cdot x$, where x is the nominal thermal capacity (kW_{th})									
	Efficiency [–]				Lifetime [yr]				Aux. Electricity [kWh _{el} /yr]	
	[m]	[n]	[max]	[min]	[m]	[n]	[max]	[min]	[m]	[n]
Air-water heat pump	a				0.0104	17.3	25	16	b	
Biomass boiler	0.0001	0.83	0.92	0.76	0.0066	18.6	25	15	4.8	371.1

(continued on next page)

Table A 4 (continued)

Technology	Linear function expressed as $f(x) = n + m \cdot x$, where x is the nominal thermal capacity (kW_{th})									
	Efficiency [–]				Lifetime [yr]				Aux. Electricity [kWh_{el}/yr]	
	[m]	[n]	[max]	[min]	[m]	[n]	[max]	[min]	[m]	[n]
District heating substation	0.0001	0.97	1.00	0.95	0.0080	23.5	30	20	1.6	76.9
Electric heater	0.0000	1.00	1.00	1.00	0.0307	23.1	30	25	0.0	0.0
Gas boiler	0.0001	0.97	1.03	0.95	0.0160	19.2	30	18	1.6	92.1
Ground-water heat pump	a				0.0126	23.6	40	18	b	
Oil boiler	0.0000	0.93	0.95	0.92	0.0004	19.9	25	15	3.3	60.5

Source [72] | ^a Endogenous estimation of seasonal performance factor SPF , see Table A 6 | ^b Included in SPF .

Table A 5

Economic parameters for decentralised heat supply technologies

Technology	Country	Linear function expressed as $f(x) = n + m \cdot x$, where x is the nominal thermal capacity (kW_{th})			
		Investment [EUR_{2020}]		O&M fix [EUR_{2020}/yr]	
		[m]	[n]	[m]	[n]
Air-water heat pump	BG	354	6264	3.8	148
	DE	420	8529	6.6	253
	FI	453	8985	6.7	258
Biomass boiler	BG	122	6776	1.0	193
	DE	148	8322	1.7	329
	FI	159	8925	1.8	335
District heating substation	BG	22	1798	0.1	19
	DE	28	2769	0.1	32
	FI	30	2861	0.1	33
Electric heater *	BG	155	–	0.1	14
	DE	208	–	0.1	24
	FI	220	–	0.1	25
Gas boiler	BG	46	1441	0.5	82
	DE	55	2059	0.9	140
	FI	60	2152	0.9	142
Ground-water heat pump	BG	325	8957	2.3	116
	DE	508	14,763	3.9	198
	FI	524	15,105	4.0	202
Oil boiler	BG	49	2737	1.0	63
	DE	59	3506	1.7	108
	FI	64	3732	1.7	110

Source: [72], cost adjustments as described in Section 2.3 | * Backup heater for heat pump systems without base investment

Table A 6

Seasonal performance factor SPF of decentralised heat pump systems: space heating alone (and combined with water heating) SPF for bivalent heat pump system with backup electric heater, shown as the mean energy-weighted average for 125 buildings per country and renovation package | See Equation 4

Type	Country	Renovation package		
		EXISTING	STANDARD	ADVANCED
Air-water heat pump	BG	2.28 (2.61)	2.40 (2.92)	2.51 (3.03)
	DE	2.34 (2.70)	2.58 (3.14)	2.76 (3.34)
	FI	2.01 (2.45)	2.12 (2.67)	2.18 (2.81)
Ground-water heat pump	BG	3.27 (3.50)	3.47 (3.66)	3.79 (3.88)
	DE	3.01 (3.31)	3.28 (3.58)	3.67 (3.83)
	FI	2.81 (3.19)	2.94 (3.30)	3.19 (3.51)

Centralised heat supply.

Table A 7

Technical parameters for centralised heat supply technologies

Technology	Linear function expressed as $f(x) = n + m \cdot x$, where x is the nominal thermal capacity (MW_{th})							
	Efficiency [–]				Lifetime [yr]			
	[m]	[n]	[max]	[min]	[m]	[n]	[max]	[min]
Air source heat pump	*				1.643	7.5	40	15
Electrode boiler	0.0003	0.98	0.99	0.98	0.000	20.0	20	20
Gas boiler	0.0126	0.94	1.05	0.93	0.000	25.0	25	25
Geothermal heat pump	0.0854	3.81	5.45	4.17	0.339	22.7	30	25
Straw boiler	0.1801	–0.08	1.04	0.88	11.746	–42.8	35	20
Wood chip boiler	0.1687	–0.01	1.15	0.89	6.688	–15.8	35	20
Wood pellet boiler	0.1825	–0.09	1.02	0.90	16.140	–68.1	35	20

Source [76]: | * Endogenous estimation of seasonal coefficient of performance, see Section 2.3.2 and Table A 9

Table An 8

Economic parameters for centralised heat supply technologies

Technology	Country	Linear function expressed as $f(x) = n + m \cdot x$, where x is the nominal thermal capacity (MW_{th})											
		Investment [$kEUR_{2020}/MW_{th}$]				O&M fix [$kEUR_{2020}/MW_{th}/yr$]				O&M var [EUR_{2020}/MWh_{th}]			
		[m]	[n]	[max]	[min]	[m]	[n]	[max]	[min]	[m]	[n]	[max]	[min]
Air source heat pump	BG	27.7	354	913	490	0.07	0.26	1.53	0.51	0.04	0.51	1.38	0.77
	DE	27.7	465	1049	586	0.11	0.44	2.66	0.89	0.07	0.89	2.39	1.33
	FI	31.0	492	1139	632	0.12	0.45	2.71	0.90	0.07	0.90	2.43	1.35
Electrode boiler	BG	4.2	22	126	17	0.00	0.52	0.56	0.51	0.00	0.22	0.26	0.20
	DE	5.2	23	151	18	0.00	0.91	0.98	0.89	0.00	0.39	0.44	0.36
	FI	5.6	26	163	20	0.00	0.92	0.99	0.90	0.00	0.39	0.45	0.36
Gas boiler	BG	12.9	1	145	23	0.08	0.50	1.28	0.51	0.08	0.17	1.02	0.26
	DE	20.1	-3	222	31	0.14	0.88	2.22	0.89	0.14	0.30	1.78	0.44
	FI	20.7	-3	230	33	0.14	0.89	2.26	0.90	0.14	0.30	1.80	0.45
Geothermal heat pump	BG	116.5	639	2909	1164	0.00	11.50	11.50	11.50	0.03	2.42	2.95	2.52
	DE	145.0	761	3588	1417	0.00	19.98	19.98	19.98	0.05	4.21	5.13	4.38
	FI	155.1	820	3845	1522	0.00	20.30	20.30	20.30	0.05	4.27	5.21	4.45
Straw boiler	BG	137.2	-352	559	382	7.05	-15.51	30.47	22.19	0.17	-0.64	0.45	0.25
	DE	224.4	-522	960	678	12.25	-26.94	52.93	38.55	0.29	-1.12	0.78	0.44
	FI	229.8	-543	977	686	12.44	-27.36	53.77	39.15	0.30	-1.14	0.79	0.44
Wood chip boiler	BG	56.9	36	461	341	2.49	0.91	19.27	14.21	0.21	-0.72	0.88	0.42
	DE	89.2	57	723	534	4.32	1.58	33.48	24.69	0.37	-1.26	1.52	0.73
	FI	91.9	59	745	550	4.39	1.60	34.01	25.08	0.38	-1.28	1.55	0.75
Wood pellet boiler	BG	146.9	-436	495	366	5.98	-18.29	19.37	14.31	0.17	-0.70	0.35	0.21
	DE	222.3	-659	748	553	10.39	-31.78	33.66	24.87	0.29	-1.21	0.61	0.37
	FI	230.3	-683	775	573	10.55	-32.28	34.19	25.26	0.29	-1.23	0.62	0.37

Source: [76], cost adjustments as described in Section 2.3

Table A 9

Seasonal coefficient of performance for centralised air source heat pumps

COP for 85% share in annual heat demand, excluding efficiency of peak boiler, see Equation 3

Technology	Country	Renovation package		
		EXISTING	STANDARD	ADVANCED
Air source heat pump	BG	3.76	4.20	4.47
	DE	3.80	4.25	4.53
	FI	3.65	4.06	4.31

Table A 10

Techno-economic data for district heating network pipes

Variable	Pipe code	Internal diameter [m]	Country		
			BG	DE	FI
Specific investment costs [EUR_{2020}/m]	DN20	0.022	294	556	572
	DN25	0.029	298	563	579
	DN32	0.037	318	601	618
	DN40	0.043	329	621	639
	DN50	0.055	372	704	724
	DN65	0.070	404	764	786
	DN80	0.083	463	876	901
	DN100	0.107	572	1081	1112
	DN125	0.133	687	1299	1336
	DN200	0.210	986	1864	1918
	DN250	0.263	1320	2496	2568
	DN300	0.313	1654	3129	3219
	DN350	0.344	1989	3762	3870
	DN400	0.394	2323	4393	4519
	DN450	0.445	2658	5026	5170
Lifetime [yr]	–	–	40	40	40
Variable O&M [EUR_{2020}/MWh_{th}]	–	–	0.62	2.13	2.24

Source: [45,77], with cost adjustments as described in Section 2.3 | O&M operation and maintenance

Energy costs.

Table An 11

Average energy carrier mix for gaseous and liquid fuels in the EU

Energy carrier type	Supply scenario	Energy carrier	Share 2020	Share 2050
Gas	BAU	Biomethane	1.4%	30.0%
		Hydrogen	0.0%	2.0%
		Natural gas	98.6%	68.0%
	NetZERO	Synthetic methane	0.0%	0.0%
		Biomethane	1.4%	77.0%
		Hydrogen	0.0%	10.0%
	BAU	Natural gas	98.6%	3.0%
		Synthetic methane	0.0%	10.0%
		Biooil	0.5%	30.0%
Oil	BAU	Oil	99.5%	70.0%
		Synthetic fuel	0.0%	0.0%
		Biooil	0.5%	85.0%
	NetZERO	Oil	99.5%	5.0%
		Synthetic fuel	0.0%	10.0%

Source: 2020 values based on EU average fuel mix [71]; 2050 values based on [79].

Table A 12

Energy carrier prices by country, supply scenario and price pathway

Energy carrier type	Energy carrier	Country	Price (<i>EUR</i> ₂₀₂₀ / <i>MWh</i>) by supply scenario and price pathway in year 2020 (2050)				Source
			BAU		NetZero		
			High	Low	High	Low	
Biomass	Straw	BG	21.55 (26.91)	21.55 (23.18)	21.55 (29.40)	21.55 (26.91)	[85]
		DE	26.12 (32.61)	26.12 (31.16)	26.12 (34.80)	26.12 (32.61)	
		FI	27.66 (34.54)	27.66 (32.89)	27.66 (37.02)	27.66 (34.54)	
	Wood chips	BG	23.88 (29.82)	23.88 (25.70)	23.88 (32.59)	23.88 (29.82)	[85]
		DE	28.93 (36.14)	28.93 (34.52)	28.93 (38.56)	28.93 (36.14)	
		FI	30.65 (38.27)	30.65 (36.45)	30.65 (41.03)	30.65 (38.27)	
	Wood pellets	BG	31.50 (34.92)	31.50 (30.07)	31.50 (38.15)	31.50 (34.92)	[85]
		DE	38.17 (42.31)	38.17 (40.42)	38.17 (45.14)	38.17 (42.31)	
		FI	40.43 (44.81)	40.43 (42.66)	40.43 (48.02)	40.43 (44.81)	
Electricity	Electricity	BG	64.14 (67.82)	64.14 (64.57)	64.14 (104.80)	64.14 (83.39)	[81–83]
		DE	57.41 (60.70)	57.41 (57.79)	57.41 (93.68)	57.41 (74.58)	
		FI	49.93 (52.53)	49.93 (50.24)	49.93 (78.62)	49.93 (63.52)	
Gas	Biomethane	BG	75.90 (90.41)	75.90 (77.87)	75.90 (98.76)	75.90 (90.41)	[85,86]
		DE	71.40 (85.06)	71.40 (81.26)	71.40 (90.75)	71.40 (85.06)	
		FI	56.40 (67.18)	56.40 (63.97)	56.40 (72.01)	56.40 (67.18)	
	Hydrogen	BG	170.72 (117.40)	170.72 (82.60)	170.72 (82.60)	170.72 (63.80)	[87]
		DE	171.11 (117.66)	171.11 (82.78)	171.11 (82.78)	171.11 (63.95)	
		FI	172.57 (118.67)	172.57 (83.49)	172.57 (83.49)	172.57 (64.49)	
	Natural gas	BG	16.70 (16.17)	16.70 (11.07)	16.70 (11.07)	16.70 (6.68)	[80,84]
		DE	25.20 (24.40)	25.20 (16.71)	25.20 (16.71)	25.20 (10.08)	
		FI	23.10 (22.37)	23.10 (15.32)	23.10 (15.32)	23.10 (9.24)	
	Synthetic methane	BG	208.82 (146.97)	208.82 (109.02)	208.82 (109.02)	208.82 (86.85)	[87]
		DE	209.29 (147.30)	209.29 (109.27)	209.29 (109.27)	209.29 (87.04)	
		FI	211.08 (148.56)	211.08 (110.20)	211.08 (110.20)	211.08 (87.79)	
Oil	Biooil	BG	94.88 (113.01)	94.88 (97.33)	94.88 (123.45)	94.88 (113.01)	[79]
		DE	89.25 (106.33)	89.25 (101.58)	89.25 (113.43)	89.25 (106.33)	
		FI	70.50 (83.98)	70.50 (79.96)	70.50 (90.01)	70.50 (83.98)	
	Fuel oil	BG	74.62 (102.74)	74.62 (64.89)	74.62 (64.89)	74.62 (25.96)	[80,88]
		DE	54.09 (74.47)	54.09 (47.03)	54.09 (47.03)	54.09 (18.81)	
		FI	76.16 (104.85)	76.16 (66.22)	76.16 (66.22)	76.16 (26.49)	
	Synthetic fuel	BG	220.26 (156.59)	220.26 (116.61)	220.26 (116.61)	220.26 (95.07)	[87]
		DE	220.76 (156.94)	220.76 (116.87)	220.76 (116.87)	220.76 (95.28)	
		FI	222.64 (158.28)	222.64 (117.87)	222.64 (117.87)	222.64 (96.09)	

Prices excluding taxes/fees/levies and external costs.

Table A 13

Network and fuel handling charges by energy carrier type

Energy carrier type	Country code	<i>EUR</i> ₂₀₂₀ / <i>MWh</i>	Source
Biomass	BG	2.75	[85]
	DE	3.68	
	FI	3.94	
Electricity	BG	25.90	[83]
	DE	54.90	
	FI	37.80	
Gas	BG	13.50	[84]
	DE	13.20	

(continued on next page)

Table A 13 (continued)

Energy carrier type	Country code	EUR ₂₀₂₀ /MWh	Source
Oil	FI	20.10	[85]
	BG	3.44	
	DE	7.12	
	FI	7.61	

Emission factors.**Table A 14**Emission factors (g/kWh_{th}) by fuel and pollutant

Pollutant type	Greenhouse gas	Air pollution			
Fuel Pollutant	CO ₂ -eq	NM VOC	NO _x	PM	SO ₂
Biomethane	25.471	0.013	0.208	0.001	0.001
Biooil	0.930	0.010	1.017	0.024	0.001
Hydrogen *	–	–	–	–	–
Municipal waste	1.449	0.001	0.176	0.001	0.012
Natural gas	201.909	0.002	0.074	–	0.001
Oil	267.062	0.005	0.150	0.003	0.008
Straw	0.341	0.003	0.259	0.083	0.016
Synthetic fuel *	–	0.010	1.017	0.024	0.001
Synthetic methane *	–	0.013	0.208	0.001	0.001
Wood chips	0.431	0.009	0.360	0.073	0.016
Wood pellets	0.390	0.006	0.310	0.067	0.018

Source [94,95] | *Assumption

Table A 15Emission factors for grid-based electricity (g/kWh_{el}) by country, scenario, year and pollutant

Pollutant type			Greenhouse gas	Air pollution					
Country	Supply scenario	Year	CO ₂ -eq	NH ₃	NM VOC	NO _x	PM ₁₀	PM _{2.5}	SO ₂
BG	BAU	2020	362.0	0.000	0.019	0.346	0.006	0.005	0.767
		2050	43.8	0.000	0.002	0.042	0.001	0.001	0.093
	NETZERO	2020	362.0	0.000	0.019	0.346	0.006	0.005	0.767
		2050	18.1	0.000	0.001	0.017	0.000	0.000	0.038
FI	BAU	2020	64.0	0.000	0.012	0.136	0.007	0.002	0.054
		2050	19.5	0.000	0.004	0.041	0.002	0.001	0.016
	NETZERO	2020	64.0	0.000	0.012	0.136	0.007	0.002	0.054
		2050	3.2	0.000	0.001	0.007	0.000	0.000	0.003
DE	BAU	2020	314.0	0.001	0.011	0.319	0.007	0.006	0.143
		2050	71.6	0.000	0.003	0.073	0.002	0.001	0.033
	NETZERO	2020	314.0	0.001	0.011	0.319	0.007	0.006	0.143
		2050	15.7	0.000	0.001	0.016	0.000	0.000	0.007

Source: [81,96,97], see Section 2.3.5

External costs.**Table A 16**

Value factors by receptor, emission source, and air pollutant

Receptor	Emission source	Value factor by pollutant (EUR ₂₀₂₀ /t)						
		NH ₃	NM VOC	NO _x	PM	PM ₁₀	PM _{2.5}	SO ₂
Health damage	Energy supply	13,131 to 25,000	683 to 1300	6093 to 11,600	262.6 to 500.0	12,238 to 23,300	17,386 to 33,100	7038 to 13,400
	Buildings	13,026 to 24,800	683 to 1300	8719 to 16,600	998 to 1900	43,018 to 81,900	61,087 to 116,300	8141 to 15,500
Biodiversity losses	–	6298 to 11,990	–	1444 to 2750	–	–	–	556.8 to 1060.0
Crop damage	–	–190.0 to –99.8	525.3 to 1000.0	446.5 to 850.0	–	–	–	–170.0 to –89.3
Material damage	–	–	–	73.5 to 140.0	–	–	–	336.2 to 640.0

Source [91,92] | Ranges across countries (BG, DE, FI)

Table A 17

Social cost of carbon by discount rate

Receptor	Emission source	Discount rate	EUR ₂₀₂₀ /tCO ₂ eq	USD ₂₀₂₀ /tCO ₂ eq
Climate damage	–	3.0%	72	80
		2.5%	106	118
		2.0%	167	185
		1.5%	277	308

Source [99]:

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