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Citation (APA)
Loche, I., Recart, C., Ricci, D., Konstantinou, T., Kuijer, L., & Loonen, R. (2026). Re-sizing energy retrofits for low-temperature district heating: Integrating residents' heating practices and a multi-criteria selection. *Energy and Buildings*, *372*, Article 118303. https://doi.org/10.1016/j.enbuild.2026.118303

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Energy & Buildings 372 (2026) 118303

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Re-sizing energy retrofits for low-temperature district heating: Integrating residents' heating practices and a multi-criteria selection

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ARTICLE INFO

Keywords:
Energy practices
Occupant behaviour
Sustainable renovation
Just energy transition
Prebound and rebound effect

ABSTRACT

To connect dwellings to sustainable low-temperature district heating (LTDH), it is typically recommended that dwellings with low or moderately insulated envelopes undergo deep renovation. These recommendations are grounded in standardized assumptions about thermal comfort, which do not reflect the diversity of residents' heating practices. As a result, deep retrofit interventions often prove costly, highly disruptive, and may fail to achieve the projected energy savings. This study addresses this gap by integrating residents' heating practices into retrofit decision-making to reassess the scale of renovations necessary for LTDH readiness. Using a Dutch terraced house as a reference case, we apply a multi-criteria framework combined with parametric simulations to evaluate renovation strategies in terms of thermal comfort, heating savings, environmental impacts, costs, and resident nuisance. The results indicate that although deep retrofits with full radiator upgrades emerge as the most technically robust solution, their benefits are not distributed equally across resident profiles. For households with economical heating behaviour, deep renovation yields significantly lower-than-expected savings and carbon reductions, and considerably longer payback times. Conversely, less intensive strategies, such as radiator upgrades alone or combined with single or moderate retrofit packages, are technically sufficient to enable connection to LTDH, often at lower cost and reduced disruption. Rather than converging to one standardized solution, the analysis identifies up to 28 viable retrofit pathways depending on the resident profile. These findings challenge the prevailing one-size-fits-all deep renovations and demonstrate how integrating residents' practices can resize renovation, supporting flexible, resource-efficient, and socially just pathways toward low-carbon heating transitions.

List of abbreviations

ACH	Air change rate per hour
BAU	Business-as-usual
BPS	Building performance simulation
CO_2	Carbon dioxide
DH	District heating
DR	Deep retrofit
EC3	Embodied Carbon in Construction Calculator
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene
EU	European Union
GWP	Global warming potential
HRE	Heat Roadmap Europe
KPI (s)	Key performance indicator
LTDH	Low-temperature district heating
MR	Moderate retrofit
PCS	Personal comfort system
PU	Polyurethane
Rc	Thermal resistance of building component (m^2.K/W)
SHGC	Solar heat gain coefficient
SP1-a	Setpoint temperature 1: all rooms heated at very high temperature
SP1-lr	Setpoint temperature 1: living area heated at very high temperature

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https://doi.org/10.1016/j.enbuild.2026.118303
Received 25 February 2026; Received in revised form 1 June 2026; Accepted 22 September 2026
Available online 23 September 2026
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SP2-a	Setpoint temperature 2: all rooms heated at high temperature
SP2-lr	Setpoint temperature 2: living area heated at high temperature
SP3-a	Setpoint temperature 3: all rooms heated at standard temperature
SP3-lr	Setpoint temperature 3: living area heated at standard temperature
SP4-a	Setpoint temperature 4: all rooms heated at moderate temperature
SP4-lr	Setpoint temperature 4: living area heated at moderate temperature
SP5-a	Setpoint temperature 5: all rooms heated at low temperature
SP5-lr	Setpoint temperature 5: living area heated at low temperature
SR	Single retrofit
Ug	Window thermal transmittance ($W/m^2.K$)
ULTDH	Ultra-low-temperature district heating
WoON	Housing Survey Netherlands (WoON Onderzoek Nederland)

1. Introduction

1.1. Background

Despite ongoing efforts to decarbonize the residential sector, households still account for 26% of total energy consumption in Europe, with natural gas representing 30% of this demand in 2023 [1]. Phasing out natural gas in the residential sector is therefore critical to achieving CO_2 neutrality by 2050. A promising pathway is the replacement of individual gas boilers with collective low-temperature district heating (LTDH). These networks are increasingly recognized as cost-effective solutions for dense urban areas [2]. Operating at supply temperatures below 55 °C, significantly lower than conventional gas-fired systems (>80 °C), LTDH can integrate multiple renewable sources, such as geothermal, solar, and industrial waste heat [3,4]. By 2050, Heat Roadmap Europe (HRE), which assesses district heating (DH) potential across Europe, projects that DH could supply at least 50% of the EU's heating demand; yet in 2024 it accounted for only 10% [5–7].

The transition from individual heating systems to LTDH is impeded by technical, social and regulatory challenges that consider both supply and demand [4,8–10]. On the supply side, parts of existing DH infrastructure must be adapted to integrate renewable energy sources, while new networks need to be developed [11]. On the demand side, the technical viability of connecting to LTDH depends on the building's heating demand, as this determines whether desired indoor temperatures can be maintained with a lower supply temperature [9,12]. This heating demand is shaped by two key aspects: the thermal performance of the building, such as insulation level, airtightness and heating system performance [4,11] and residents' heating practices, such as preferred indoor temperature, heating schedules and the number of rooms heated [13,14].

Most studies and policies evaluate dwellings' readiness for LTDH primarily from an energy efficiency perspective [9,12]. While newly built homes generally meet stringent insulation standards and are considered suitable for LTDH, existing dwellings with low or moderately insulated envelopes are typically recommended to undergo deep renovation to enable connection to low-carbon energy sources such as LTDH [15]. For example, Wahi et al. [12] assessed a mid-row Dutch terraced house to determine the renovation measures necessary for compatibility with LTDH. Their findings indicate that, for supply temperatures below 55 °C, deep renovations are required, including insulation of external walls, floors, and roof, as well as replacement of windows and radiator upgrades. Likewise, Wang et al. [9] concluded that a deep retrofit was needed to connect a Swedish apartment building to a LTDH with 45 °C supply temperature, including roof and wall insulation, airtightness improvements, mechanical ventilation with heat recovery, and window upgrades.

Yet, this predominantly technical framing captures only part of the picture. Heating demand is not determined solely by building efficiency. Residents' heating practices, such as preferred indoor temperatures, which rooms are heated, and ventilation preferences, strongly influence operational heat demand and, therefore, the readiness of dwellings to operate effectively with LTDH [16–18]. These practices are, however, often overlooked when planning energy retrofits for DH compatibility. Standardized comfort assumptions in building energy calculations typically presume that households heat their homes uniformly to relatively high indoor temperatures (20 °C) [19]. However, field studies highlight substantial variations in indoor temperature preferences [20,21]. For example, van Wieringen et al. [21] and de Koning et al. [20] documented residents with contrasting comfort needs: one felt comfortable at 15 °C while using blankets in the living room, whereas another found 22 °C, the maximum temperature provided by floor heating, insufficient to stay warm. By stipulating uniform conditions across households, this narrow technical perspective overlooks the question of what level of comfort is actually desired or needed by different residents [22].

1.2. Integrating efficiency and sufficiency in building retrofits

Energy efficiency has been central to reducing operational energy demand in buildings. However, the IPCC's Sixth Annual Report emphasizes that substantial emissions reductions require combining efficiency improvements with demand-side sufficiency strategies [23]. Sufficiency promotes daily practices that avoid unnecessary demand for energy, materials, land and water, while ensuring human well-being within planetary boundaries [24]. It introduces a dual dimension: establishing a minimum level of provision to ensure decent living standards for all, while setting a maximum to align consumption with environmental limits.

Applied to energy-efficiency retrofits, this approach acknowledges that diverse experiences of comfort are often overlooked in decision-making, despite being essential to ensure equitable outcomes [23,25,26]. A sufficiency-oriented retrofit integrates residents' actual heating practices into the design of sustainable renovations. This means recognizing that households may heat selectively, accept lower indoor temperatures combined with small adjustments such as blankets or personal comfort systems, or adapt their energy practices seasonally. Rather than prescribing one-size-fits-all deep retrofit solutions, preparing dwellings for LTDH can strategically combine heating practices and technical measures tailored to household needs. While deep retrofit approaches can be prohibitively expensive, leading to renovations that never happen, a less intensive retrofit combined with residents' heating practices could reduce excessive material use, accelerate implementation, and generate less resistance among residents [16,27].

This targeted approach also addresses a critical policy gap: the focus on operational emissions often neglects the embodied carbon of retrofit materials [28]. Deep retrofits involving extensive insulation and high-performance glazing may entail substantial embodied carbon emissions that are not fully offset over the building's lifetime, especially in contexts of grid decarbonization or when projected energy savings are not realized. Integrating sufficiency principles into retrofit planning can moderate material use while maintaining effective LTDH readiness [29].

1.3. The social housing context and energy justice implications

Disregarding the variability of residents' heating practices in the retrofit decision-making for LTDH not only has technical but also social implications, particularly in social housing. In the Netherlands, social housing accommodates tenants with diverse socio-economic and cultural backgrounds and, correspondingly, a wide range of heating routines and comfort strategies: including practices aligned with sufficiency principles, such as heating fewer rooms or maintaining lower temperatures [20,21].

When actual user behaviour diverges from standard assumptions, retrofits may deliver lower-than-expected reductions in heating demand due to prebound and rebound effects [30–32]. This can lead to over-specification of renovation packages that are economically and materially intensive and may not be environmentally justified for all

households. Meanwhile, housing associations aim to make 450,000 homes natural-gas-free by 2030, and prepare buildings for future LTDH connections [33]. Achieving these targets require substantial labour and time, potentially slowing or inhibiting the transition to LTDH [34].

From a social perspective, retrofit dynamics raise concerns related to energy justice [35]. Recognition justice calls for acknowledging the diversity of residents' needs and practices rather than assuming homogeneous household behaviour. Distributive justice concerns how the benefits and burdens of retrofits, such as comfort improvements, energy savings, financial costs, and renovation-related disruptions, are allocated among residents. Aligning retrofit decisions with residents' actual heating practices may therefore support a more just, resident-centred transition to LTDH by reducing unnecessary burdens and recognizing diverse comfort needs [35,36].

1.4. Research gap and goal

In practice, connecting dwellings to LTDH is often associated with uniform deep retrofit recommendations based on standard occupant assumptions embedded in energy models and regulations [19,37]. Existing LTDH retrofit studies, including those from the Danish context [38–40], have established the technical conditions for lower supply temperatures in existing dwellings. However, residents' heating practices lead to variations in thermostat setpoints, ventilation preferences, and spatial heating patterns, directly influencing heating demand and LTDH compatibility. Yet, these implications are rarely integrated into the technical retrofit frameworks [20,21,41]. This paper addresses this gap by focusing on the demand side of the transition to LTDH, integrating residents' heating practices into retrofit decision-making to reassess whether deep retrofit interventions are technically necessary for LTDH readiness. Using a terraced house as a reference case, we apply a multi-criteria retrofit selection framework combined with parametric simulations to assess how diverse heating practices affect LTDH readiness. Renovation strategies are assessed by balancing thermal comfort, energy savings, environmental impacts, economic costs, and nuisance to residents.

While most studies assess the suitability of connecting dwellings to low-temperature district heating primarily in terms of reducing unmet hours and increasing energy savings [9,12,42], this study additionally incorporates social and environmental KPIs into the selection of viable retrofit pathways. In doing so, the study moves beyond standardized one-size-fits-all renovation approaches and evaluates a broader range of technically feasible and socially acceptable solutions. We argue that integrating the diversity of residents' heating practices into retrofit decision-making offers a promising pathway for the transition to LTDH through more effective use of material resources (construction materials, financial resources, skilled personnel) and immaterial resources (time, nuisance, emotional and social impacts).

2. Methods

The research methodology was structured into six steps, as illustrated in Fig. 1. Step 1 defined the reference case: a single-family terraced house located mid-row and equipped with a gas boiler, which must be prepared for connection to LTDH, with 45 °C supply temperature. Step 2 involved defining ten resident profiles to capture the variability of heating practices in Dutch social housing. Step 3 focused on selecting energy retrofit measures, including building-envelope upgrades and radiator improvements, resulting in a total of 33 retrofit packages. In Step 4, we established the settings required to run 330 building performance simulation scenarios, resulting from the combination of 33 retrofit packages and ten resident profiles. Step 5 described the five key performance metrics used to analyse these scenarios. Finally, Step 6 outlined the workflow used for the multi-criteria selection of scenarios for each resident profile.

2.1. Reference case and heating system

2.1.1. Reference case: Mid-row terraced house

Representing over 2 million homes (27% of the national residential stock), the social housing sector primarily consists of rented dwellings owned by non-profit housing associations [43]. The reference case in this study represents a typical single-family terraced house, a typology that accounts for 42% of the national building stock [14]. The house has three floors: the ground floor serves as the living area, the first floor contains the bedrooms, and the second floor consists of the attic (Fig. 2a). The house is oriented along a north-south axis and is located in the middle of a row, therefore with shared internal walls on both sides (Fig. 2b).

The reference terraced house was constructed in the post-war period (1946–1964) and features low levels of thermal insulation. The dwelling envelope thermal properties were selected based on the *Voorbeeldwoningen* (Example Dwellings) 2022 report [44], which defines the envelope performance of the Dutch building stock by building typology and construction period, as summarised in Table 1.

2.1.2. Low-temperature district heating (LTDH)

The reference case was assumed to be connected to a district heating network operating at a constant supply temperature of 45 °C throughout the year. This temperature was selected based on the Dutch policy context, in which the Programma Aardgasvrije Wijken (PAW) [45] has piloted low- and very-low-temperature district heating since 2018, with supply temperatures between 30 and 55 °C. A 45 °C target is also reflected in the national planning work by PBL [46] indicating a broad

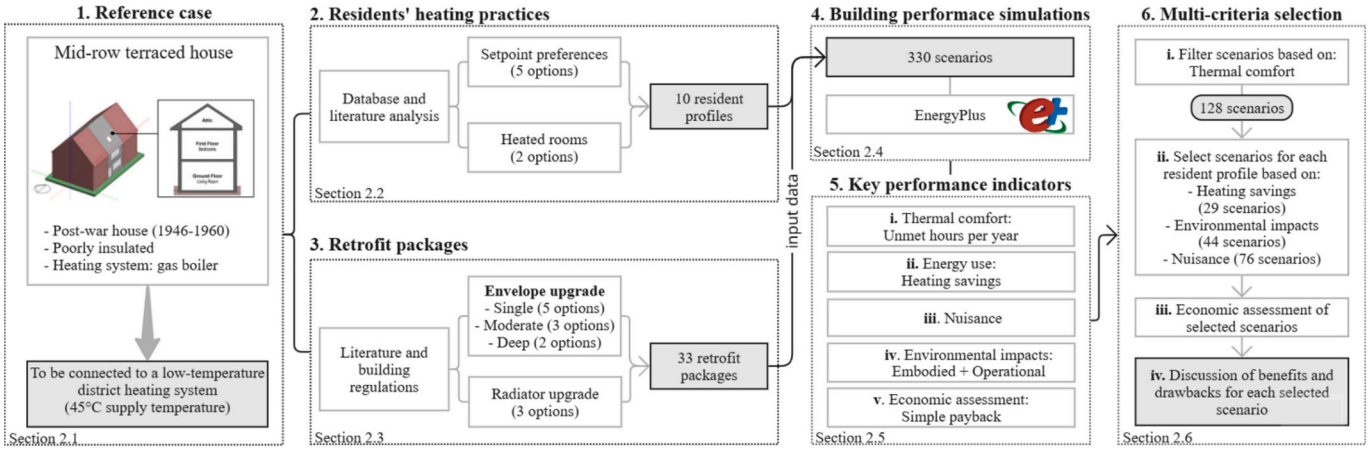
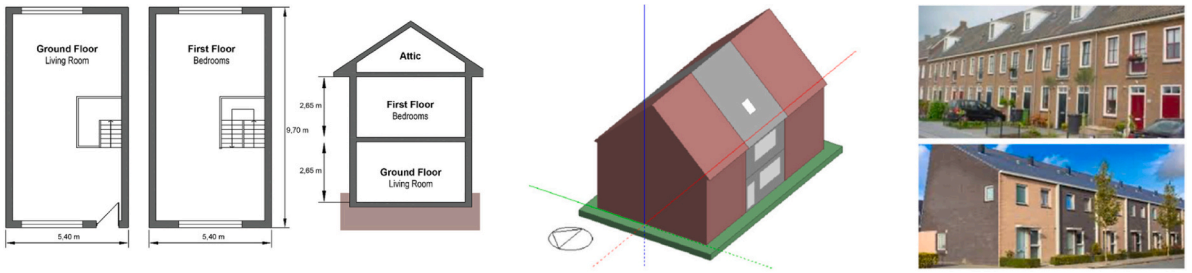


Fig. 1. Overview of the methodology used in this study.



a) Simplified floor plans and section

b) Elevation of the reference case (in grey) situated in the middle of a row, with neighbouring houses shown in red.

c) Example of Dutch terraced houses

Fig. 2. Reference case characteristics.

Table 1
Reference case's envelope thermal properties.

Envelope component	Thermal properties
External walls	Rc: 0.7 m^2.K/W
Ground floor	Rc: 0.8 m^2.K/W
Pitched roof	Rc: 1.7 m^2.K/W
Windows: double glazing	Ug: 2.7 W/m^2.K / SHGC: 0.75
Infiltration	0.7 air change rate per hour (ach)
Ventilation type	Natural ventilation
Radiator type (per floor)	One radiator type 11 and one type 22
Heating system	Gas boiler

agreement in the Dutch policy landscape that this is a reasonable design parameter, particularly in terms of future-proofing the building stock and substantially lowering the carbon impact of residential heating. Lower supply temperatures reduce distribution heat losses and enable heat generation at higher efficiencies and their compatibility with a wider range of sustainable heat sources compared to higher-temperature alternatives, which are relevant to the Dutch decarbonisation goals.

It is important to note that the classification of district heating supply temperature ranges is not fully consistent across the literature. Some frameworks categorise 45 °C within the ultra-low-temperature district heating (ULTDH) range [38], while others, classify supply temperatures between 30 and 60 °C as medium-to-low temperature systems [12]. Despite these differing definitions, the present study adopts a constant supply temperature of 45 °C as a boundary condition and considers it the lower boundary of low-temperature district heating.

2.2. Residents' heating practices

In the Netherlands, social housing is home to tenants from diverse backgrounds, with a wide variety of heating practices. To capture this variability, we identified ten resident profiles based on previous research conducted by the authors, which analysed a national database containing information from 1160 households on energy use in social housing [14]. Additional insights were drawn from a field study by MilieuCentraal on indoor temperature preferences among diverse cultural groups in the Netherlands [47]. Key factors considered to develop the profiles included setpoint temperature, the rooms heated within the dwelling, household size, and natural ventilation preferences, presented in the following subsections.

2.2.1. Number of heated rooms

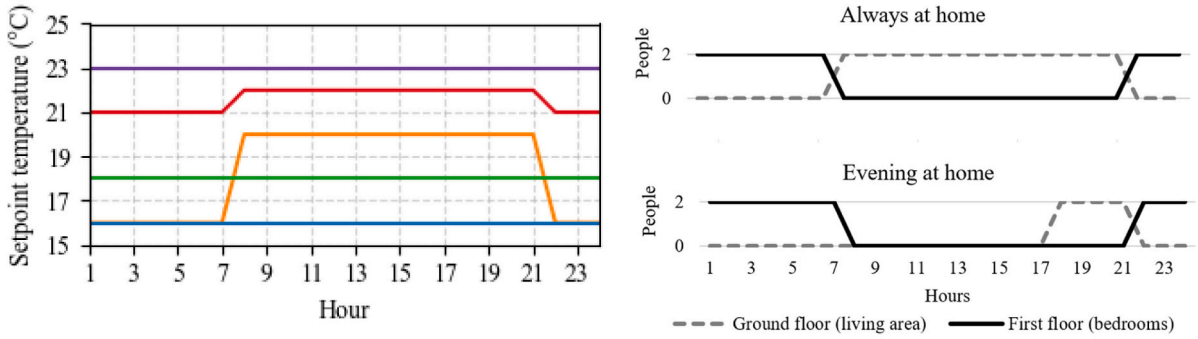
Two options were considered for the number of heated rooms: (1) both the ground floor (living area) and the first floor (bedrooms) are heated, or (2) only the ground floor (living area) is heated. The second floor (attic) was assumed to be unoccupied and therefore not heated. This choice was informed by previous research conducted by the authors based on the woON database [48], which showed that 63% of residents reported that, when the living room is heated, bedrooms are never or rarely heated. This pattern is further supported by field studies conducted by de Koning et al. [20] and van Wieringen et al. [21] with social housing residents in two Dutch cities, which revealed that many residents enjoy sleeping in a cooler, "fresh" environment, as it creates a pleasant contrast with the warmth of their blankets.

2.2.2. Setpoint preferences and occupancy patterns

To represent the variability in residents' preferred indoor temperatures, we defined five representative heating setpoint profiles. Setpoint 1 (SP1) corresponds to very high indoor temperatures (23 °C), while Setpoint 2 (SP2) represents high indoor temperatures (21–22 °C). Setpoint 3 (SP3) aligns with the NTA 8800:2024 standard [19], maintaining 20 °C during the day with a night setback of 16 °C. Setpoint 4 (SP4) reflects a moderate temperature of 18 °C, and Setpoint 5 (SP5) represents a low indoor temperature of 16 °C (Fig. 3a).

SP1 was defined based on research by MilieuCentraal [47], which examined heating energy use across diverse cultural groups living in the Netherlands. Their field studies revealed that setpoint temperatures can reach as high as 23 °C during winter, particularly among residents from different cultural backgrounds. SP2, SP4, and SP5 were derived from the authors' previous research about residents' heating practices in social housing [14], in which a large dataset on energy practices in Dutch households (WoON 2018 [48]) was used to extract data for creating resident profiles. SP3 was selected to represent standard occupancy conditions, reflecting the temperature parameters prescribed in the Dutch regulation NTA 8800, which establishes design criteria for domestic buildings and is widely applied as a reference for energy labelling and retrofit decision-making [19].Occupancy patterns were aligned with setpoint preferences: Very high (SP1), high (SP2), and standard (SP3) temperatures were associated with residents who stay at home all day (e.g., retirees or those working from home). Moderate (SP4) and low (SP5) setpoint temperatures were linked to residents who spend most of the day outside the home for work or study and return only in the evening (Fig. 3b).

For SP4 (moderate temperature) and SP5 (low temperature), we envision occupants to achieve individual comfort with complementary systems, such as warmer clothing, couch blankets, and static or wearable personal comfort systems (PCS). These setpoint temperatures were derived from the woON database [48], a national quantitative study in which 1160 households living in social housing reported their indoor temperature preferences throughout the day. As the dataset relies on reported numerical values, the underlying motivations behind these preferences are not captured. Therefore, to contextualize these findings, we draw on supporting literature showing that thermal comfort can be achieved with PCS at low indoor temperatures, as low as 15 °C [49–51]. Moreover, field studies conducted by de Koning et al. [20] and van



a) Setpoint temperature variation b) Occupancy patterns

Fig. 3. Heating setpoint preferences and occupancy patterns.

Wieringen et al. [21] revealed that thermal comfort is more closely associated with specific locations rather than entire rooms. These studies found that residents often referred to particular spots to keep warm, where they engage in sedentary activities, such as the couch for watching TV or a chair for reading. This further supports the feasibility of the use of personal comfort systems to achieve thermal comfort at lower setpoint temperatures.

It is important to note that the setpoints are defined as the threshold temperature that activates the heating system. However, the resulting indoor temperature also depends on several additional factors, including outdoor conditions, internal heat gains, solar heat gains, and the thermal mass of the building envelope. Therefore, this does not imply that the dwelling remains constantly at the defined setpoint temperature; rather, represents the minimum temperature allowed in the heated rooms, although this temperature may often be not reached in the case of lower setpoint temperatures, such as SP4 and SP5.

2.2.3. Household size and natural ventilation preferences

Household size was defined as two residents, consistent with the size of the terraced house selected as the reference case. This household size also represents 30% of social housing respondents in the WoON database [14,48].

According to the authors' earlier work, residents reported keeping ventilation grilles permanently open and leaving windows occasionally ajar during the heating season, both in bedrooms and living rooms [14]. Field studies by de Koning et al. [20] further explained the motivations for opening windows during winter, including eliminating odours, mitigating the noise from mechanical ventilation systems, and the perception that fresh air promotes health. Based on these findings, it was assumed that grilles remain open and windows are left slightly ajar in both the living room and bedrooms when occupied, across all profiles.

2.2.4. Resident profiles

Table 2 summarises the ten resident profiles created by combining the parameters defined in Sections 2.1.2 to 2.1.1.3. Fig. 4 illustrates the variability in energy consumption across these profiles, obtained through the building performance simulation further described in Section 2.3. This confirms the increased spread in energy use when broader assumptions about residents' heating practices are considered.

2.3. Definition of retrofit packages

The retrofit packages were defined considering improvements in the building envelope and radiator upgrades. In total, 10 packages of building envelope energy-efficiency measures were defined and 2 radiator upgrades. Along with the pre-retrofit state, this leads to 33 building variants, as detailed in the following subsections.

Table 2
Profiles of residents' heating practices selected for this study.

Profile	Setpoint temperature	Heated rooms	Occupancy	Household size	Natural ventilation
SP1-a SP1-lr	SP1: Very high temperature (23 °C)	All rooms Living area	Always at home	2 people	Grilles open and windows slightly ajar when occupied
SP2-a SP2-lr	SP2: High temperature (21 - 22 °C)	All rooms Living area			
SP3-a* SP3-lr	SP3: Standard (20 °C and 16 °C setback)	All rooms Living area			
SP4-a SP4-lr	SP4: Mild temperature (18 °C)	All rooms Living area	Evening at home		
SP5-a SP5-lr	SP5: Low temperature (16 °C)	All rooms Living area			

* standard occupancy used in the Dutch energy label regulation NTA8800:2024 [19].

2.3.1. Building envelope energy-saving measures

The following envelope energy-efficiency measures were considered: cavity wall insulation, external wall insulation (applied to the exterior side), ground floor insulation, roof insulation, window upgrades, and airtightness improvements to reduce infiltration (Table 4). The measures were combined at three levels: Single-measure retrofit (SR) - five options, each targeting a specific envelope component; Moderate retrofit (MR) - three options, combining two measures; and Deep retrofit (DR) - two options, integrating all improvements along with enhanced airtightness (Tables 3 and 4).

For the deep retrofit (DR) options, the strategies were aligned with current retrofit standards. DR1 follows the Dutch government's recommendations for insulation upgrades in housing retrofits, which promote highly insulated envelopes to make existing buildings "future-proof" and prepared for the transition to a gas-free building stock [37]. DR2 is based on the EnerPHit standard for energy retrofits in cool-temperate climates [52]. This standard provides two compliance paths: achieving a performance threshold of 25 kWh/m^2 or meeting prescriptive values for envelope components. For this study, the prescriptive approach was adopted to enable direct comparison with the other proposed packages.

2.3.2. Radiators upgrade

The existing heating system comprises two radiators per heated floor

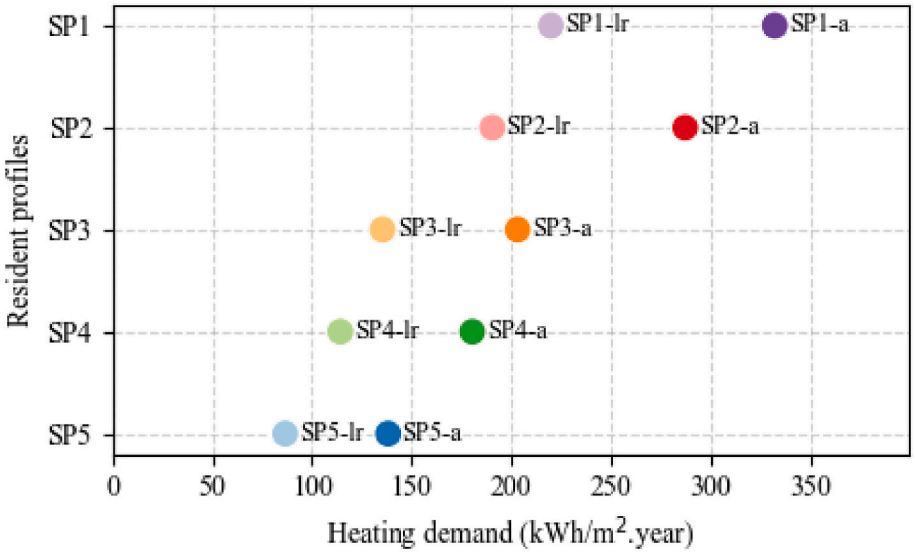


Fig. 4. Variability in heating demand for resident profiles.

Table 3
Retrofit packages and thermal properties (Rc values).

Upgraded component	Reference case	Single retrofit					Moderate retrofit			Deep retrofit	
		S1	S2	S3	S4	S5	M1	M2	M3	D1	D2
External walls - cavity (m^2 K/W)	0.7	2.2	7.3	–	–	–	7.3	7.3	7.3	7.3	7.3
External walls - exterior side (m^2 K/W)		–		–	–	–					
Ground floor (m^2 K/W)	0.8	–	–	3.8	–	–	3.8	–	–	3.8	7.1
Roof (m^2 K/W)	1.7	–	–	–	8.3	–	–	8.3	–	8.3	8.3
Windows (W/m^2K / SHGC)	2.7/ 0.75	–	–	–		1.0/ 0.5	–	–	1.0/ 0.5	1.0/ 0.5	0.8/ 0.5
Infiltration (ach)	0.7	–	–	–		–	–	–	–	0.5	0.3

Table 4
Materials of energy-efficiency measures.

Envelope component	Material
External walls (cavity)	Polyurethane (PU) foam
External walls (exterior side)	Expanded polystyrene (EPS) plus finish
Roof insulation	Mineral wool inside sloping roof plus finish
Ground floor	1. Expanded polystyrene (EPS) 120 mm 2. Expanded polystyrene (EPS) 250 mm
Windows	1. Double-pane low emissivity glass 2. Window triple pane
Infiltration upgrade	Wall, roof and windows sealing

(ground floor and first floor): one type 11 and one type 22. These radiator types have the same width and length but vary in depth, as described in Table 5. Their corresponding heating capacities were determined based on the heating demand calculated for a gas boiler system with high supply temperature (80 °C), incorporating an oversizing factor as proposed by Wahi et al. [42,51] as a common robustness measure. The oversizing factor was calculated as 20 times the heated floor area of the thermal zone and added to its design heating capacity. As each floor of the terraced house has an area of 53 m^2, this resulted in approximately 1 kW being added to the design heating capacity of the radiators per floor, representing 20% of the total design heating capacity per floor (5 kW).

Considering this robustness measure is important because it reflects common radiator sizing practice, in which radiators are typically oversized for peak winter conditions. Therefore, current radiators may still provide sufficient heating capacity under reduced supply temperatures, which is important when assessing whether radiator upgrades are necessary when connecting homes to low-temperature district heating. It is important to note that radiator oversizing may also occur for other reasons, such as previous renovation or the installation of larger radiators than required based on market availability and installer preferences. The oversizing equation adopted in this study represents an assumption based on the currently available literature. However, actual radiator capacities may vary between dwellings and can be either higher or lower than estimated.Two upgrade scenarios were assessed, as described in Table 5. The selection of these scenarios was informed by specifications available on a commercial radiator supplier's website [53]. To minimise potential impacts on the interior layout, reduce disruption to residents, and ensure that this intervention would be suitable for most existing dwellings, the radiators height and width were kept constant in the upgrade scenarios, and only the depth was increased.

Table 5
Radiator upgrade.

	No radiator upgrade	1: 50% of radiators upgraded	2: All radiators upgraded
Radiator type	11 and 22	Replacement of radiator type 11 to radiator type 33	Replacement of both radiators to type 33
Radiator size [width x length x depth (cm)]	Type 11: 60x160x5 Type 22: 60x160x10.3	Type 22: 60x160x10.3 Type 33: 60x160x16.1	Type 33: 60x160x16.1
Heating design capacity at 80 °C (kW)	5	9	12

2.3.3. Costs and carbon embodied of retrofit packages

The costs of the renovation packages were sourced from RVO's Kostenkentallen database [54], reflecting the price level of July 2024. These costs include materials, labour, and equipment, selected based on dwelling type (single-family) for a project-based approach in the Netherlands (Fig. 5a).

The embodied carbon in the renovation materials was estimated using Environmental Product Declarations (EPDs) available in the Embodied Carbon in Construction Calculator tool (EC3) [55]. The EPDs provide data on the carbon emissions of construction materials during the A-1 to A-3 stages of their production, known as the cradle-to-gate stages. It accounts for emissions up to the point of production but excludes transportation to the site, operational emissions, and end-of-life impacts (Fig. 5b).

2.4. Building performance simulations (BPS)

The reference case was modelled as the baseline input for the building performance simulations and was then combined with the retrofit packages and resident profiles, resulting in 320 simulation scenarios. All simulations were conducted using EnergyPlus, using a typical meteorological year derived from the 1996–2015 period in De Bilt, the Netherlands [43].

The natural ventilation was modelled considering grilles and windows left ajar during occupied hours, assuming an air change rate of 1.2 ACH, which is considered a sufficient ventilation level according to NEN 1087 [56]. The thermal properties of the envelope materials for both the reference building and the energy-saving measures were modelled as described in Table 3.

2.4.1. Modelling approach for the low-temperature district heating

The LTDH system was modelled using a simplified approach focusing on building-level analysis, consistent with approaches adopted in previous studies [12,57]. A gas boiler was used in EnergyPlus to supply hot water to the radiators, with the hot water loop setpoint reduced to 45 °C. The radiators were modelled using the heating capacities indicated in Table 5, with their heat output constrained by the reduced supply temperature. The return temperature was dynamically calculated by EnergyPlus at each simulation timestep, based on the radiator heat output, water mass flow rate, and inlet water temperature. The return temperature was therefore not fixed but automatically adjusted according to the heating demand and radiator performance [58]. This method allows assessment of how a lower supply temperature affects the radiators' ability to maintain the desired indoor air temperature setpoint, while accounting for the building thermal characteristics (infiltration and envelope thermal properties defined by the retrofit packages) and residents' heating practices (indoor temperature preferences, heated rooms and ventilation losses, defined by resident profiles), without the need to model the entire district heating network.

2.4.2. Validation of the building performance simulations

To validate the simulations, an order-of-magnitude check was performed, following the approach suggested by Zhai et al. [59] as a validation practice for simulation-based research. The simulated heating demand of the reference case, operating with a gas boiler under a standard occupancy pattern (profile SP3-a), was compared with benchmark values from a national database. According to *Voorbeeldwoningen* (Example Dwellings) 2022 report [44], dwellings with similar construction period and envelope characteristics exhibit an average heating demand of approximately 200 kWh/m^2. This value closely aligns with the simulated demand of 203 kWh/m^2 (Fig. 4), thereby supporting the accuracy of the simulation results. Additionally, the geometry and thermal properties of the reference building closely align with those of the model used by Xu et al. [60], which was calibrated with in-situ measurements. This provides further confidence in the accuracy of the modelling assumptions and input parameters adopted in this study.

Based on this validated reference case, the parametric set of 330 scenarios was developed, in which scenarios differ only in heating practices and retrofit packages. This approach ensures a consistent modelling framework and enables a robust evaluation of the impact of these variables on building performance.

2.5. Key performance indicators (KPIs)

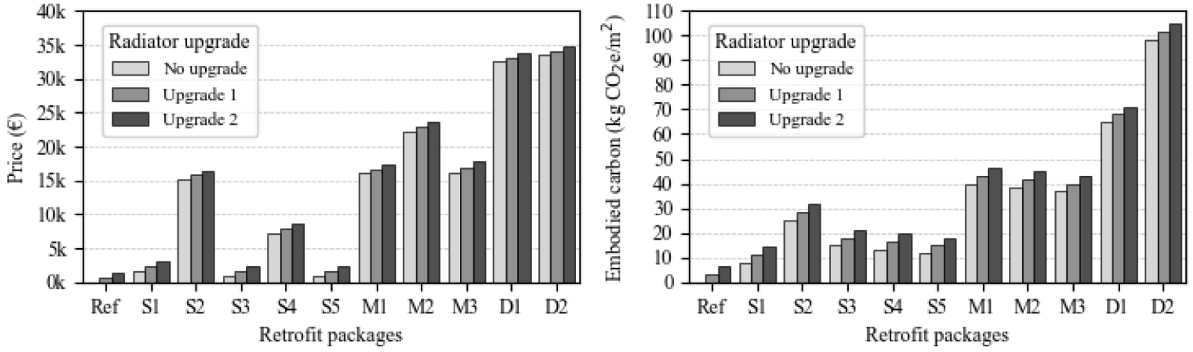
Five KPIs were used to analyse the results in terms of thermal comfort, energy use for space heating, nuisance, environmental impacts, and economic payback.

2.5.1. Thermal comfort: Unmet hours per year (%)

Thermal comfort was assessed based on the dwelling's and radiators' ability to achieve the desired indoor temperature defined by each resident profile, expressed as unmet hours per year (%). This indicator represents the percentage of occupied hours per year when the indoor temperature is lower than 0.5 °C below the heating setpoint specified for each profile.

2.5.2. Energy use for space heating: Heating savings (kWh/m^2)

The heating demand (kWh/m^2) of each scenario represents the amount of heat required to maintain the indoor temperature specified for each resident profile, expressed per unit of heated floor area and calculated through building performance simulations. Heating savings (kWh/m^2) were determined by comparing the heating demand for space heating of the reference case, without retrofit and operating with a gas



a) Costs of retrofit packages

b) Embodied carbon in the retrofit packages

Fig. 5. Costs and embodied carbon of renovation packages.

boiler, with the heating demand of the retrofit scenarios connected to a LTDH system (45 °C).

It is important to note that the energy use for personal comfort systems, assumed to be used for profiles with moderate (SP4) and low (SP5) setpoint temperatures, were not included in the analysis, as their energy use is considered negligible when compared to space heating demand [49].

2.5.3. Nuisance

The level of nuisance refers to disruptions to residents' daily lives caused by renovations. Such disturbances may arise from temporary relocation, noise, dust, or other factors that temporarily reduce quality of life. Additional impacts can also affect usable space and interior layout, such as the installation of additional pipes and larger radiators that can reduce available living space. Research indicates that nuisance is a decisive factor influencing tenants' willingness to accept proposed renovations, making it a critical consideration in retrofit planning [61,62].

The level of disruption was defined based on Tzortzopoulos et al. [63]. A low-level disruption occurs when renovations take place outside the home, causing minimal disturbance; medium-level disruption involves long durations, temporary blockages, or excessive dust; and high-level disruption includes activities that significantly affect daily life and may require temporary relocation (Table 6). In this study, external wall insulation and cavity wall insulation were considered to take place outside the home and were therefore classified as low disruption. Roof insulation was assumed to be installed in the attic and was classified as medium disruption, as the attic is unoccupied but accessed from within the dwelling. As the reference case in this study does not include a crawl space, ground floor insulation was assumed to be carried out from inside the house and was therefore classified as high disruption.

2.5.4. Environmental impacts: Total global warming potential (kg CO2 e/m^2.25 years)

This indicator represents the sum of the embodied carbon emissions in the retrofit packages and the operational carbon emissions over 25 years. Embodied carbon emissions for each retrofit package were calculated using the EC3 calculator [55], explained in Section 2.2.3 and illustrated in Fig. 5a. Operational emissions were calculated based on annual heating demand results from building performance simulations, projected over a 25-year period. The carbon emission factor for natural gas, calculated for the operational carbon emissions for the reference case, was considered as 56.2 kgCO_2e/GJ sourced from NEA (2025) [64].

Annual average carbon emissions factors for different District Heating systems in the Netherlands were collected from [65–67]. An emission factor of 18 kgCO_2e/GJ was used for the analysis. This emission factor represents district heating systems that utilize sources other than natural gas for peak demand and backup power in their total energy mix, representing a natural gas-free scenario. Additionally, we assumed constant emissions factors throughout the 25-year analysis period, without accounting for potential grid decarbonization or policy interventions.

Table 6
Nuisance level for each energy-efficiency measure and active systems.

		Current radiator	Radiator upgrade 1	Radiator upgrade 2
S1:	Cavity insulation	Low	Medium	Medium
S2:	Cavity + external wall	Low	Medium	Medium
S3:	Ground floor	High	High	High
S4:	Roof insulation	Medium	Medium	Medium
S5:	Windows	Medium	Medium	Medium
M1:	Walls + ground floor	High	High	High
M2:	Walls + roof	Medium	Medium	Medium
M3:	Walls + windows	Medium	Medium	Medium
D1:	All	High	High	High
D2:	All	High	High	High

2.5.5. Economic assessment: Simple payback (years)

The simple payback period (years) represents the time required to recover the initial investment in each retrofit package (Fig. 5a) through yearly savings on the energy bill. These savings were calculated based on the heating demand obtained from building performance simulations, considering a tariff of €0.158 per kWh, valid for 2025 [68]. In the Netherlands, legislation stipulates that the variable price of district heating is capped at the equivalent price of natural gas (*niet-meer-dan-anders* principle) [69]. Therefore, we applied the same tariff to both the natural gas used in the reference case and the district heating used in the retrofit scenarios, considering only the variable costs associated with energy consumption for space heating.

2.6. Multi-criteria selection of retrofit scenarios

The goal of the multi-criteria selection was to consider multiple perspectives when identifying a range of possible renovations that allow the transition from a gas boiler to LTDH. The multi-criteria selection does not aim to identify a single 'optimal' solution, but to reveal a set of viable pathways reflecting different priorities and resident profiles. The retrofit scenarios were chosen considering quantitative and qualitative KPIs, supporting a multi-criteria selection based on thermal comfort assessment, heating savings, environmental impacts, retrofit costs and nuisance to residents. The analysis explicitly accounts for diverse heating practices and their implications for retrofit performance. Having multiple criteria explicitly considered can also facilitate negotiations among diverse stakeholders as well as integrating social (or resident-oriented aspects) dimensions in design decisions.

First, we selected the feasible scenarios based on their ability to meet the desirable setpoint temperatures defined for each resident profile. In this initial screening, scenarios that fail to meet basic comfort expectations were excluded. In the second selection step, we identified the best-performing scenarios for each KPI, acknowledging that priorities vary among residents and/or stakeholders. Therefore, the selection focused on the top-performing solutions for each criterion: lowest nuisance, highest heating savings, and lowest environmental impacts (Fig. 6).

3. Results

3.1. Thermal comfort: Unmet hours (%)

The annual percentage of unmet hours indicates whether a dwelling can maintain the desired indoor temperature throughout the year. In this study, the desired indoor temperature is defined according to each resident profile's heating practices. Because residents' thermal comfort requirements are already embedded in these profiles, unmet hours was used as the first screening criterion for selecting suitable renovation packages. Scenarios that failed to achieve the desired indoor temperature for a given profile – defined as any occurrence of unmet hours (>0%) - were therefore excluded from further analysis. Fig. 7 shows the percentage of unmet hours per year across all scenarios and resident profiles.

The results reveal a strong relationship between unmet hours and resident profiles, highlighting the importance of considering residents' heating practices in retrofit decision-making. For example, in the reference case (no envelope retrofit and no radiator upgrade) connected to LTDH, the profile that heats all rooms to a very high setpoint (SP1-a) experienced 45% unmet hours per year, whereas the profile heating only the living room to a low temperature (SP5-lr) experienced only 5%. This difference is largely reduced when radiators are upgraded. Upgrading all radiators without any envelope retrofit also proves to be a feasible strategy for profiles heating all rooms homogeneously to high (SP2-a), standard (SP3-a), moderate (SP4-a), and low (SP5-a) temperatures. Only

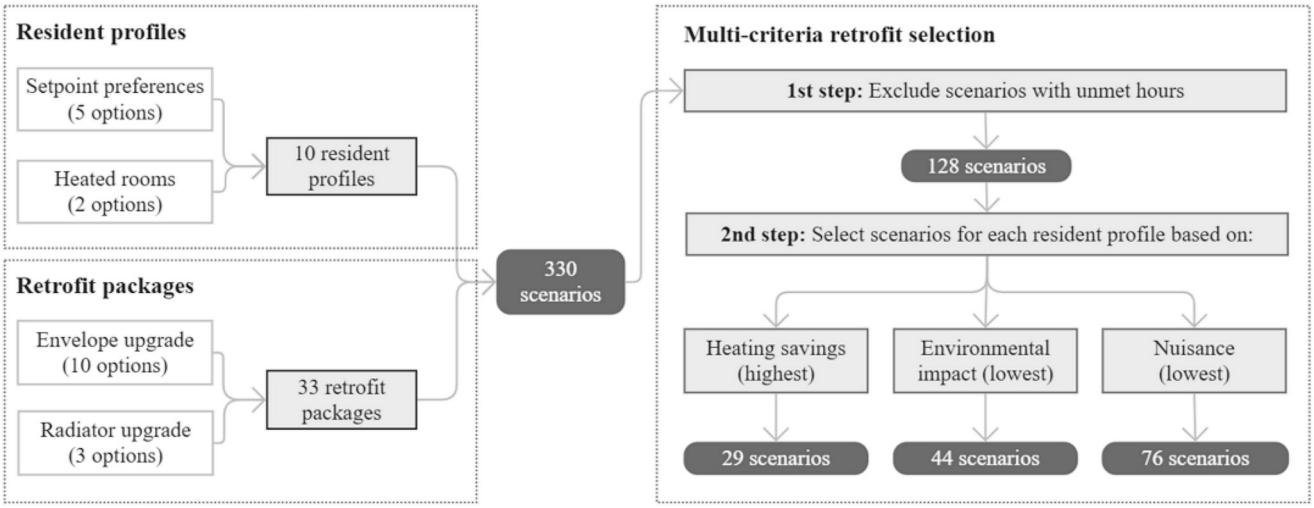


Fig. 6. Workflow for multi-criteria scenario selection.

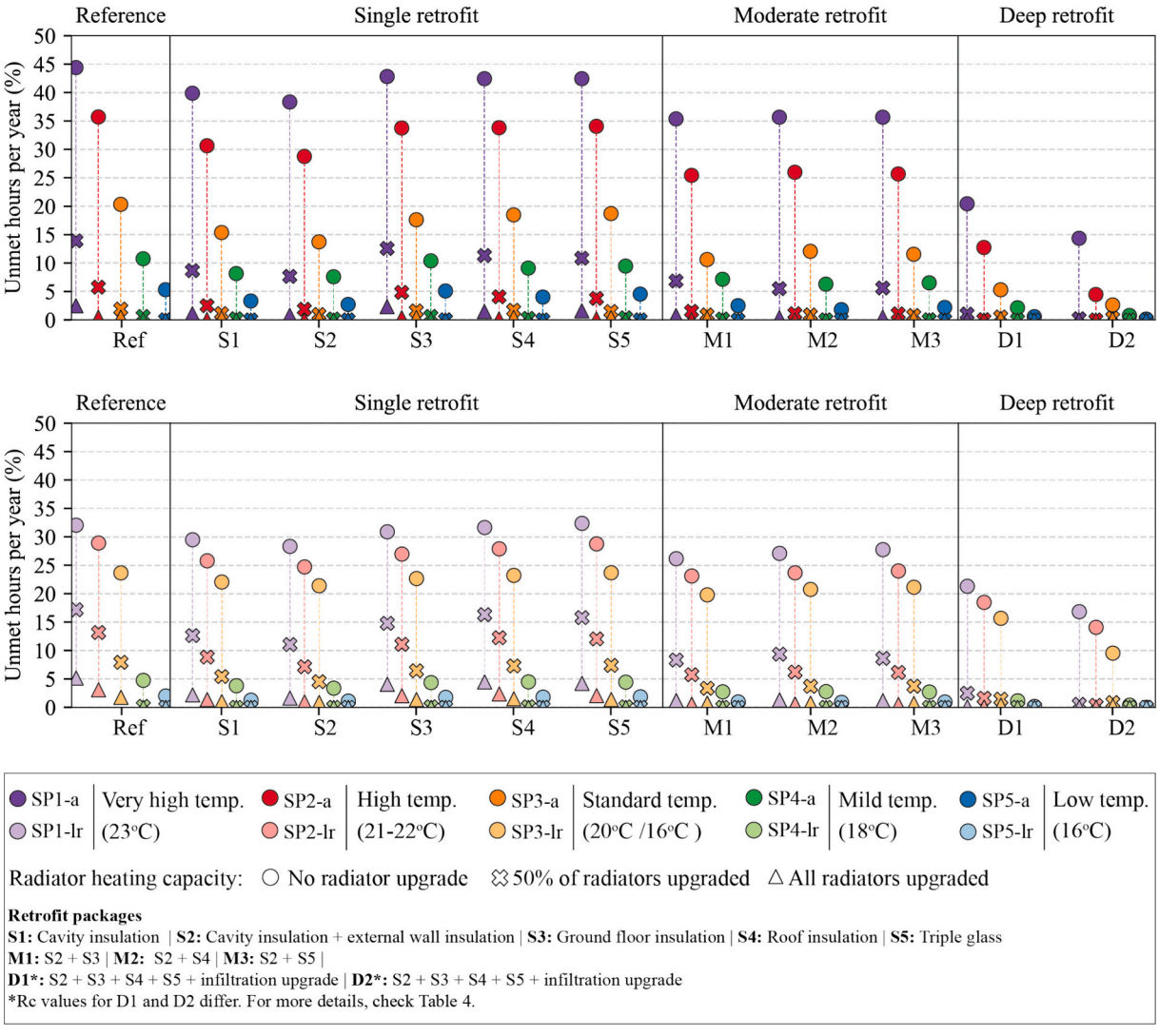


Fig. 7. Percentage of unmet hours per year, considering all scenarios. Scenarios without unmet hours (0%) were selected in the first filter as feasible scenarios in terms of thermal comfort.

the profile with very high setpoints in all rooms (SP1-a) requires at least a moderate or deep retrofit combined with radiator upgrades to avoid

unmet hours.

It is important to highlight that a sufficiency-based practice of heating only the living area can, counterintuitively, require more intensive envelope retrofits and radiator upgrades than heating all rooms homogeneously under LTDH. This occurs because larger temperature differences between heated and unheated rooms increase heat losses through internal partitions, making it more difficult to maintain comfort in the heated space at low supply temperatures. For example, profiles heating only the living area to very high (SP1-lr) or standard temperatures (SP3-lr) require a moderate or deep retrofit combined with a full radiator upgrade. In contrast, the corresponding profiles heating all rooms (SP2-a and SP3-a) can eliminate unmet hours with radiator upgrades alone.

3.2. Filtered scenarios: Heating savings, environmental impacts and nuisance

In a second selection step, the scenarios without unmet hours (0%) were evaluated based on heating savings, environmental impacts, and nuisance. Scenarios excluded during the thermal comfort screening are shown as grey dots in Fig. 8. Among the thermally feasible scenarios, the best-performing options for each key performance indicator (KPI) were identified, focusing individually on lowest nuisance, highest heating savings, and lowest environmental impacts. Fig. 8 reveals distinct patterns in retrofit performance across resident profiles, which are discussed in the following subsections.

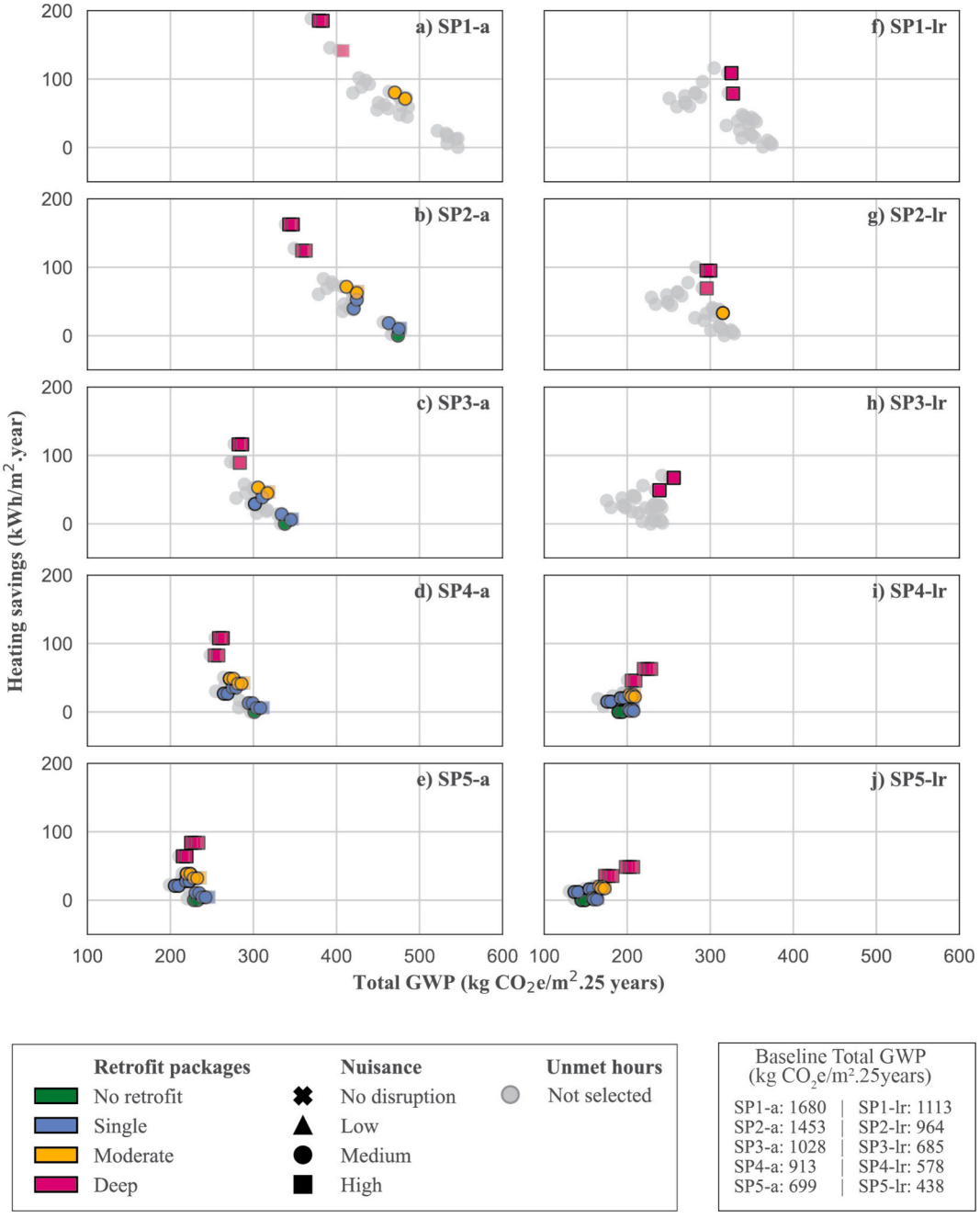


Fig. 8. Scatterplot for all scenarios showing heating savings (axis y) and environmental impacts (axis x). Scenarios not selected in the first filter are displayed in grey, while the ones selected are displayed with colours and grey edges. Scenarios selected in the second filter are displayed with colours and black edges.

3.2.1. Heating savings

Heating savings were calculated by comparing the heating demand (kWh/m^2) of the reference case (operating with a gas boiler and no retrofit measures) with scenarios that include envelope and/or radiator upgrades connected to a LTDH system. Across all resident profiles, deep retrofits achieved the highest absolute heating savings; however, the magnitude of these savings varies substantially between profiles (Fig. 8).

Profiles heating all rooms to very high (SP1-a) or high temperatures (SP2-a) exhibit the largest reductions in heating demand under deep retrofit scenarios, reaching up to 188 and 163 kWh/m^2 per year, respectively. These values outperform those achieved with moderate retrofit packages, which result in savings of up to 102 and 83 kWh/m^2 per year for the same profiles. In contrast, profiles following less intensive heating practices, such as heating only the living area to moderate (SP4-lr) or low (SP5-lr) temperatures, show much smaller differences in heating savings across deep, moderate, and single retrofit options. For example, profile SP5-lr achieves heating savings of up to 49, 20, and 17 kWh/m^2 per year under deep, moderate, and single retrofit packages, respectively.

These results demonstrate that the benefits of deep retrofits are not uniform across resident profiles. Relying on a single "standard" heating profile to guide retrofit decision-making may therefore lead to an overestimation of benefits for some households. For several profiles, substantial heating savings can be achieved with less intensive retrofit packages, emphasizing the importance of considering residents' heating practices in the selection of renovation strategies.

3.2.2. Environmental impacts

Environmental impacts were calculated as the sum of embodied carbon emissions associated with the retrofit packages and operational carbon emissions over a 25-year period, based on the heating demand of each resident profile and retrofit scenario. A shift is observed in the environmental performance of retrofit strategies between profiles with high and low heating demand. For resident profiles with higher heating demand, such as those heating all rooms to very high (SP1-a), high (SP2-a), or standard (SP3-a) temperatures, deep retrofits result in the lowest environmental impacts, as reductions in operational emissions outweigh the additional embodied carbon associated with more intensive retrofit measures. In contrast, for profiles with lower heating demand, including those heating all rooms to moderate (SP4-a) or low (SP5-a) temperatures, the environmental impacts of deep, moderate, and single retrofit options are very similar, differing by up to 40 kgCO$_2$e/m^2. For the lowest-demand profiles, those heating only the living area to moderate (SP4-lr) or low (SP5-lr) temperatures, an inversion occurs: deep retrofits generate higher environmental impacts (up to 220 and 198 kgCO$_2$e/m^2, respectively) than moderate (up to 194 and 161 kgCO$_2$e/m^2, respectively) or single retrofit measures (up to 183 and 149 kgCO$_2$e/m^2, respectively). In these cases, the embodied carbon associated with the retrofit strategies outweighs the reductions in operational emissions.

When compared with the reference case operating with a gas boiler, the transition to LTDH remains environmentally beneficial across all resident profiles and retrofit packages. For example, even the scenario with the highest environmental impact (deep retrofit) for the lowest-consumption profile (SP5-lr) results in 198 kgCO$_2$e/m^2 over a 25-year period, which is substantially lower than the 438 kgCO$_2$e/m^2 observed for the same resident profile (SP5-lr), considering the reference case (no envelope retrofit or radiator upgrade) operating with a gas boiler (Fig. 8). It should be noted that this assessment considers operational carbon emissions and the embodied carbon associated with building envelope retrofit measures and radiator upgrades. Additional sources of embodied carbon, such as those related to pipe insulation and the construction or upgrading of LTDH infrastructure, were not included in the analysis.

3.2.3. Nuisance

For almost all resident profiles, the minimum level of nuisance associated with preparing existing dwellings for the transition from a gas boiler to LTDH is classified as medium, according to the nuisance considered in Table 6. An exception is observed for profiles that heat only the living area to very high (SP1-lr) or standard (SP3-lr) temperatures. For these profiles, achieving the required thermal comfort conditions requires a deep retrofit, leaving high-nuisance solutions as the only feasible option, as explained in Section 3.1.

3.3. Benefits and drawbacks of selected scenarios

The retrofit scenarios selected through the multi-criteria selection are quantified in Table 7 and illustrated in Fig. 9. For each resident profile, scenarios were selected based on their performance with respect to four KPIs: unmet hours (=0%), heating savings (highest values), environmental impacts (lowest values), and nuisance (lowest category). The colours in the matrix indicate the KPI driving the selection, while the codes shown within each cell identify the main drawback associated with the corresponding scenario. White cells represent scenarios that were excluded during the thermal comfort screening due to the presence of unmet hours (> 0%).

Current approaches to preparing dwellings for natural gas-free heating systems, such as LTDH, typically assume a standard profile (SP3-a), with a primary focus on avoiding unmet hours and reducing heating demands. This logic is reflected in the simulation results: for profile SP3-a, a deep retrofit combined with radiator upgrades emerges as the most effective strategy for reducing heating demand. Because this assessment is based on a single, standardized occupant profile, the selected retrofit scenario involves envelope- and system-oriented measures that perform well under these assumptions. As a result, this approach tends to promote a narrow set of renovation solutions applied uniformly across dwellings, following the logic of insulation standards and energy label improvements, rather than accounting for residents' diverse practices and individual needs, which are not adequately addressed by a one-size-fits-all solution.

When a broader range of residents' heating practices is considered, together with additional KPIs such as environmental impacts and nuisance, a wider set of viable retrofit pathways emerges. Table 7 summarises the number of scenarios selected for each resident profile across the different KPIs. Rather than converging on only two retrofit options (indicated in orange text in Table 7), the analysis identifies up to 28 potential retrofit solutions, depending on the resident profile considered.

The matrix, illustrated in Fig. 9, puts all the chosen scenarios for each profile and KPI into perspective. Fig. 10 complements this overview by presenting the payback periods of the selected scenarios, highlighting their economic implications. Some patterns can be observed:

3.3.1. Scenarios selected based on thermal comfort

The reference case (without retrofit measures or radiator upgrades), single retrofit package S3 (ground floor insulation), and moderate retrofit package M1 (cavity insulation + external wall insulation + ground floor insulation) are never selected for any profile, as these retrofit packages fail to meet the thermal comfort requirements (unmet hours >0%). For some profiles (SP2-a, SP3-a, SP4-a, SP5-a, SP4-lr and SP5-lr), a radiator upgrade is the minimum upgrade requirement when transitioning from a gas boiler to LTDH.

3.3.2. Scenarios selected based on heating savings

In terms of heating savings, a deep retrofit combined with a full radiator upgrade emerges as the most robust scenario and is selected as the best-performing option across all resident profiles. However, the benefits of this strategy vary substantially depending on residents' heating practices. For profiles with the highest energy consumption, those heating all rooms to very high (SP1-a) or high temperatures (SP2-a), the deep retrofit achieves savings in the range of 150–190 kWh/m^2 per year. In contrast, for profiles with lower energy consumption, the

Table 7
Number of selected scenarios for each resident profile based on each KPI.

	SP1-a	SP2-a	SP3-a	SP4-a	SP5-a	SP1-lr	SP2-lr	SP3-lr	SP4-lr	SP5-lr
Heating savings (highest)	2	2	2	2	5	1	2	2	5	6
Environmental impact (lowest)	2	4	4	7	9	2	4	2	5	5
Nuisance (lowest)	2	7	7	13	14	2	1	2	14	14
Total	**6**	**13**	**13**	**22**	**28**	**5**	**7**	**6**	**24**	**25**

same retrofit strategy yields only about one-third of these savings, reaching the 30–60 kWh/m^2 per year category (Fig. 9).

These differences in heating savings are directly reflected in the payback periods of the renovation measures. For instance, while the highest-consumption profile (SP1-a) achieves a payback period of approximately 11 years for a deep retrofit with a full radiator upgrade, the lowest-consumption profile (SP5-lr) achieved a payback period nearly four times longer, reaching 44 years for the same scenario (Fig. 10).

In addition, these solutions are associated with a high level of nuisance due to the combination of deep retrofits and full radiator upgrades, as shown in the symbols “xx” in the matrix. Such interventions can significantly disrupt residents' daily lives, as they may require temporary relocation and cause noise and dust, while also affecting the use of indoor space and interior layouts, given that the larger radiators required for low-temperature operation typically extend further into the room than those used in the reference case. This high disruption level may make deep retrofits unacceptable to residents, regardless of their energy and environmental benefits.

3.3.3. Scenarios selected based on environmental impacts

A deep retrofit combined with a full radiator upgrade delivers the lowest CO_2 emissions by 2050 for almost all resident profiles, except for the lowest-consumption profiles (SP4-lr and SP5-lr). For these profiles, radiator upgrades alone, or in combination with external wall insulation (S1 and S2), result in the lowest environmental impacts. While these options minimise environmental impacts, they yield only limited heating savings (0–30 kWh/m^2). However, they are associated with medium nuisance and relatively short payback periods (approximately six years) and are considerably less disruptive than deep retrofit solutions (Figs. 9 and 10).

For profiles heating all rooms to standard (SP3-a) moderate (SP4-a), and low (SP5-a) temperatures, a deep retrofit also emerges as the best-performing strategy in terms of environmental impacts. For profile SP3-a, a single retrofit measure (S1: cavity insulation) combined with a radiator upgrade also performs well environmentally, although it similarly delivers limited heating savings. For profiles SP4-a and SP5-a, a moderate retrofit (M2: external wall and ground floor insulation) appears as a viable environmental option, associated with medium nuisance and payback periods of 28 and 37 years, respectively. These payback periods are longer than those of deep retrofits (19 and 25 years, respectively), despite deep retrofits being associated with higher levels of nuisance (Figs. 9 and 10).

3.3.4. Scenarios selected based on nuisance

When preparing dwellings for LTDH, the minimum achievable level of nuisance for almost all resident profiles is classified as medium, except for profiles heating only the living room to very high (SP1-lr) or standard (SP3-lr) temperatures. By explicitly considering nuisance as a key performance indicator in the retrofit selection process, the analysis identifies a broader range of feasible alternatives for transitioning from natural gas to a low-carbon heat source. These solutions may be more acceptable to certain households and can therefore support higher overall acceptance of retrofit interventions and LTDH connection (Fig. 9).

The feasible retrofit scenarios vary according to the thermal requirements of each resident profile. For example, for the profile with heating all rooms to very high temperature (SP1-a), the least intensive scenario selected based on nuisance consists of a moderate retrofit (M1 or M2) combined with a full radiator upgrade. In contrast, for profiles heating all rooms to high (SP2-a), standard (SP3-a), moderate (SP4-a), or low temperatures (SP5-a), as well as for profiles heating only the living room to moderate (SP4-lr) or low temperatures (SP5-lr), a radiator upgrade alone is sufficient to enable connection to LTDH. For these profiles, additional low-intensity renovation options combined with radiator upgrades are also feasible, including single retrofit packages, such as cavity insulation (S1), cavity plus external wall insulation (S2), roof insulation (S4), or triple glazing (S5) (Fig. 9).

In terms of economic performance, for profile SP1-a, both deep (D2) and moderate (M2 and M3) retrofit packages result in relatively favourable payback periods of 11, 17, and 15 years, respectively. For profiles SP2-a, SP3-a, SP4-a, SP4-lr, and SP5-lr, a single retrofit measure (S1: cavity insulation) achieves the shortest payback periods, ranging from 5 to 15 years depending on the resident profile. These solutions are particularly cost-effective for profiles heating only the living room to moderate (SP4-lr) or low (SP5-lr) temperatures, for which deep retrofits would result in considerably longer payback periods of 33 and 43 years, respectively (Fig. 10).

The colours represent the KPI used to select each scenario, while colour intensity reflects the level of performance for each KPI. The symbols x and o in the matrix represent the drawbacks of each chosen scenario.

4. Discussion of main findings

Current retrofit planning for connecting dwellings to LTDH commonly relies on deep retrofit strategies grounded in standardized assumptions about thermal comfort. In doing so, it largely overlooks the diversity of residents' heating practices and comfort needs. This one-size-fits-all approach can result in costly, disruptive, and material-intensive interventions that may hinder resident acceptance and slow down implementation. By integrating residents' heating practices into a multi-criteria retrofit selection framework for a terraced house, this study evaluates LTDH readiness in terms of thermal comfort, energy savings, environmental impacts, economic performance, and resident nuisance. The main findings are discussed below.

4.1. Re-sizing energy retrofit by integrating residents' heating practices and multi-criteria performance

A deep retrofit (D2) combined with a full radiator upgrade emerges as the most technically robust strategy across all resident profiles, supporting the logic embedded in current insulation standards [19,37] and prior LTDH readiness studies. This is consistent with findings from the Danish context, where envelope upgrades and radiator interventions have been shown to enable lower supply temperatures in existing dwellings [38,39]. Similarly, Wahi et al. [12] and Wang et al. [9] argue that, under standardized occupancy assumptions, deep envelope retrofits and full radiator upgrades are necessary to enable the transition from gas boilers to LTDH. However, while D2 is technically robust, its benefits are not evenly distributed across resident profiles. Its performance varies substantially in terms of absolute heating savings, payback period, and environmental impacts.

For the standard profile (SP3-a), D2 yielded heating savings of 117

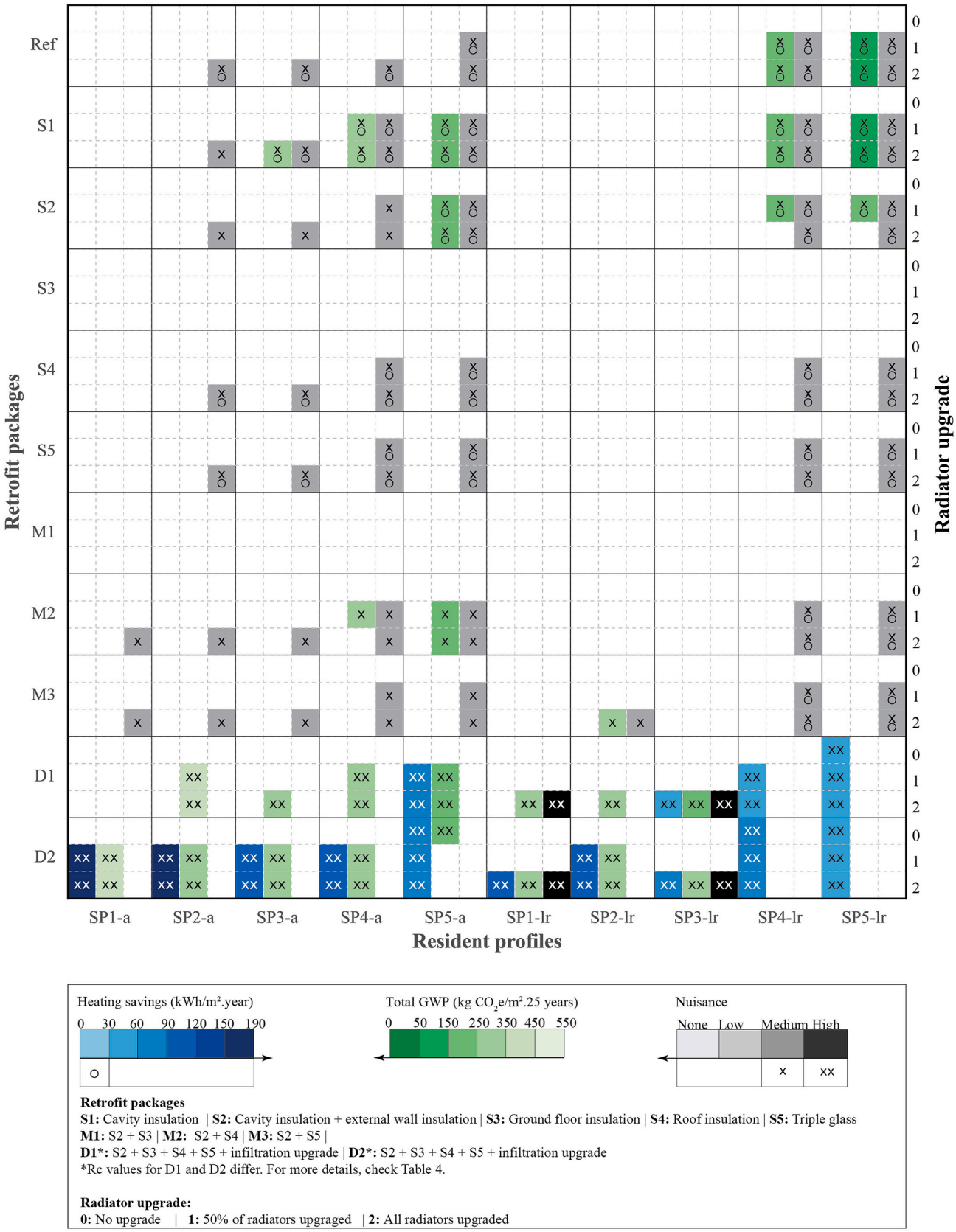


Fig. 9. Benefits and drawbacks of the selected retrofit scenarios based on the multi-criteria selection.

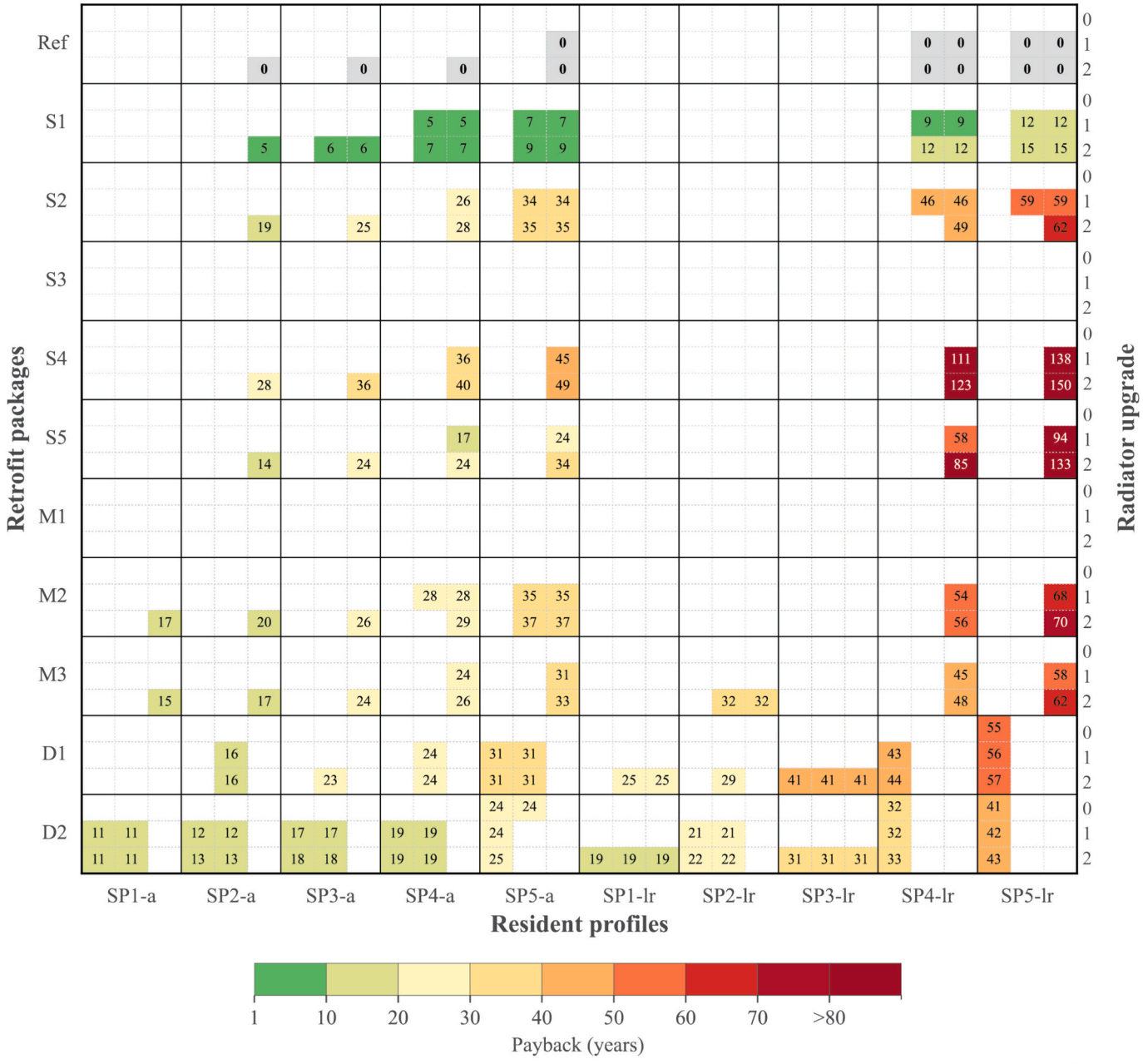


Fig. 10. Simple payback in years for each chosen scenario.

kWh/m^2·year. In contrast, for the most economical profile (SP5-lr), savings were limited to 49 kWh/m^2·year, representing only 42% of the savings observed under standard assumptions. These lower-than-expected savings directly translate into divergent economic outcomes: the payback period increases from 18 years for the standard profile (SP3-a) to 43 years for the most economical profile (SP5-lr). This substantial gap illustrates the risk of prebound effects when retrofit decisions rely exclusively on standardized occupancy assumptions. For households that already exhibit economical heating behaviour prior to renovation, the actual performance of deep retrofit strategies is lower than the expected performance when a standard profile is assumed, resulting in substantially longer payback periods.

When additional criteria are considered, including environmental impacts and qualitative indicators such as resident nuisance, less intensive strategies emerge as viable alternatives. Single and moderate retrofit packages can still enable the transition to LTDH, while involving lower financial investments and reduced disruption to residents. A field study conducted by Furman and Hadrij [70] argues that energy

renovations are more likely to be accepted when they respond to residents' actual rather than assumed needs. This is particularly relevant in the Dutch social housing context, where renovation projects require the approval of at least 70% of tenants to be implemented[1]. In this sense, integrating behavioural diversity into retrofit planning does not only refine technical performance assessments, but may also contribute to accelerating the transition to LTDH by reducing resistance barriers.

Several resident profiles share a set of viable retrofit options, including those heating the entire dwelling to high (SP2-a), standard (SP3-a), moderate (SP4-a) and low (SP5-a) temperatures, as well as those heating only the living area to moderate (SP4-lr) and low (SP5-lr) temperatures. These include full radiator upgrades alone or combined with single retrofit packages (S1, S2, S4, S5), and moderate retrofit packages (M2 and M3). These packages are technically viable to enable connection to LTDH, and given the more sustainable energy source, they deliver environmental benefits regardless of their limited or no additional energy savings compared to the reference case.

From a resident perspective, however, the impact of single and moderate retrofit packages on energy bills remains modest and should be clearly discussed with households. Despite these limitations, less intensive retrofit strategies remain valid and potentially preferable alternatives. Single or moderate retrofits may be more acceptable to residents than deep renovations, which risk being rejected and therefore not implemented at all. From a system-level perspective, such approaches can also accelerate the energy transition in the face of constraints related to available funding, prohibitively high renovation costs, time, skilled labour, and construction capacity to deeply renovate the entire housing stock. In this context, insisting on deep renovations as the default pathway risks resulting in inaction, underscoring the need to reconsider prevailing retrofit strategies.

4.2. Risks and barriers of tailored retrofit

4.2.1. Justice concerns

Careful and active alignment with residents is required to identify the underlying causes of residents' heating practices and in the selection of less intensive strategies to avoid inadvertently reinforcing energy poverty within the social housing sector, where energy (in)justice concerns are more pronounced [35,71,72]. The results therefore highlight the importance of recognizing residents' diverse needs and engaging tenants in transparent and inclusive decision-making processes. Participatory approaches embedded in the local context, such as Living Labs, may help align renovation strategies with situated practices, local needs and capacities [73].

4.2.2. Practical challenges

Tailoring retrofit solutions to resident profiles in Dutch social housing raises practical implementation challenges. Social housing dwellings are typically owned by non-profit housing associations and rented to tenants, whose occupancy may change over time. While individualized retrofit solutions can improve resource efficiency and cost-effectiveness for specific households, they may reduce flexibility in housing allocation if future tenants have different heating practices or comfort preferences. One potential organizational response is to characterise dwellings based on temperature preferences and align these with prospective tenants during allocation. Although such matching mechanisms introduce administrative complexity, they may help preserve the benefits of tailored retrofit pathways. The findings are also relevant for owner-occupied housing, where longer occupancy durations reduce the risks associated with profile mismatches.

4.3. Further opportunities: Promoting sufficiency heating practices

Some households may be willing to adapt their heating practices in exchange for less disruptive retrofit interventions. For example, residents heating the entire dwelling to 23 °C (SP1-a) may accept a modest reduction to 21 °C (SP2-a), thereby enabling less intensive solutions such as radiator-only upgrades or single retrofit packages (S1, S2, S4, and S5) combined with radiator upgrades. Such shifts toward more sufficiency-oriented heating practices can be supported by adopting "heating-the-body" strategies, including personal comfort systems (PCS), blankets, and infrared heating, which provides localized thermal comfort while allowing lower space setpoint temperatures [49–51,74].

These findings indicate that, where acceptable to residents, modest adaptations in heating practices can interact with less intensive retrofit strategies to enable more flexible and scalable renovation pathways. This aligns with Morley's argument that sufficiency-oriented policy-making could address "excess" heating of spaces, understood as energy-intensive practice configurations that exceed what is necessary for wellbeing, by broadening the notion of thermal comfort beyond air temperature, including practices such as clothing, personal comfort systems, and radiant heat [26]. Quantifying the potential benefits of sufficiency-oriented heating practices can help make the implications of aligning such practices with different retrofit solutions more transparent to residents. At the same time, changes in heating practices often entail adjustments to daily routines and comfort expectations and will not be feasible or acceptable for all households, reinforcing the importance of resident participation and a multi-criteria evaluation in retrofit decision-making.

Resident profiles that heat only the living area while keeping bedrooms cooler achieve up to 57% lower energy use compared to profiles heating the entire dwelling at the same setpoint temperature (Fig. 4). Under conventional high-temperature heating systems, this sufficiency-oriented heating practice can be considered an effective energy-saving strategy. However, when transitioning to LTDH, it introduces specific technical challenges. Profiles that heat only the living area to very high (SP1-lr), high (SP2-lr), or standard temperatures (SP3-lr) require deep envelope retrofits combined with full radiator upgrades to avoid unmet hours. In contrast, profiles heating the entire dwelling homogeneously at the same setpoint temperatures (SP1-a, SP2-a, and SP3-a) allow a broader range of retrofit solutions, including single or moderate retrofit packages combined with radiator upgrades. This counterintuitive result is driven by increased heat losses through internal partitions, caused by larger temperature gradients between heated and unheated rooms.

For households following such heating practices, internal insulation strategies that thermally isolate the heated living area may offer an alternative pathway. This approach, commonly referred to as thermal compartmentation, has been explored in a limited number of field studies and shown to improve local thermal performance by reducing heat losses between heated and unheated zone [75]. While this strategy is not currently aligned with prevailing insulation regulations [26,37], and was not considered in our simulations, it highlights a potential direction for future research aimed at enabling less intensive retrofit pathways for specific heating practices under LTDH.

4.4. Limitations and prospects for future studies

The following aspects are recognized as limitations and opportunities for future studies:

First, the analysis is based on a single residential typology (mid-row terraced house). While the methodology is transferable, future studies should apply it to other dwelling types, such as corner terraced houses, detached houses and apartment buildings, to assess the robustness of the

[1] Dutch legislation (*Het Burgerlijk Wetboek* 7:220, paragraph 2 BW) states that energy renovation projects may proceed when at least 70% of tenants within a building, or within a cluster of at least ten dwellings in a neighbourhood, approve the proposed measures [88]. In practice, however, tenant involvement is often limited to approving or rejecting predefined plans, rather than actively contributing to the development of renovation strategies, indicating limited meaningful participation in decision-making [70].

findings across different typologies. Moreover, this case study focused on social housing dwellings. Since social housing in the Netherlands is typically rented, future studies should assess how tailored retrofit solutions can be implemented when tenants may change over time. This would require organizational strategies to better match dwellings with future occupants who share similar heating practices. Additionally, further research is needed to ensure that tailored retrofit approaches are implemented equitably, where the pursuit of emission reductions and cost savings does not result in tenants living in poor quality housing [76].

In terms of heating practices, resident profiles were defined by setpoint temperatures, number of heated rooms, and occupancy patterns. Future studies could expand these profiles to include a wider range of indoor setpoint temperatures, ventilation behaviour, temporal variations in setpoints, different household sizes and occupation patterns, internal door use, domestic hot water consumption, and cooking and laundry practices. Additionally, potential rebound effects due to changes in heating practices after retrofitting were not considered [77–81]. Future research could examine how tailored retrofit solutions influence rebound effects compared to standardized approaches.

This study did not consider the impacts of lower setpoint temperatures on energy poverty and their socio-economic implications. Further studies should include the social dimensions of energy poverty and examine their implications for both energy use and household wellbeing.

The analysis of LTDH readiness focused on meeting residents' heating comfort requirements during winter. However, thermal performance during summer or overheating risks were not considered. Future studies should include overheating risk assessments for the proposed retrofit measures and identify additional strategies to address summer comfort while maintaining LTDH readiness.

For the environmental analysis, carbon emissions included operational carbon and embodied carbon of envelope-oriented measures and radiator upgrades only. The embodied carbon of district heating infrastructure installation and piping insulation represents a large share of embodied carbon when connecting homes to LTDH was not considered [82,83]. Future research should include the embodied carbon of LTDH infrastructure to understand the trade-offs at a larger scale.

As the heat losses in LTDH systems are reported to be significantly lower than those in conventional high-temperature systems [84,85], heat losses in the district heating network were not explicitly modelled. However, we acknowledge that distribution losses are also dependent on factors such as pipe insulation quality, network layout, pipe length, and the specific configurations of the district heating system [86]. Therefore, future studies could include detailed network-level modelling to assess the influence of distribution losses on heating demand and operational carbon emissions.

In this study we considered a stringent constant low supply temperature of 45 °C for the LTDH throughout the entire year to evaluate the scale of retrofit interventions required for the transition from gas boiler to LTDH when residents' heating practices are included in retrofit decision-making. However, Lund et al. [87] highlight the possibility of more flexible LTDH operation, such as temporarily increasing the temperature to 70 °C during winter peak conditions. This represents a path for future research, as the implementation of more flexible operational strategies could potentially enable less intensive retrofit strategies, particularly when aligned with sufficiency-oriented heating practices, as highlighted in this study. While higher supply temperatures may reduce the sustainability benefits associated with lower-temperature heat sources, they may also reduce the need for retrofit interventions and the embodied carbon associated with renovation materials. Therefore, future studies should examine these trade-offs from a whole-life carbon perspective, considering both operational and embodied carbon impacts.

We acknowledge that at a supply temperature of 45 °C, domestic hot water cannot be delivered at safe tap temperatures (≥60 °C for Legionella control) without a local boosting unit. This study does not model domestic hot water delivery or the associated boosting equipment, and this is an explicit boundary condition of the analysis. Future work should incorporate boosting units and account for their additional energy demand and cost implications.

In addition, the analysed scenarios represent conceptual models, making physical measurements unfeasible. The use of building performance simulations enables the systematic exploration of a large number of scenarios that would not be feasible to implement and test in practice. Although all input data were carefully defined based on well-established sources and realistic assumptions, future research could include empirical calibration with monitoring data to further strengthen the robustness of the findings.

5. Conclusion

Preparing existing dwellings for low-temperature district heating (LTDH) is commonly approached through deep retrofit strategies based on standardized assumptions about thermal comfort. This study demonstrates that while deep retrofits combined with full radiator upgrades remain technically robust, they entail high nuisance and deliver uneven benefits across resident profiles. When renovation strategies are aligned with sufficiency-oriented heating practices, less intensive retrofit packages, such as radiator upgrades alone or combined with single or moderate envelope measures, can be enough to enable connection to LTDH, while reducing costs, disruption, and embodied emissions.

By integrating residents' heating practices, e.g. setpoint temperatures and the number of rooms heated, into a multi-criteria assessment for selecting retrofit packages, this study reveals a range of viable pathways to LTDH readiness. Including single and moderate retrofit options broadens the solution space, enabling faster implementation and reducing potential resistance among residents, while making more room for sufficiency-oriented heating and renovation practices. These findings challenge one-size-fits-all renovation logics and highlights opportunities for more efficient, socially just and practically implementable heating transition. Aligning retrofit strategies with residents' actual heating practices and comfort preferences emerges as a promising pathway for advancing meaningful progress in the transition to LTDH and toward sustainability goals.

CRediT authorship contribution statement

Iris Loche: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Carolina Recart:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Diletta Ricci:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Thaleia Konstantinou:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition. **Lenneke Kuijer:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Roel Loonen:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

Acknowledgements

This research is part of the JUST PREPARE project, funded by the Dutch Research Council (NWO) in the KIC-call ‘Energietransitie als

maatschappelijk-technische uitdaging' (Project number: KICH1.ED03.20.001) and the BEHeaT (Built Environment Heat Transition) program, funded by the Eindhoven Institute for Renewable Energy Systems (EIRES) at the Eindhoven University of Technology.

Data availability

Data will be made available on request.

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