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DOI
10.1016/j.jobe.2022.105811

Publication date
2023

Document Version
Final published version

Published in
Journal of Building Engineering

Journal of Building Engineering 65 (2023) 105811

Contents lists available at ScienceDirect

Journal of Building Engineering

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

Lower temperature heating integration in the residential building stock: A review of decision-making parameters for lower-temperature-ready energy renovations

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A R T I C L E I N F O

Keywords:
Lower temperature supply
Existing residential stock
Energy transition
Sustainable heating sources
Decision-making process

A B S T R A C T

Lower temperature heating (LTH) involves using the lowest possible supply temperatures to meet residential heating demands, thus supporting the integration of sustainable heating sources and decarbonising the existing residential stock. However, choosing appropriate energy renovation options to prepare existing dwellings for LTH presents decision-making challenges due to the heterogenous dwelling stock with varying building characteristics, numerous renovation options, and various performance indicators for evaluating trade-offs. This study aims to review the scientific literature on integrating LTH into existing dwellings to identify the building characteristics for evaluating the potential of using LTH and the necessity for renovations, presents a systematic method for organising renovation options and summarises key performance indicators. The study employed the SALSA (search, appraisal, synthesis and analysis) framework for systematic review and identified 24 scientific publications. Findings show that dwelling characteristics such as compactness ratio, thermal insulation, thermal bridges, airtightness, ventilation systems, space heating system capacity and supply temperature level are essential for investigating LTH potential and the need for renovations. Most research lacks qualitative renovation criteria and product-level information for selecting renovation options. Key performance indicators related to energy efficiency, thermal comfort and quality-of-services can help indicate the possible solutions, while those related to environmental and economic performance indicate the feasibility of possible solutions. Nevertheless, there is a lack of standard set of criteria for indicating the dwelling's readiness for using LTH. These findings can help address the decision-making challenges of selecting appropriate renovation strategies to enable the use of LTH and contribute to decarbonising the built environment.

List of abbreviations

3GDH	3rd Generation District Heating
LT	Low-Temperature
4GDH	4th Generation District Heating
LTH	Lower Temperature Heating
AB	Apartment Blocks

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https://doi.org/10.1016/j.jobe.2022.105811
Received 2 November 2022; Received in revised form 23 December 2022; Accepted 30 December 2022
Available online 1 January 2023

MFH	Multi-Family Houses
CHP	Combined Heat and Power
MT	Medium-Temperature
DGU	Double Glazing Unit
NPV	Net Present Value
DH	District Heating
PD	Percentage of Dissatisfaction
DHW	Domestic Hot Water
PMV	Predicted Mean Vote
EU	European Union
PPD	Predicted Percentage of Dissatisfied
GHG	Greenhouse Gas
RH	Relative Humidity
GWP	Global Warming Potential
SALSA	Search, Appraisal, Synthesis and Analysis
HP	Heat Pumps
SFH	Single-Family Houses
HT	High-Temperature
SH	Space Heating
HVAC	Heating, Ventilating and Air Conditioning
SSM	Soft System Methodology
KPIs	Key Performance Indicators
TGU	Triple Glazing Unit
LCC	Life Cycle Costs
TH	Terraced Houses
LCCA	Life Cycle Cost Analysis
ULT	Ultra-Low Temperature
LMTD	Logarithmic Mean Temperature Difference
VFT	Value-Focused Thinking

1. Introduction

Globally, fossil fuels continue to be the primary sources of energy, with oil, natural gas and coal accounting for 82.21% of the total primary energy sources, resulting in 34.8 billion tonnes of fossil fuel-related CO_2 emissions in 2020 [1,2]. Comparatively, the European Union (EU27) is responsible for 7% of the total fossil fuel consumption, with households being one of the three dominant final energy consumers (28%) [1,3]. The majority of this energy is used to meet domestic heating requirements, with around 64% for space heating and 15% for hot water preparation [4]. Due to the predominance of fossil fuels as the energy source, approximately 20% of the greenhouse gas (GHG) emissions are attributable to the residential sector in the EU [5]. To reduce these emissions, a shift towards sustainable energy sources is necessary. One approach for achieving this is by adopting lower temperature heating (LTH) solutions. The term "LTH" represents supply temperature levels comprising medium, low and ultra-low, the definitions of which vary by country.

LTH involves operating heating systems at the lowest supply temperatures while meeting space heating and hot water demands [6]. Lower supply temperatures allow heat from sustainable sources such as geothermal, solar, ambient and residual heat from industrial processes [7–10] to satisfy the low-exergy heating needs of the dwelling. In recent years, studies have investigated the potential of LTH in both newly built [11–15] and existing dwellings [6,10,16,17]. The former typically have lower space heating demands that can be achieved through LTH solutions [8,14,15]. Existing dwellings, on the other hand, often require energy renovations to use a lower temperature supply to reach comfortable indoor temperatures through space heating [9,18–20].

Energy renovations aim to reduce heating demands, thereby making it suitable for LTH supplied by sustainable systems [21–23]. Many authors have further investigated different renovation options for the building envelope, space heating, hot water and ventilation systems to make existing dwellings suitable for LTH [16,18,24,25]. However, selecting appropriate renovation strategies for integrating LTH in a particular dwelling is a complex challenge and requires further studies.

According to Wu et al. [26], the difficulty in choosing suitable strategies stems from a large number of demand (building level) and supply (heat supply systems) side renovation options. In addition, the challenge is exacerbated by the fact that renovation options vary by context, building type, construction profile, occupant behaviour and decision-makers' goals [10,26]. Another issue discussed by Wang et al. [18,27] pertains to balancing the trade-offs associated with different renovation options. For instance, while improving only space heating systems could be a low-cost, quick-fix solution for using LTH [16], it has no potential for energy savings. Likewise, although retrofitting the building envelope can reduce the energy demand, it is frequently expensive, has a long installation time, and creates difficulties for occupants [16,27]. Hence, there is a need for a systematic decision-making approach for selecting renovation strategies for using LTH and eventually contributing to the energy transition of the existing residential stock.

Within the context of renovation, a systematic decision-making process includes various stages such as investigation of the problem, determining objectives and evaluation criteria, generation of alternative solutions, their evaluation and selection of the appropriate solutions [28–30]. Furthermore, the same process can be extended for planning necessary actions for implementing selected renovations [28]. Henceforth, a literature review is conducted as a first step toward addressing the challenges associated with effective decision-making regarding energy renovations for LTH.

Previous reviews considering the integration of LTH solutions have been conducted by Ovchinnikov et al. [31], who reviewed the potential of low-temperature hydronic space heating systems and their apparent application in Russia, and Regius et al. [32], who

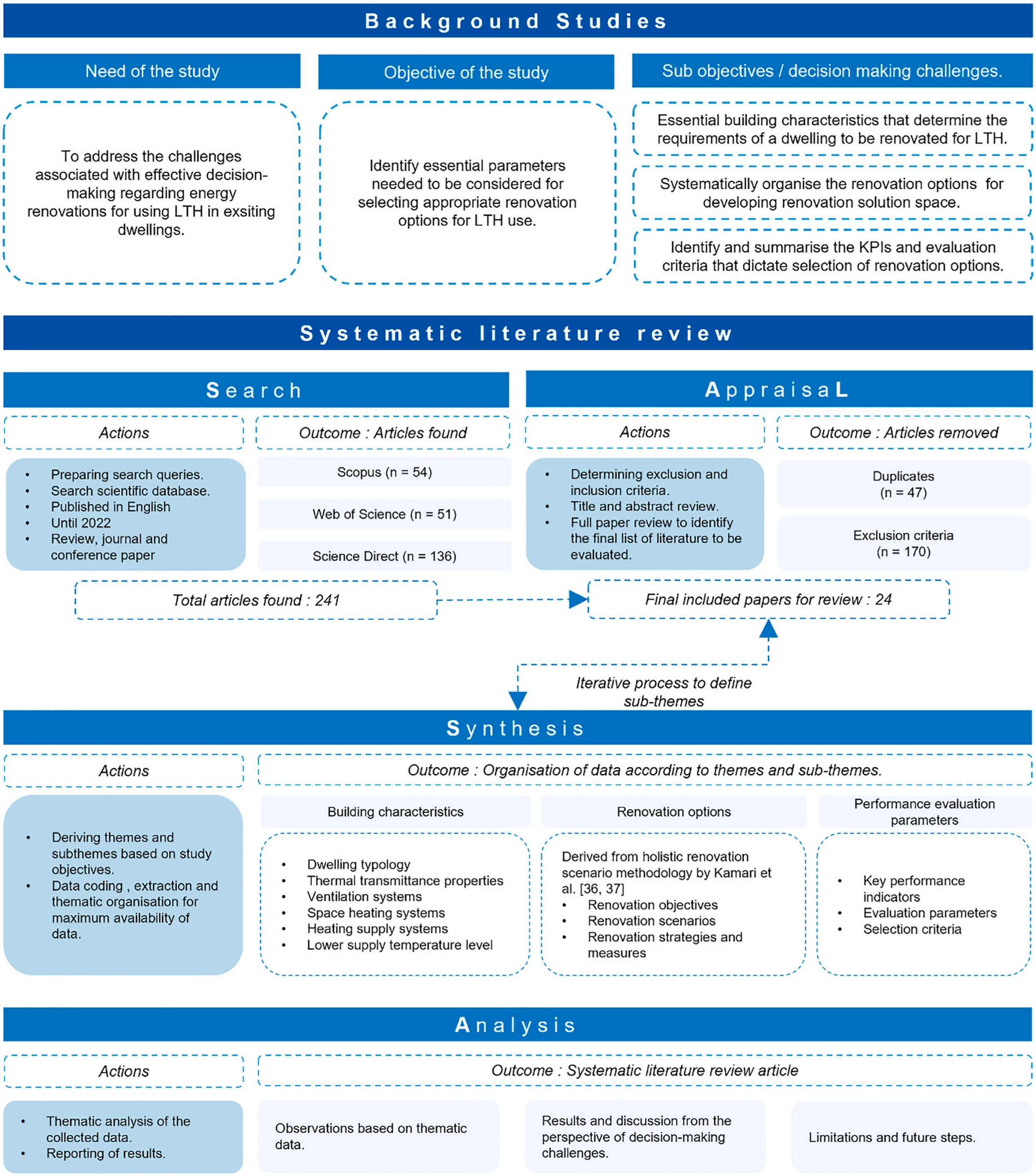

Fig. 1. Research framework and different steps for conducting a systematic literature review. SALSA framework adapted from Amo et al. [35]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reviewed studies using LTH and the challenges of its application in the UK. Nevertheless, both studies were limited to the impact of lower temperatures on space heating systems. Ovchinnikov et al. compared various space heating systems and emitters against standardised performance criteria, including energy consumption, thermal performance and environmental impact. Similarly, Regius et al. reviewed the design and performance of existing heating systems with lower temperature supply in the UK. Despite the fact that both reviews ascertain the need for minimal retrofitting, such as increasing airtightness, replacing windows, changing critical radiators, and oversizing the radiators to use LTH comfortably, the studies notably lack discussion about decision-making aspects for selecting appropriate renovation strategies for heating existing dwellings with LTH. Bearing this in mind, the current knowledge base requires expansion from a renovation decision-making standpoint. As a result, the primary objective of this review is to identify essential parameters needed to be considered for selecting appropriate renovation options for LTH use.

The specific decision-making challenges related to the impact of building characteristics, applicable renovation options, selection of performance indicators and evaluation criteria may influence the selection of renovation option/s at the building level for using LTH. Hence, the primary objective could be further compartmentalised into the following sub-objectives.

- To identify the essential building characteristics that determine the requirements of a dwelling to be renovated for using LTH.
- To systematically organise the renovation options from the literature for developing a renovation solution space.
- To identify and summarise the key performance indicators and evaluation criteria that determine the selection of renovation options.

After the introduction, the paper describes the method for assembling relevant studies from scientific databases. Next, the results and discussion section first summarises different building characteristics and discusses their impact on using LTH in existing dwellings. As previously stated, since the decision-making problem is also related to various renovation possibilities, renovation options mentioned in the selected studies are methodically summarised. Finally, a summary of the key performance indicators and evaluation criteria utilised by the studies to evaluate renovation choices is provided. The conclusion summarises the findings and further steps for addressing the decision-making challenges for selecting renovations to prepare the existing dwelling stock for LTH.

2. Materials and methods

This study used a systematic literature review to identify and evaluate existing scientific articles. According to Booth et al. [33], a systematic review ensures the review process's clarity, validity, and replicability. As a result, the review was carried out using the SALSA (Search, Appraisal, Synthesis and Analysis) framework as a systematic method [33,34]. Fig. 1 illustrates the research framework and the steps followed for conducting the review.

2.1. Stage 1: Search

This stage involved searching scientific databases for relevant articles with the help of key concepts and their synonyms, such as lower temperature heating, existing residential buildings, renovation options and decision-making. However, the search queries combined with the decision-making concept returned very few papers, none of which discussed the issue directly. Therefore, keywords related to decision-making were removed from the final iteration of searching databases. Fig. 2 shows the word combinations used, excluding the decision-making keyword to create search queries, while Table A1 in the appendix illustrates the exact search strings used in the databases.

Prior to stage 2, the articles discovered through the search queries were screened for eligibility. As a result, only review, journal or conference papers, and book chapters published in English before 2022 were included. Fig. 1 summarises the number of articles identified during the preliminary screening process before stage 2.

2.2. Stage 2: Appraisal

After preliminary screening in stage 1, 241 articles were identified and further subjected to a more thorough evaluation. Firstly, 47 identical results were removed from the initial 241 papers during the screening stage of the appraisal. The remaining papers were then analysed for the availability of keywords, relevance of the abstract, and retrievability of papers. Finally, full papers were reviewed to eliminate papers according to the exclusion criteria. Table 1 depicts the articles screened, removed, and the exclusion criteria at each stage of the process, resulting in the selection of 24 papers for the synthesis stage.

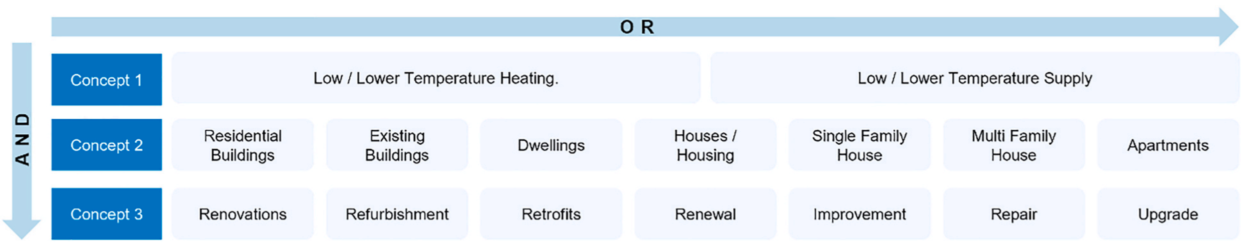

Fig. 2. Combination of words used for creating search queries. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Steps used for appraising the search results. The table includes the number of articles screened and removed, along with the exclusion criteria for removing articles.

Steps	Records Screened	Records removed	Exclusion Criteria
Screening	241	47	Duplicate records
Eligibility	194	137	Keywords present in the title, list of keywords, and abstract but not related to the research scope • No relevance of abstract • Not retrievable
	57	16	• System design, network typologies
		9	• No relationship between LTH and renovations
		7	• Newly constructed dwellings that do not require renovations for LTH
		1	• Internal duplicity
Final papers to be included for review	**24**		

2.3. *Stage 3: Synthesis*

This stage involved extracting and organising the data from the selected papers. The study employed the thematic synthesis method, where the aggregative themes were derived from the research objectives. According to Booth et al. [33], thematically organising the extracted data can provide opportunities for consistent analysis across multiple studies. For operationalising the data collection, sub-themes were further identified depending on the maximum availability of the information. However, for organising and comparing renovation options across different studies, the review used the holistic renovation scenario methodology by Kamari et al. [36,37]. This methodology allows a common platform to observe different aspects together. Fig. 1 illustrates the themes and sub-themes used to extract the data from the 24 selected articles.

2.4. *Stage 4: Analysis*

The final stage of the study included evaluating the collected data across all the studies. The analysis drew observations and compared the thematic data for identifying parameters essential for selecting strategies to use LTH. Furthermore, the results from the analysis were discussed from the perspective of decision-making for selecting options for renovating existing dwellings to use LTH.

3. Results and discussion

In this section, the results of the review are presented and organised according to the themes illustrated in Fig. 1. These themes are based on the sub-objectives of the research aim discussed in the introduction. Furthermore, the thematic analysis results are discussed concerning their implications on addressing decision-making challenges for selecting appropriate renovation solutions for using LTH.

3.1. *Overview of building characteristics*

In this theme, data were extracted and analysed regarding the characteristics of the dwellings studied by different authors for using LTH. Table 2 illustrates the data from the literature organised based on the dwelling typology, thermal transmittance of the envelope, ventilation systems, space heating systems and criteria for selecting them for renovations. Additionally, these parameters reflect the state of the dwelling prior to any renovations considered by individual studies for integrating LTH.

3.1.1. *Dwelling typologies*

The dwelling typologies were defined using three subcategories: dwelling size, subtypes, and age. The typical house sizes are based on the typology matrix used by the TABULA project to harmonise national building stock across the EU [38]. As a result, dwelling size includes single-family houses (SFH), terraced houses (TH), multi-family houses (MFH), and apartment blocks (AB). Additionally, dwelling subtypes such as detached, semi-detached, low-rise, and high-rise were identified. Finally, the dwelling age refers to the year of construction, which indicates the dwelling's typical construction and material properties [39].

Due to the heterogeneous residential stock, most studies identified typical or archetype dwellings for investigating LTH usability. Some studies selected archetypes representing dwellings that comprise a significant proportion of the existing housing stock. For instance, the high-rise AB represent a large fraction of dwellings in the urban areas of Denmark [9], while the SFH constitutes the most typical dwelling type in Denmark [40]. However, many studies choose representative dwellings based on typical construction years [26,41] as it indicates standard constructional styles and thermal properties of most dwellings built during that period. For example, in Sweden, 1.4 million dwellings comprising SFH, MFH, and AB were constructed en masse during the million programme (1950–1975) [18,25,42]. Considering modern standards, these dwellings with similar constructional styles also exhibit higher energy demands, thus, requiring renovations to improve energy efficiency [20,25,42].

Similarly, Table 2 shows that most dwellings investigated for using LTH were constructed before or around the 1970s. They are expected to perform poorly in energy efficiency, as they were built before the widespread implementation of the first thermal regulations throughout Europe [19,43,44]. Another important aspect relates to the position of the dwelling. For instance, the corner apartments with higher envelope areas result in higher heat losses, thus causing increased energy demand and lower thermal comfort

Table 2
Data collection: Dwelling typologies, thermal insulation values, HVAC system and the criteria for selecting the dwellings for renovation.

Author	Country	Dwelling typology			Insulation values (U-value) [W/m^{2}K]				HVAC		Criteria for selection
		Size	Subtype	Age	Wall	Roof	Floor	Window	Ventilation system	Space heating system	
[47]	Germany	–	Semi-Detached Low rise (<5 floors)	1970	3.69	1.51	1.59	4.3	–	Radiators	Built before the thermal regulation of 1992.
				1994	0.49	0.32	0.56	2.8	–		Built after the thermal regulations of 1992.
[16]	Denmark	SFH	Detached	1973	–	–	0.48	3.2	–	Type 21 Radiators	Houses built in the 70s were designed for HT supply. Therefore, a reduction in supply temperature may cause thermal discomfort.
[42]	Sweden	AB, MFH	Low rise (<5 floors)	1946–1960	0.41	0.21	–	2.8–2.9	Mechanical Exhaust	HT hydraulic radiator	Residential boom during 1950–1975. These houses are at least 40 years with high final energy use.
		AB. MFH	High rise (>5 floors)	1961–1975	0.33	0.17	–	2.3	Mechanical exhaust with Heat recovery	HT hydraulic radiators	
		SFH	–	Before 1945	0.47	0.30	–	2.5	Natural Ventilation	Electric heater	
[18,27]		AB, MFH (2)	Low rise (<5 floors)	1965–1975	0.48	0.26	–	2.85	Decentralised exhaust air ventilation	Conventional hydronic radiators	During 1965-75 massive amounts of low-rise MFH were constructed. However, these houses are 40–50 years old and cannot meet energy and thermal comfort requirements.
[41]	Italy	14 typical units representative of building stock		Before 1960	1.03	–	–	5.69	–	Hydronic radiators	37% of residential buildings were built before 1960.
				1960–1991	0.82	–	–	5.69	–		49% of residential buildings were built before 1960–1991.
				After 1991	0.45	–	–	3.44	–		14% of residential buildings were built after 1991.
[9]	Denmark	AB	High rise (>5 floors)	1910	1.34	0.2	1.5	2.9	Natural ventilation	Radiators dimensioned for 70/40	Representative of a large portion of buildings in urban areas with energy-saving potential.
		AB	High rise (>5 floors)	1906	1.34	1.2	1.2	4.5			
[48]	Denmark	SFH (4)	–	1930	0.78	0.15–0.37	–	1.5–4.3	Natural Ventilation	Hydraulic radiators	SFH accounts for 60% of the residential sector.
[40]	Denmark	SFH (3)	–	1900–1960	–	–	–	–	–	Radiators dimensioned for 90/70	
		SFH	–	1961–1972	–	–	–	–	–	Radiators dimensioned for 80/60	
		SFH	–	1973–1978	–	–	–	–	–	Radiators dimensioned for 80/40	
		SFH	–	1979–1998	–	–	–	–	–	Radiators dimensioned for 70/40	
[25]	Sweden	AB, MFH	Low rise (<5 floors)	1961–1980	0.6	0.6	–	2.58–2.72	Mechanical exhaust	Hydronic radiators	2.5 million MFH, out of which 75% are 40 years old. There is a need for renovation for energy-saving potential.

(*continued on next page*)

Table 2 (*continued*)

Author	Country	Dwelling typology			Insulation values (U-value) [W/ m^2K]				HVAC		Criteria for selection
		Size	Subtype	Age	Wall	Roof	Floor	Window	Ventilation system	Space heating system	
[45]	Spain	AB, MFH	High rise (>5 floors)	1959–1961	0.74	2.7	2.27	2.76	–	Electric heaters	56% of 2.6 million dwellings were built before the thermal regulations of 1980. These dwellings need to be renovated to achieve a 20% reduction in primary energy.
[26]	Switzerland	Detached Semi-detached Large		Before 1900	1.54	0.79	1.42	2.5	–	Oil/electric heaters	Eleven representative building typologies from different construction years were selected for optimising retrofits.
		Detached and Large		1900–59	2.04	1.29	1.18	2.5	–		
		Semi-detached, detached and large		1960–79	1.78	1.38	1.95	2.5	–		
		Semi-detached, detached and large		1980–99	0.53	0.33	0.56	2.5	–		
[49]	Nordic countries	–	–	1975–2000	0.25	–	–	2.1	Exhaust ventilation	Conventional radiators	85% of the buildings were constructed before 1975. A frequent problem with low indoor air temperature.
[46]	Germany	AB, MFH	Low rise (<5 floors)	1958–1968	1.4	0.6	1	2.93	–	–	
[43]	Scotland	Tenement flats, AB	Low rise (<5 floors)	Typical 20th century	1	2.5	0.78	5.8	–	–	74% of the housing stock was built pre-1982. These need to be upgraded to EPC C by 2040.
[19]	Latvia	–	Townhouse	70s	0.85	0.8	0.8	2.21	Exhaust ventilation	Convector radiator	Buildings are poorly insulated from the 70s.
[20]	Sweden	MFH	Low rise (<5 floors)	1965–1974	0.34	0.24	–	3.15	Mechanical exhaust	Panel radiators	They were constructed during the million homes programme. After 40–50 years, they need renovations.

SFH: single-family houses, MFH: Multi-family houses, AB: Apartment Blocks, HT: High-Temperature Supply.

[19,27,45,46].

From the perspective of renovation decision-making, identifying dwelling types is essential for evaluating their suitability for using LTH and proposing renovation solutions. The findings suggested identifying archetypes representative of the diverse residential stock to investigate LTH usage. For developing such archetypes, the dwelling size subcategory does not provide enough information to indicate if a dwelling can be supplied with LTH.

This could be explained due to differences in the national-level definitions of dwelling sizes subcategories (SFH, TH, MFH, AB). In contrast, the compactness of a dwelling might better suggest the usability of LTH since it indicates the energy losses dictating the heating and cooling requirements of a dwelling [50,51]. As a result, dwellings with a higher envelope surface area in relation to their volume or useable (heated) floor area often correspond to higher heat losses. For instance, building subtypes such as detached, semi-detached, and dwelling position in terraced houses and apartment blocks will significantly impact LTH use and the need for renovations. Lastly, the construction year indicates the dwelling's thermal properties and typical constructional style. These parameters are essential to estimate the energy performance of the dwelling and the possibility of renovations to make a dwelling suitable for LTH, respectively.

3.1.2. Building envelope characteristics

The utilisation of LTH for comfortably heating homes depends on the space heating demands and the ability of the space heating systems to compensate for it [40]. However, with a lower supply temperature, the heating capacity of the space heating systems designed for a higher temperature (HT) supply is often reduced [24,31]. As a result, a mismatch between higher space heating demands and reduced heating capacity of the space heating systems could cause thermal discomfort for the occupants (Fig. 3).

Space heating demands are governed by the building envelope's transmission, infiltration and ventilation heat losses, combined with solar and internal gains [40,42], even though solar and internal gains are often ignored for system sizing. The energy loss factors through a building envelope correspond to its orientation, shape, compactness ratio, and thermo-physical properties [50,52]. However, for existing buildings altering orientation and shape is difficult. Therefore, the building envelope's compactness ratio and its thermal properties are essential factors for determining the usability of LTH.

The impact of the compactness ratio on building heat losses is well documented in the literature [50,51,53,54]. It is often calculated as the ratio between the building envelope surface area and its useable heated area [53] or between the envelope surface area and the volume of the building [50,55]. In either definition, a dwelling with a compact form has lower heat losses and eventually lower heating demands [50,53]. In other words, smaller dwellings, such as single-family houses, would experience higher heat losses than multi-story dwellings [53]. As a result, it can be argued that dwellings with a lower compactness ratio would require more renovation interventions on the building envelope to curb heat losses for using LTH. Similarly, in apartment buildings, dwellings located on the corner with higher envelope areas result in higher heat losses, thus impacting the use of LTH for comfortably heating dwellings [19,27,45,46]. Therefore, the compactness ratio is an essential parameter to be considered while evaluating the possibility of using LTH, although it is not widely discussed within the selected literature studies.

The thermal transmittance of the building envelope is another essential parameter for determining the space heating demands from the transmission losses. Fig. 4 illustrates the thermal transmittance values of the building envelope components of the dwellings

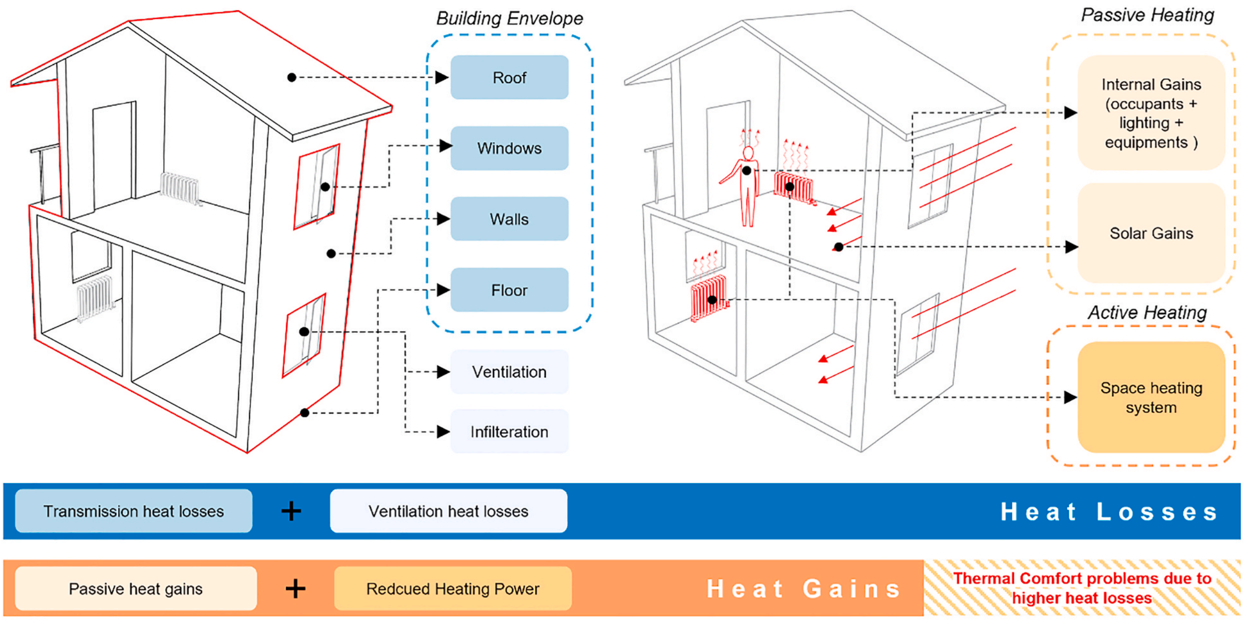

Fig. 3. Thermal comfort problems due to higher heat losses and inability to compensate them by heat gains due to reduced heating power of the space heating systems under lower supply temperatures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

investigated by different authors. It can be observed that, generally, windows have the lowest insulation values (i.e. highest U-Values), indicating the presence of single glass units [40] or older double glazing units [42]. Next to the windows, the external walls or façade of the opaque part of the building envelope have lower insulation values (higher U-values). Therefore, the thermal insulation of the building envelope acts as a barrier to transmission heat losses, thus, impacting the use of LTH. Combined with the transmission loss, heat is also dissipated through the poor airtightness of the envelope and ventilation requirements of the dwelling.

3.1.3. Ventilation systems

The ventilation heat losses caused by air infiltration through cracks and joints of the building envelope and the systems used to introduce fresh air can substantially affect the energy efficiency and indoor air quality of a dwelling [56,57]. The infiltration rate of a dwelling depends on the constructional quality dictating the airtightness of the dwelling. As a result, existing dwellings are expected to have lower airtightness resulting in higher heating demands and local comfort problems such as cold draught [58].

The ventilation systems utilised in a dwelling typically depend on its type (low rise or high rise) and the ventilation needs of the dwelling, as specified by local building standards and guidelines [59]. Natural, mechanical, balanced and hybrid systems are examples of typical ventilation systems. In natural ventilation systems, fresh air is supplied and exhausted via adjustable grilles and windows [56,59], while in mechanical systems, this is achieved through ventilators or vertical channels [56,59]. Another variation of this system is a balanced ventilation system with both mechanical supply and exhaust and a heat recovery unit [56]. Lastly, hybrid systems provide ventilation by switching between natural and mechanical modes based on outdoor conditions [60].

As observed in Table 2, the dwellings constructed before the 1950s are equipped with natural ventilation [9,42,48], whereas those constructed after with mechanical exhaust systems [18–20,25,27,42,49]. However, only one instance of heat recovery combined with exhaust ventilation was found [42], and no studies utilising hybrid ventilation systems were found. According to Hesaraki [57], ventilation heat losses account for 20–60% of the total heat loss in a dwelling, depending on the dwelling type and its properties. Consequently, it is essential to consider the effect of heat losses due to ventilation when renovating dwellings to minimise heating demands for using LTH.

3.1.4. Space heating systems

Regarding space heating systems, conventional hydronic radiators are generally designed to operate at higher temperatures of 90/70 °C. Nevertheless, in some cases from Denmark and Sweden [9,40] the radiator was designed for lower temperatures of 70/40 °C, as required by national regulations. As mentioned in section 3.1.2, the space heating system's heating output designed for higher supply temperatures will be reduced under lower supply temperatures [24,31]. Significantly, higher heat losses in existing dwellings and the reduced heating capacity of the radiators may result in thermal comfort issues for the occupants. However, many authors assert that existing radiators designed for HT supply are frequently over-dimensioned due to having been designed for extreme conditions as well as due to a lack of consideration for solar or internal heat gains, part-load operation in a year, reduction in energy demands due to renovations and reduced heating days resulting from climate change [24,31,32,40]. As a result, it is essential to evaluate the possibility of existing radiator systems for adequately heating a dwelling even when the temperature supply is reduced.

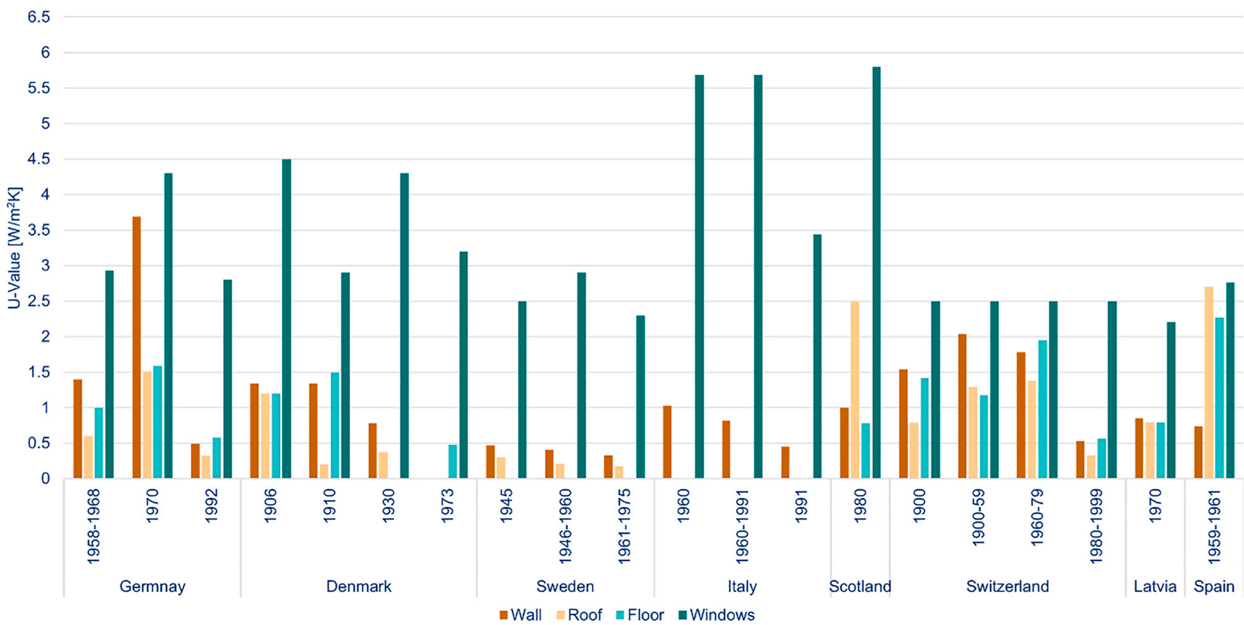

Fig. 4. Insulation (U-Value) of building envelope of the dwellings investigated by different authors before renovations. The data belonging to individual studies can be found in Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1.5. Heat generation systems

The heat generation systems investigated by different authors were further categorised as collective, individual, or combined systems. In this study, collective systems represent the centralised heat generation on a neighbourhood level, commonly known as district heating (DH) [61,62]. A DH system distributes heat through insulated pipes or heat networks using water as a medium to meet space heating and hot water demands [61,62]. It is considered an efficient and cost-effective way of delivering heat to dense urban areas where many houses can be connected to the heat network [63,64].

Table 3 shows that most studies using the DH system were conducted in Sweden or Denmark. The prime reason is the early uptake of DH technologies with supply temperatures lower than 100 °C in those countries, also referred to as the third generation of DH technology [64]. In addition, the vast majority of the buildings there are already connected to DH networks. For instance, around 40% of single-family houses in Denmark are connected to the DH [40], while 35% of the multi-family houses in Sweden are connected to the DH network [18]. Therefore, the usability of lower temperature DH would largely depend on the available infrastructure.

On the other hand, individual systems, such as boilers and heat pumps, correspond to locally installed heat generation systems in a

Table 3
Data collection: Different authors investigated primary heating systems, heating sources, and existing high supply temperatures. The table also indicates the new lower supply temperature levels studied by different authors.

Author	Country	Existing High-Temperature Heating			Lower Temperature Heating		
		Supply system	Heating source	Temperature (supply/return) in °C	Supply system	Heating source	Temperature (supply/return) in °C
Collective Systems							
[16]	Denmark	3GDH	–	70/40	4GDH	100% renewable heat source	50/24[1]
[42]	Sweden	3GDH Electric heating	Biomass-based CHP Electricity, Swedish mix	75/50 –	4GDH	Biomass-based CHP	MT: 55/45[2] LT: 35/28[2]
[18]		3GDH	Biomass, biogas, sewage sludge and surplus heat from the industrial process as CHP sources	75/50	3GDH	Biomass, biogas, sewage sludge and surplus heat from the industrial process as CHP sources	45/40[2]
[41]	Italy	3GDH	Biomass boiler	90	3GDH	Biomass boiler	65[2]
[9]	Denmark	3GDH	–	70/40	4GDH	–	55/25[1]
[48]	Denmark	Gas boilers	Natural gas	70/40	4GDH	–	50/27[1]
[40]	Denmark	Fossil fuel-based burners or 3GDH	Fossil fuels: coal, coke, oil or natural gas	90/70 to 70/40	4GDH	–	55/35[1]
[19]	Latvia	3GDH	Natural gas-fired water boilers	75/55	4GDH	Natural gas co-generation unit and wooden biomass water boiler and natural gas water boiler	55/35[2]
[66]	Denmark	3GDH	–	80/45	4GDH	–	55/30[2]
Individual Systems							
[47]	Germany	Low-efficiency natural gas boiler	Natural gas	Supply more than 100	Infrared heating	Electricity	Supply<100
[10]	Switzerland	Conventional boilers	Oil	55	Heat Pumps	Electricity	40[1]
[45]	Spain	Electric heaters	Electricity	–	Gas boilers	Natural gas	60[1]
[43]	Scotland	Gas boiler	Natural gas	82/71	Boiler with HP	Natural gas and electricity	65[1]
Combined Systems							
[27]	Sweden	3GDH	Swedish mix	75/50	Heat pump for space heating, DH for hot water	Electricity	LT:45[2] ULT:35[2]
[25]	Sweden	3GDH	Swedish mix	78	DH with HP	Swedish mix for DH and electricity	55[2]
[20]	Sweden	3GDH	–	78	DH with HP	–	55/25[2]
[65]	Netherlands	Collective and individual	Natural gas grid and electricity grid	HT thermal grid Supply >65 Return: 45	3GDH	–	MT[2] Supply>55 Return: 35
					4GDH	–	LT[2] Supply: 30-35 Return: 20-25
					4GDH	–	ULT[2] Supply: 12-20 Return: 5-12

1: maximum supply temperature reduction achieved from the highest level of renovations.
2: fixed lower temperature levels considered for evaluation.

dwelling. Several authors have investigated the transition from fossil fuel-based to individual electric solutions [10,47] either due to a lack of DH networks [45] or higher connection costs to DH networks because of poor dwelling conditions [43]. In contrast, some authors have also investigated the combination of collective and individual systems for meeting residential heating demands [20,25,27,65].

Regarding the existing heating supply system, most apartment blocks found in the studies are served by district heating systems with local substations that include circulation pumps to maintain hydronic circulation throughout the building [18,27]. Simultaneously, most single-family homes rely on individual heating systems to meet their heating needs [31]. However, it cannot be concluded that the size or type of the building has any bearing on the heating supply system chosen, as this would depend on the availability of infrastructure capable of providing lower temperature heat.

3.1.6. Lower supply temperature level

Analysing the temperature provided by the supply systems from Table 3, it was observed that most of the higher temperature levels correspond to the supply temperature of 90–70 °C, with return temperatures between 70–40 °C. The reduced supply temperature investigated by different authors was either fixed for evaluation [18–20,25,27,41,42,65,66] or was achieved after the highest level of renovations [9,10,16,40,43,45,48].

The studies also found that the limiting factor for supply temperature reduction after renovations often relates to the preparation of hot tap water. For instance, the space heating demand with extensive renovations and efficient heating systems can be met by the supply system temperatures as low as 30 °C [67]. However, to prevent the risk of legionella growth, water must be heated to at least 60 °C for hot tap water [67]. In cases where the supply temperatures are lower than 60 °C, heat can be upgraded through additional systems such as instantaneous heat exchangers, booster pumps or UV lamps to treat water [16,17]. However, these additional systems often run on electricity, resulting in additional primary energy consumption [16,42].

The review of different studies further indicates a defragmented definition of lower supply and return temperatures to be considered for using LTH. Lower supply temperatures depend on supply systems (individual or collective), which are governed by available heat sources and countrywide infrastructure and regulations. Furthermore, reducing the supply temperature for LTH must be carefully selected as it will impact the necessity of additional systems for upgrading the heat for space heating or hot water. These additional systems may further affect the investment cost, primary energy consumption and environmental performance. Therefore, the range of supply temperatures must be based on the direct use of heat for space heating and hot water (Fig. 5).

3.2. Overview of renovation options for using LTH

Developing viable strategies for retrofitting existing housing stock to accommodate lower temperature heating is a significant challenge [27]. One reason is that technical solutions are abundant on both the supply and demand sides. This issue can be resolved by systematically organising the renovation options needed for using LTH. Moreover, a well-organised solution space may facilitate the selection of retrofit options tailored to the specific needs of the dwelling in question. Thus, the renovation options investigated in the selected studies were organised systematically using the methodology for generating holistic renovation scenarios by Kamari et al. [36,37]. Fig. 6 illustrates an adapted version of the methodology with its four essential components.

The renovation objectives can be defined as the context or purpose of the renovations and should ideally be established by decision-makers before developing renovation scenarios [68]. After establishing the renovation objectives, various renovation scenarios can be developed as alternative situations to evaluate these objectives and determine the level of upgrade required to achieve the renovation goals [69]. A renovation scenario can be segmented into distinct renovation strategies and measure combinations [68], where a renovation strategy is either individual or a combination of different renovation approaches, while renovation measures correspond to various techniques within a renovation strategy [68,70]. Additionally, the renovation measures can be extended to include available products with specific properties such as cost, thermal properties and environmental product declarations to aid the selection of renovation options in the decision-making process.

Table A2 in the appendix illustrates the data extracted from the selected literature studies and organised using the methodology

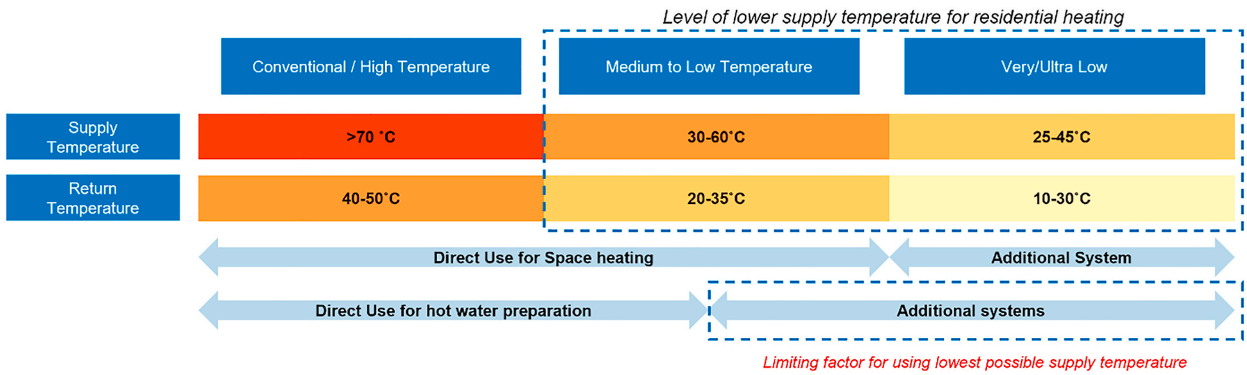

Fig. 5. Range of supply and return temperatures for lower temperature heating based on direct and indirect use of heat for space heating and hot tap water. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

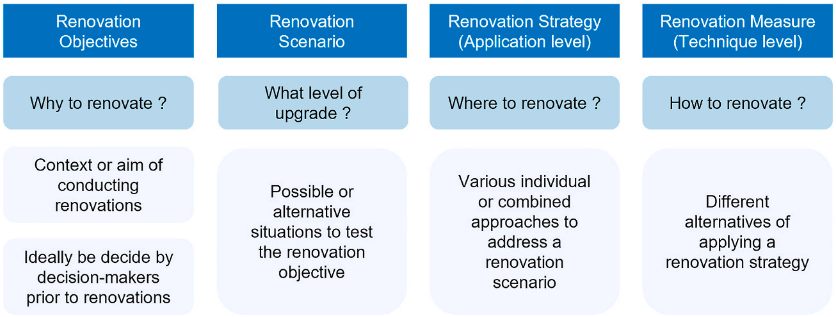

Fig. 6. Methodology for organising renovation options investigated by different authors. The methodology is adapted from Kamari et al. [36]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

described above to comprehend the objectives of renovations, the scenarios for achieving the objectives, and the various renovation strategies and measures that comprise the scenarios.

3.2.1. Renovation objectives

Using the Soft System Methodology (SSM) and Value Focused Thinking (VFT), Kamari et al. [37] identified three broad categories of sustainability-focused renovation objectives comprised of Functionality, Accountability, and Feasibility. These categories enable decision-makers to assess the quantitative and qualitative aspects of renovation options. The three categories are further subdivided into 18 sustainable-value-oriented criteria that indicate the performance indicators that must be used to evaluate a renovation scenario (Table 4).

Table 5 summarises the renovation objectives and associated value-oriented criteria identified from the selected literature studies. Under the quantitative functionality objective, the indoor comfort criterion assesses the impact of renovations on thermal comfort due to LTH. Furthermore, the energy efficiency criterion focuses on minimising operational or primary energy consumption, while materials & waste refer to the environmental impact of renovations due to direct or indirect embodied emissions. Finally, quality-of-services corresponds to maintaining lower supply and return temperatures in the heating supply systems.

Thirteen studies have looked at the functionality objective, the majority of which focused on energy efficiency and indoor comfort criteria. This corresponds to the studies examining the utilisation of LTH by lowering supply temperatures in conjunction with energy renovations while maintaining an acceptable level of indoor thermal comfort [9,10,16,18,46]. In some studies, the criteria for achieving energy efficiency and indoor comfort with lower temperatures also included assessing the renovation options' environmental impact [27,42,43]. However, few studies assessed indoor comfort associated with LTH without requiring renovations [19,48].

The feasibility renovation objective consists of criteria evaluating the economic viability of renovations for using LTH, where financial structures correspond to the affordability or payback period of the renovations. At the same time, investment costs include the cost incurred during the application of the renovations. A total of five studies evaluated the feasibility of the renovations in conjunction with the functional objectives. All five studies evaluated the feasibility of renovations for using LTH from a holistic or integrated perspective, taking into account the energy performance, thermal comfort, environmental and economic benefits over the life of the dwelling [25,26,41,45,47].

The analysis of the identified renovation objectives shows that the current literature is limited to the quantifiable criteria of functionality and feasibility, and no direct relation was found between the qualitative criteria of accountability as renovation objective. Therefore, it is argued that the soft criteria should also be involved in selecting renovation options from the holistic decision-making perspective.

3.2.2. Renovation scenarios

The renovation scenarios investigated by various studies (Table A2) mostly begin with the base case scenario when evaluating renovations for LTH. The base case scenario is frequently referred to as the no-renovation stage or as-built condition of the dwelling [16,26,27,42,45,47] because it is used to ascertain the existing performance of the dwelling and ultimately develop the benchmarks for further evaluations. Next to the base case, the authors investigated scenarios with only one strategy [10,18,42] or with different

Table 4
Sustainability objectives and value-focused criteria for developing holistic renovation scenarios. Kamari et al. [36].

Functionality	Accountability	Feasibility
Technical, environmental and used resources	*Architectural, cultural, human and community*	*Financial, process management and education*
Quantifiable (Hard Criteria)	*Qualitative (Soft Criteria)*	*Mixed (Quantitative and Qualitative)*
Indoor Comfort	Aesthetic	Investment Cost
Energy Efficiency	Integrity	Operation & Maintenance Cost
Material & Waste	Identity	Financial Structures
Water Efficiency	Security & Safety	Flexibility & Management
Pollution	Sociality	Innovation
Quality-of-services	Spatial	Stakeholders' Engagement & Education

Table 5
Renovation objectives and criteria investigated by different authors for using LTH.

Authors	Functionality				Feasibility
	Indoor Comfort	Energy Efficiency	Material & Waste	Quality-of-Services	Financial Structures and Investment Costs
Anastaselos et al. [47]	x	x	x		x
Brand & Svendsen [16]	x	x		x	
Nagy et al. [10]	x	x			
Wang, Laurenti, et al. [42]		x	x		
Wang, Ploskic et al. [18]	x	x			
Wang et al. [27]	x	x	x		
Prando et al. [41]		x			x
Harrestrup & Svendsen [9]	x	x		x	
Østergaard & Svendsen [48]	x	x		x	
Østergaard & Svendsen [40]		x			
Gustafsson et al. [25]		x	x		x
Terés-Zubaiga et al. [45]	x	x			x
Wu et al. [26]		x	x		x
Jin et al. [49]	x				
Safizadeh et al. [46]	x	x			
Millar et al. [43]		x	x	x	
Zajacs & Brodinecs [19]	x				
Lidberg et al. [20]		x		x	

strategies to evaluate the combined effect [9,16,25,26].

The scenarios that investigated combined strategies are often classified as *"basic, minimum, or minor", "light, intermediate, or partial," or "deep, extensive or ambitious"* [9,16,25,43,45,46]. The minimum or minor renovations could relate to changing the radiator systems only to provide thermal comfort with LTH [19,48]. Even though the solutions are quick and cheap, with minor inconvenience to the occupants, they have a minimal impact on energy savings [16]. On the other hand, the light renovations would correspond to selected improvements to the building envelope, mainly with window improvements, as they can provide significant energy benefits with a comparatively small investment [9,16]. This level could also include improving the ventilation systems, airtightness and thermal bridges [18,27,45,46]. Finally, extensive renovations result in the most significant changes to the building with maximum energy savings while incurring high costs and inconvenience for the occupants [9,16,45,46].

For developing renovation scenarios with relevant strategies, it is necessary to determine the depth of the renovations, which is defined as the extent of renovation interventions necessary to achieve a predetermined level of performance [71]. Some literature defines the depth of renovations to achieve operational or primary energy savings due to renovations in a given year [71,72], commonly implemented measures in practice [10,18,40,41] or the percentage of envelope renovated [73]. Although, it can also be argued that the depth of renovations may stem from the constructional limitations of the dwelling depending on the construction year and compactness ratio. Therefore, determining the depth of renovations is an essential step in the decision-making process from the perspective of making renovation scenarios for evaluating different strategies required to integrate LTH.

3.2.3. Renovation strategies and measures

The renovation scenarios indicate renovation strategies and specific measures for achieving the renovation objectives, where renovation strategies are the different approaches to addressing a renovation scenario, and renovation measures are the alternative techniques for a particular renovation strategy. A wide-ranging list of numerous strategies for renovating an existing building was developed by Kamari and Corrao [69], where 26 categories of renovation strategies were identified through a comprehensive review of the literature, various databases and European renovation projects.

Table 6 illustrates the different renovation strategies investigated by the studies, which were divided into building envelop, system and control levels. The strategies at the building envelope level focused on reducing the heat losses due to transmission, infiltration and ventilation. The system-level strategies correspond to approaches focused on improving the efficiency of active systems for space heating, hot water, ventilation, heating supply and electrical systems. Finally, the control level includes strategies for indoor setpoint temperature or maintaining the supply and return temperature from the heating systems. Table 7 and Table 8 summarise the renovation strategies and corresponding measures investigated by different authors applicable to building envelopes, systems and services.

From the analysis, it is observed that for using LTH, most of the studies investigated the strategies applicable to the building envelope, where upgrading the window can be considered a low-hanging fruit due to the fact that new windows with better insulation and airtightness can reduce space heating demands with relatively less investment [16,70]. At the system level, strategies to upgrade the space heating system are often combined with envelope strategies, followed by ventilation strategies. Few studies have also investigated the combination of space heating and ventilation strategy through measures such as ventilation radiators [20,27,42,49]. However, there is a probability that the ventilation radiator will interfere with the otherwise well-balanced mechanical ventilation system in the house [31]. Therefore, it is essential to identify the conflicts between different approaches while selecting renovation strategies. From identifying the different renovation measures, it was observed that most studies are limited at the strategy level. However, in practice, it is essential to understand the exact techniques required for deciding on renovations. Therefore, it is argued that the renovation measures must be elaborated with product-level information in the decision-making process for analysing renovation options to select them effectively for using LTH.

Table 6
Renovation strategies for using LTH identified from the selected literature.

Authors	Building Envelope			Systems					Control
	Insulation Approaches	Window & Door Replacement	Airtightness and Thermal Bridges	HVAC (SH)	HVAC (DHW)	HVAC (Ventilation)	Heat Generation Systems	Electrical Systems	
Anastaselos et al. [47]	x	x					x		
Brand & Svendsen [16]	x	x	x	x					x
Nagy et al. [10]	x	x	x						
Wang, Laurenti, et al. [42]	x	x	x	x				x	
Wang, Ploskic et al. [18]	x	x	x	x		x			
Wang et al. [27]				x		x	x		
Prando et al. [41]	x	x		x		x			
Harrestrup & Svendsen [9]	x	x				x			x
Østergaard & Svendsen [48]				x					
Østergaard & Svendsen [40]	x	x							
Gustafsson et al. [25]	x	x		x	x	x	x		
Terés-Zubaiga et al. [45]	x	x		x			x		x
Wu et al. [26]	x	x					x		
Jin et al. [49]				x					
Safizadeh et al. [46]	x	x	x						x
Millar et al. [43]	x	x					x		
Zajacs & Brodinecs [19]	x	x	x			x			x
Lidberg et al. [20]	x	x		x		x	x		

Table 7
Renovation strategies and measures investigated by authors at the building envelope level. Different standards used by authors are indicated.

Renovation Strategies	Renovation Measures						
		Component	EnEV09	EnEV 2016	Passive House	SIA 380 Target	SIA 380 Limit
Insulation Approaches	Higher insulation values for opaque elements. Insulation values to comply with country-specific standards.	Façade (W/m^2K)	0.28	0.25	0.14	0.25	0.15
		Roof (W/m^2K)	0.2	0.2	0.11	0.25	0.15
		Floor (W/m^2K)	0.2	0.32	0.23	0.3	0.2
Window and Doors Replacement	High-performance glazing is often (DGU or TGU) accompanied by changing frames with better insulation. Insulation values to comply with country-specific standards. Replacing windows that exceeded 30 years of service life. PVC, aluminium Window frames	Windows (W/m^2K)	1.3	1.2	0.89	1.3	0.9
Airtightness	Often followed by improved window frames. The airtightness values to comply with country-specific standards	Airtightness (1/h)	–	0.2–0.1	0.1–0.05	0.4	0.3
Envelope (Exterior and Interior Finishes)	Increasing insulation thickness Plaster insulation Aerogel thickness						
Solar Gain	Sun shading systems						
Thermal Bridges	Sealing all joints and intersections between the balcony and external wall.						

3.3. Overview of performance evaluation parameters

The methodology of organising renovation options discussed in section 3.2 inherited the decision-making aspect of evaluating renovation scenarios and selecting strategies and measures for using LTH. As mentioned before, the stakeholder must determine the renovation objectives and criteria before the renovation process. These objectives can also dictate the selection of key performance indicators (KPIs) that enable evaluating possible renovation scenarios and quantifying the progress towards achieving the renovation goals [68,74]. Furthermore, the KPIs provide opportunities to identify the trade-offs due to the concurrent effects of various renovation strategies and measures. Therefore, this thematic category summarises the various KPIs, associated evaluation methods, and selection criteria used by the studies to assess the renovation options for using LTH.

Table 9 summarises the different KPIs found in the selected studies, where they are organised based on the renovation objective and value-oriented criteria identified in section 3.2.1. In addition to the KPIs, the table also shows the various evaluation methods used by the authors to quantify the KPIs and subsequent selection criteria to determine benchmarks or limiting values for choosing particular renovation options. For instance, some authors evaluated the impact of renovation options on thermal comfort using the PMV/PPD model as an evaluation method and selected the one with the performance within the acceptable range according to the ASHRAE or

Table 8
Renovation strategies and measures investigated by authors for building services and systems.

Renovation Strategies	Renovation Measures
HVAC (Space Heating)	Existing Radiators
	Low-Temperature Radiators
	Low-Temperature Radiators with add-on fans
	Low-Temperature Ventilation Radiators
	Baseboard Radiators
	Infrared Panels
	Underfloor Heating Systems
HVAC (Hot Water Preparation)	Showering Heads
	Flow Reducing Taps
	Instantaneous Heat Exchanger
	Heat Pump Boosting at Substations
HVAC (Ventilation)	Mechanical Ventilation with Heat Recovery
	Ducts and Air Handling Units
Heat Generation Systems	High-Efficiency Gas Boiler
	Condensing Boiler
	Biomass Boiler
	Ground Source Heat Pump
	Electric Heat Pump
	Water Source Heat Pump
	Exhaust Air Heat Pump
	Low-Temperature District Heating
	Photovoltaic Panels
	Solar Thermal Collectors
Electrical Systems	Efficient Lighting
	Efficient Circulation Pump for Hydronic System
Controls	Indoor Operative Temperature Control between 19 and 22 °C
	30K–20K Temperature Difference between Supply/Return.

ISO standards [18,46,47].

As previously discussed, there is a direct relationship between the renovation objectives and criteria and the KPIs used to evaluate them. For example, Fig. 7 shows that most studies used energy efficiency and indoor comfort KPIs, similar to the trend of renovation objectives and the criteria investigated by different studies, as shown in Table 5.

Regarding energy efficiency, the majority of studies assessed operational energy consumption, which corresponds to heating demands or net energy use due to space heating, hot water, and electrical consumption [9,16,41,42,47]. In addition, six studies assessed the effect of the shift toward sustainable heat generation systems and LTH on primary energy consumption [6,25,27,42,45,47]. However, only a single study by Terés-Zubiaga et al. [45] examined the effect of occupants on the actual energy savings after renovations. The author demonstrated the impact of the rebound effect, i.e., increased energy consumption after energy-efficient renovations, by taking into account the general tendency of occupants to set higher indoor setpoint temperatures when utilising LTH. The author concludes that a 2 °C increase in the indoor heating setpoint from 19 °C can reduce the expected energy savings and economic viability of the renovations. This suggests that it is essential to evaluate occupants' impact along with energy efficiency indicators to minimise the gap between the theoretical and actual energy savings while considering LTH.

In addition to energy efficiency, studies have investigated the performance of renovations on thermal comfort when using LTH for evaluating indoor comfort. For example, several studies considered the impact of renovations in maintaining operative temperatures above desired setpoint temperatures [9,10,19,45,48], while others evaluated using the PMV/PPD thermal comfort models [18,46,47]. Nevertheless, Safizadeh et al. [46] argue that the PMV method is unsuitable for evaluating radiant heating effects using LTH-based solutions. Furthermore, Wang et al. [18] analysed local comfort due to LTH by assessing annual surface and floor temperatures. There was only one study, however, that assessed other aspects of indoor comfort, i.e. indoor air quality [27]. In addition, no study thus far has considered the acoustical or visual aspects of indoor comfort nor the effect of summer overheating after renovations because of rising outdoor temperatures and the increasing need for cooling in the dwellings.

Seven studies evaluated the environmental and economic impact of renovations for using LTH. The KPIs related to material and waste criteria included environmental impact categories of different renovation options [27,47], reduction in GHG or carbon emissions [25,26,42,43] and the period required by the primary energy savings to offset embodied energy of the retrofitted options [27]. The KPIs related to financial feasibility included the economic viability of carrying out renovations, where the indicators were used to determine the trade-offs between investment costs, payback periods and long-term economic performance of the renovation options [25,26,41,45,47]. Finally, the KPIs for quality-of-service criteria constituted maintaining the heating system's lower supply and return temperatures. This KPI is essential in identifying the critical radiators [48], the lowest supply temperature required for maintaining thermal comfort [16,20,43], and the temperature difference between supply and return to increase heat generation systems' efficiency [9,10].

The analysis of the identified KPIs from the literature reveals a variety of indicators and evaluation methods representing a lack of a standard set of criteria to assess the effect of renovation on LTH utilisation. From the perspective of decision-making, this can result in challenges when selecting relevant KPIs and methods for aiding any decision on renovations. The complexity is exacerbated by the fact

Table 9
Key performance indicators and evaluation parameters used by different authors to investigate the performance of renovation scenarios. The table also provides information on the selection criteria as benchmarks used by different authors.

Renovation Objective		Key Performance Indicator	Evaluation Method	Selection Criteria	Authors
Category	Criteria				
Functionality	Indoor Comfort	Thermal Comfort	Predicted Mean Vote (PMV)	Within acceptable range according to ASHRAE standard 55.	[46,47]
			Predicted Mean Vote (PMV) based Percentage of People Dissatisfied (PPD)	At least 15% PPD, according to ISO 7730.	[18]
			% Hours below set point temperature as discomfort hours due to underheating	Lowest % of discomfort hours compared to the base case.	[9,19,45,46]
				Comfortable temperature range 20–24 °C according to Swiss standard SIA 2024.	[10]
				Operative temperatures 0.5 °C below set point temperatures for identifying critical radiators.	[48]
			Operative temperature fluctuations	1 °C allowable variation limit according to ASHARE for drifts and ramps.	[18]
			Annual floor surface temperature	Annual floor surface temperature ranges from 21 to 28.5 °C for bare feet.	[18]
			Thermal sensation survey according to ISO 2005		[49]
		Indoor Air Quality	CO_2 concentration	CO_2 concentration within 700 ppm from annual outdoor CO_2 concentration.	[27]
			Percentage Dissatisfied (PD) due to air quality	Below 20% PD.	[27]
			Relative Humidity (RH)	Acceptable RH range according to ASHRAE: 25–60%.	[27]
	Energy Efficiency	Final Energy Consumption	Space heating energy/demand and heat losses	The highest energy savings compared to the base case.	[10,16,40,43,47,48]
			Heat Losses	The highest reduction in heat losses compared to the base case.	[46]
			Space heating peak loads	The highest reduction in space heating peak loads compared to the base case.	[9]
			Space Heating capacity of emission systems	If heating capacity could compensate for space heating demands.	[40]
			Annual Net energy demand for space heating, hot water and electricity	Compared to the base case or following country regulations. Swedish BBR limitations for annual net energy demand. Non-electrically heated: 90 kWh/m^2 Electrically heated: 55 kWh/m^2 Danish building regulations limitations: (52.5 + 1650/A) kWh/m^2, A is the heated area.	[9,18,20,26,27,41,42,45]
		Total Primary Energy Consumption	Total Primary energy consumption	The highest primary energy savings compared to the base case.	[18,25,27,42,45,47]
		Prebound Effect	The ratio between theoretical and actual energy savings after renovations	Evaluating the effect of occupants on energy consumption after renovations.	[45]
	Material & Waste	Environmental Impact Categories	Emissions for impact categories Climate change: CO_2 eq. Acidification: SO_2 eq. Eutrophication: PO_4 eq. Photochemical oxidation: C_2H_4 eq.	The highest reduction in emissions compared to the base case and evaluated using LCC methodology for 30 years life span.	[47]
			16 environmental impact categories according to IPCC 2013 GWP 100a and ILCD 2011 midpoint + methods	Analysing the positive and negative effects of renovation strategies on impact categories.	[27]
		Embodied Energy and GHG Emissions	Estimation of Embodied energy and GHG emission for all the materials in retrofit options	Comparison of the impact of retrofit option on energy savings with embodied energy and GHG emissions.	[26,42]
		Break-Even Years	Timespan required by the primary energy savings by a retrofit option to offset embodied energy of the retrofit	Lowest time span.	[42]

(continued on next page)

Table 9 (*continued*)

Renovation Objective		Key Performance Indicator	Evaluation Method	Selection Criteria	Authors
Category	Criteria				
		CO_2 Emissions		The highest reduction in CO_2 emission due to renovations compared to the base case.	[25,43]
	Quality-of-Services	Supply/Return Temperatures	Lowest Supply Temperature	Lowest supply temperature to maintain the setpoint temperature.	[16,43]
			Lower supply/return temperature regime	Maintaining a lower supply/temperature regime of 55/25 °C for most parts of the year.	[20]
			Difference between supply and return temperatures	Maintaining a 30K temperature difference for most of the year due to the existing capacities of DH networks.	[9]
			Logarithmic mean temperature difference (LMTD) between supply and return temperatures. Calculated for each room and average of the entire house	LMTD of a room above average LMTD of the dwelling indicates the presence of critical radiators.	[48]
Feasibility	Financial Structures	Net Present Value (NPV)	Long term economic performance of renovation scenario using NPV	Positive NPV for an evaluation period of 30 years.	[47]
			Calculated using the methodology of EU244/2012 and computed according to EN15459:2009	Minimum NPV for an evaluation period of 30 years.	[41]
			Discounted payback period using NPV	The minimum period taken by the savings due to renovations to repay investment costs.	[25,45]
	Investment Costs	Investment Costs	Life cycle cost analysis (LCCA)	Lowest LCCA for an evaluation period of 30 years.	[25]
			LCC as a function of investment costs and operation costs in two scenarios: 1. Retrofit and energy system upgrades combined. 2. Retrofit prior to energy system upgrade	Lowest LCC for a period of 30 years.	[45]
			Retrofit costs evaluated using Swiss building energy and retrofit tool	Minimum retrofit costs in a period of 50 years.	[26]

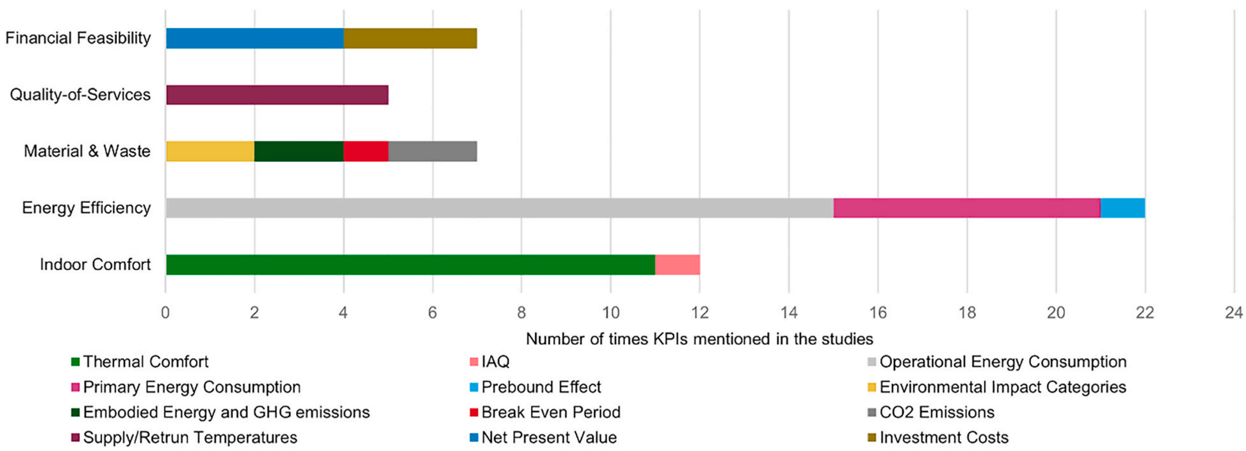

Fig. 7. KPIs used by different studies for evaluating the renovation options. The KPIs are arranged based on the renovation objectives described in section 3.2.1. The KPIs related to indoor comfort, energy efficiency, material & waste and quality of services correspond to the functionality objective, while KPIs for financial feasibility correspond to the feasibility objective. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

that indicators can be definitive, comparative or both. For instance, KPIs related to indoor comfort are definitive, i.e., benchmarks or limits can be quantified based on national or international standards, while KPIs related to environmental or economic impact are comparative, i.e., a benchmark needs to be defined from a base case, and the performance of renovation options are compared to this base case. Therefore, the indicators, evaluation methods and selection criteria must be chosen depending on the decision-making boundaries stemming from the renovation objectives decided early on by the stakeholders. For example, the KPIs related to energy efficiency and indoor comfort ascertain the "possible" renovation options that could provide thermal comfort by using LTH and achieving a certain level of energy efficiency. However, the "possible" renovation options may not be "desirable" in terms of service quality or environmental performance indicators, nor "feasible" in terms of financial investments. Similarly, "desirable" strategies may not be "possible" nor "feasible." As a result, it is essential to determine the KPIs and the renovation objectives by determining the possible, desirable, and feasible boundaries.

4. Conclusions

The purpose of this study was to review the scientific literature on integrating LTH into existing dwellings. The study aimed to identify the parameters that can help inform the decision-making process when selecting appropriate renovation solutions for using LTH. The study employed the SALSA (search, appraisal, synthesis and analysis) framework for a systematic review to address the decision-making challenges that arise due to the heterogenous dwelling stock with varying building characteristics, a wide range of renovation solutions, and various key performance indicators for evaluating the trade-offs and selection of renovation options for using LTH.

The findings from the review suggest that dwelling characteristics such as compactness ratio, thermal insulation, thermal bridges, airtightness of the building envelope, ventilation systems, the capacity of the existing space heating system and supply temperatures are essential parameters when investigating the potential of the existing dwelling to be heated with LTH and the necessity of renovations.

The parameters indicated above can be collected for a specific dwelling case, although different archetypes representing the most typical properties could be developed for investigating the diverse residential stock. Most studies identified archetypes based on dwellings representative of different construction years. It can indicate the dwelling's standard thermal properties and prevalent construction style in the selected year. However, it is argued that a performance gap may occur when selecting representative dwellings based on construction year, as in reality, the dwellings may already be renovated to improve energy efficiency. Furthermore, no significant relationship was found between dwelling size and the usability of LTH. In contrast, the compactness ratio, which includes the dwelling size and position, might help develop archetypes when combined with typical construction years.

Another decision-making challenge is related to numerous renovation alternatives available at the building level, some of which may nullify one another's impacts, thus making selection difficult. Therefore, the study adopted a systematic approach to developing a renovation solution space by identifying renovation objectives, depth of renovations as renovation scenarios, application-level strategies and product-level measures. Although this allowed us to narrow down the options depending on the context of the dwelling, the study found that research is limited to evaluating quantitative renovation objectives, including functionality and feasibility criteria. Therefore, the soft criteria involving qualitative aspects of renovations must be considered while developing renovation objectives. Additionally, it is argued that the existing studies are also limited to evaluating strategy-level renovation options, while product-level information is essential for making effective decisions regarding selecting renovations option for using LTH.

Finally, the study summarised the various KPIs, evaluation and selection criteria used by different studies and found a lack of standard set of criteria for indicating the readiness of a dwelling for using LTH. However, the findings suggest that KPIs related to energy efficiency, indoor comfort, and quality-of-services are essential for investigating possible renovation solutions. On the other hand, environmental and economic performance KPIs are considered constraints to evaluate the feasibility of possible renovation options. Furthermore, since the renovation objectives determine the performance indicators, this study argues that the performance indicators must be selected in collaboration with the stakeholders while developing renovation objectives.

From a decision-making perspective, it is essential to identify dwelling cases and collect data on the sensitive parameters to determine and evaluate the need for renovations for using LTH. This preliminary investigation provides the decision-makers with pertinent data for determining the renovation's objectives, intervention depth, performance assessment, and selection criteria. In addition, such boundary conditions are essential for dictating the development of renovation solution space, their evaluation, and ultimately selecting the optimal solutions by balancing all trade-offs. Therefore, stakeholder participation is a crucial part of the decision-making process. However, due to the nature of the search terms used, no studies were found that included stakeholders in decision-making when selecting LTH renovations. Thus, future review studies should explore the participation of stakeholders and their requirements for selecting renovations for using LTH from a decision-making standpoint.

CRedit authorship contribution statement

Prateek Wahi: Conceptualization, Methodology, Investigation, Writing-Original Draft, Writing-Review & Editing, Visualization, Project administration. **Thaleia Konstantinou:** Conceptualization, Methodology, Writing-Review & Editing, Supervision, Project administration, Funding acquisition. **Martin Tenpierik:** Conceptualization, Writing-Review & Editing, Supervision, Funding acquisition. **Henk Visscher:** Conceptualization, Writing-Review & Editing, Supervision, Funding acquisition.

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

No data was used for the research described in the article.

Acknowledgement

This study was carried out with the support from the MMIP 3&4 scheme of the Dutch Ministry of Economic Affairs & Climate Change and the Ministry of the Interior & Kingdom Relations. I want to express my deep appreciation to Marek Kiczkkowiak and my wife, Anagha Yoganand, for their invaluable assistance in proofreading, support and encouragement.

Appendix

Table A1
Search strings used on scientific databases and the number of articles found

SCOPUS	Articles Found
TITLE-ABS-KEY ("low* temperature" PRE/2 (heat* OR supply)) **AND** TITLE-ABS-KEY (residen* OR "Residential existing building" OR (existing W/1 building) OR dwelling OR hous* OR "Single Family House" OR "Multi Family House" OR apartment) **AND** TITLE-ABS-KEY (renovation OR refurbishment OR retrofit OR renewal OR improvement OR repair OR upgrade)	**54**
Web of Science	
Web of Science TS= ("low temperature" NEAR/2 (Heat* or supply))) **AND** TS= (Residen* OR "Residential existing building" OR Existing SAME/1 Building OR dwelling OR hous* OR "Single Family House" OR "Multi Family House" OR Apartment)) **AND** TS= (Renovation OR refurbishment OR retrofit OR renewal OR improvement OR repair OR upgrade)	**51**
Science Direct	
Article with these terms ("Low Temperature Heating" OR "Low Temperature Supply") **AND** (Residential OR House OR Dwelling OR "Single Family House" OR "Multi Family House" OR Apartment) **AND** Title, abstract or author-specified keywords (Renovation OR Retrofit OR Refurbishment OR renewal OR improvement OR repair OR upgrade)	**136**
Total Article Found	**241**

Table A2
Data collection: Organisation of renovation objectives and value-oriented criteria depending on the aim of the study, followed by renovation scenarios as the combination of renovation strategies and measures investigated by each study.

Author	Country	Dwelling Typology			Renovation Objective		Renovation Scenario		Renovation Strategy	Renovation Measure
		Size	Subtype	Age	Category	Criteria				
[47]	Germany	–	Semi-Detached (2)	1970 & 1992	Functionality	Indoor Comfort	Total of 6 renovation scenarios	Base	As built condition in 1970 and 1992	No Renovations
						Energy Efficiency Material & Waste		A - E	Insulation Approaches Window Replacement	Insulation according to EnEV09
					Feasibility	Financial Structures			HVAC	5 different primary heating systems with corresponding heat emitters, including gas boilers, heat pumps and radiative panels
[16]	Denmark	SFH	Detached	1973	Functionality	Indoor Comfort	Total of 4 renovation scenarios	No Renovation (basic and advanced)	As built condition in 1973	No renovation to the building envelope
									HVAC	Original radiator and LT radiators
									Controls	Fixed supply temperature of 70 °C Maximum flow rate of 264 L/H
						Energy Efficiency				Operative temperature of 20 °C and 22 °C

(continued on next page)

Table A2 (*continued*)

Author	Country	Dwelling Typology			Renovation Objective		Renovation Scenario		Renovation Strategy	Renovation Measure
		Size	Subtype	Age	Category	Criteria				
								Light Renovation	Window Replacement	Changing windows with 30 years of service life
									Airtightness	Improved airtightness because of better windows
									HVAC	Original radiator and LT radiators
						Quality of Service			Controls	Operative temperature of 20 °C and 22 °C
								Extensive Renovation	Insulation Approaches	Insulating envelope and reducing linear thermal loss
									Window Replacement	Windows facing west and north with a triple-glazing unit
									Airtightness	Improved airtightness because of better windows
									HVAC	Original radiator and LT radiators
									Controls	Operative temperature of 20 °C and 22 °C
[10]	Switzerland	AB	–	–	Functionality	Indoor Comfort	Total of 7 renovation scenarios	Individual	Window Replacement	–
									Insulation Approaches	Plaster insulation with 4 cm on the north and east, 6 cm on south
										Aerogel insulation on all facades
									Airtightness	Medium
						Energy Efficiency				High
								Combination 1	Window, insulation and airtightness	Plaster insulation and high airtightness
								Combination 2	Window, insulation and airtightness	Aerogel insulation and high airtightness
[42]	Sweden	AB, MFH	Low rise	1946–1960	Functionality	Energy Efficiency	13 individual scenarios	RO1-RO13	Insulation Approaches	Insulating wall, ground floor and roof/attic
									Window Replacement	High-performance glazing and frames on the south and north facade
									Airtightness	Seal all cracks and air leaks
		AB, MFH	High rise	1961–1975					HVAC (SH)	Ventilation control with heat recovery
										LTH radiator with add-on fans designed for 55/45
						Material & Waste				LTH ventilation radiator designed for 35/28
		SFH	–	Before 1945					Thermal Bridges	Balcony thermal bridges

(*continued on next page*)

Table A2 (*continued*)

Author	Country	Dwelling Typology			Renovation Objective		Renovation Scenario		Renovation Strategy	Renovation Measure
		Size	Subtype	Age	Category	Criteria				
									Electrical Systems	Efficient lighting controls
										Efficient circulation pumps for space heating
[18]	Sweden	AB, MFH (2)	Low rise	1965–1975	Functionality	Indoor Comfort	1 base case, 5 individual scenarios, 1 combined scenario	Base case	As built condition	No Renovations
								R1-R5 with LTH radiators	Insulation Approaches	New insulation layer on external walls
										New insulation on the roof and attic
									Window Replacement	High-performance glazing and window frames
						Energy Efficiency			Airtightness	Upgrading the airtightness by 60% by sealing all cracks, air leaks and joints in the balcony
									HVAC (V)	Ventilation system with heat recovery
									HVAC (SH)	Ventilation radiators designed for 45/40
								Combined	All combined with LTH radiators	
[27]	Sweden	AB, MFH (2)	Low rise	1965–1975	Functionality	Indoor Comfort	1 base case, two scenarios	Base case	As built condition	No renovations
								Two combinations of ventilation heat recovery joined with the LTH system	HVAC(V)	Ventilation with heat recovery
						Energy Efficiency			HVAC (system)	ASHP for SH
									HVAC(SH)	Ventilation radiators
						Material and Waste				Baseboard radiators
[41]	Italy	14 typical units representative of building stock		Before 1960	Functionality	Energy Efficiency	Multiple renovation scenarios created using genetic algorithms		Insulation Approaches	Insulation of roof, walls and floors with increasing thickness from 1 to 20 cm.
									Window Replacement	4 different alternatives for high-performance glazing
				1960–1991						Aluminium frames instead of wooden frames
					Feasibility	Financial Structures			HVAC(V)	Mechanical ventilation with heat recovery
				After 1991					HVAC(SH)	Underfloor heating system
[9]	Denmark	AB	–	1910	Functionality	Indoor Comfort	1 base case, 3 scenarios	Base case	As built condition	No renovations
								Window Renovations	Window Replacement	High-performance windows with solar shading
									HVAC(V)	MVHR with 85% HR
						Energy Efficiency		Intermediate Renovations	Window Replacement	High-performance windows with solar shading
									HVAC(V)	MVHR with 85% HR

(*continued on next page*)

Table A2 (*continued*)

Author	Country	Dwelling Typology			Renovation Objective		Renovation Scenario		Renovation Strategy	Renovation Measure
		Size	Subtype	Age	Category	Criteria				
		AB	–	1906					Insulation Approaches Control	Insulating ground floor and roof only Operative temperature of 20 °C and 22 °C
						Quality-of-Service		Extensive Renovations	Window Replacement	High-performance windows with solar shading
									HVAC(V)	MVHR with 85% HR
									Insulation Approaches Control	Insulating façade, roof, floor Operative temperature of 20 °C and 22 °C
[48]	Denmark	SFH (4)	–	1930	Functionality	Indoor Comfort Energy Efficiency Quality-of-Service	Only 1 scenario		HVAC(SH)	Replacing critical radiators without renovations
[40]	Denmark	SFH (3)	–	1900–1960	Functionality	Energy Efficiency	2 scenarios	Light Renovations (general maintenance)	Insulation Approaches	Roof insulation
		SFH	–	1961–1972					Window Replacement	Improving windows
		SFH	–	1973–1978				Energy Renovations	Insulation Approaches	Upgrading building envelope
		SFH	–	1979–1998					Window Replacement	High-performance glazing
[25]	Sweden	MFH	–	1961–1980	Functionality	Energy Efficiency Material and Waste	15 different scenarios from three renovation levels and five different configurations of the HVAC system	L0: Reference	Envelope Repair Window Replacement HVAC(SH) Plumbing (DHW)	Basic repair and maintenance, including façade repair, changing windows, tunning of radiator system and changing water taps
								L1	Window Replacement Plumbing (DHW)	High-performance triple-glazing unit Installing shower heads and flow-reducing water taps
								L2	Insulation Approaches Window Replacement Plumbing (DHW)	Wall and roof insulation High-performance triple-glazing unit Installing shower heads and flow-reducing water taps
					Feasibility	Investment Cost		0: Existing	As built HVAC system	As built for reference
								A	HVAC System	Mechanical ventilation with heat recovery
								B		Exhaust air heat pump for SH
						Financial Structures		C1		Exhaust air heat pump for SH and DHW
								C2		Exhaust air heat pump for SH and DHW Ventilation Radiators
[45]	Spain	MFH	–	1959–1961	Functionality	Indoor Comfort	A total of 54 scenarios were	NR: No Retrofit	As built condition	No renovations

(*continued on next page*)

Table A2 (*continued*)

Author	Country	Dwelling Typology			Renovation Objective		Renovation Scenario		Renovation Strategy	Renovation Measure
		Size	Subtype	Age	Category	Criteria				
						Energy Efficiency	generated by combining three renovation levels and different heating system strategies.	BAU: Business as Usual	Insulation Approach	Façade and roof insulation. Intermediate and usual level of energy renovations
					Feasibility	Investment Cost		BO: Best Option	Insulation Approach	Higher insulation level of roof and façade
									Window Replacement	Triple glazing unit with PVC frame
								Heating Systems	HVAC (heating system)	Two individual gas boiler systems: Low temperature natural gas boiler and condensing boilers
									Control (heat production set point)	Three set points for heat production: 60,55,50 °C
						Financial Structures			HVAC (SH system)	High-efficiency radiators designed for heat production set point temperatures with adjusted lengths
									Control (comfort temperature set point)	Three Comfort set point temperatures: 19,20,21 °C
[26]	Switzerland	Detached Semi-detached Large		Before 1900	Functionality	Energy Efficiency	Multiple scenario generation using GA	Original	As built condition	No renovations
								Base case	HVAC (heating system)	5 different primary heating systems with no renovations
		Detached and Large		1900–59				Windows and Airtightness	Window Replacement	According to SIA 380 limits
						Material & Waste				According to SIA 380 targets
		Semi-detached, detached and large		1960–79				Roof and Airtightness	Insulation Approaches	Roof according to SIA 380 limit
										Roof according to SIA 380 targets
		Semi-detached, detached and large		1980–99	Feasibility	Investment Costs		Façade and Airtightness	Insulation Approaches	Facade according to SIA 380 limit
										Facade according to SIA 380 targets
								Whole Building	Combined	According to SIA 380 limit
									Combined	According to SIA 380 target
[49]	Nordic countries	–		1975–2000	Functionality	Indoor Comfort	Two scenarios		HVAC(SH)	Ventilation radiators
										Floor heating
[46]	Germany	MFH		1958–1968	Functionality	Indoor Comfort	30 scenarios	Base case	As built condition	No renovations
								Partial Renovations	Insulation Approaches	Improved external wall according to ENEV 2016
										Improved external wall according to passive house
									Window Replacement	According to EnEV 2016

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Table A2 (*continued*)

Author	Country	Dwelling Typology			Renovation Objective		Renovation Scenario		Renovation Strategy	Renovation Measure
		Size	Subtype	Age	Category	Criteria				
										According to passive house
						Energy Efficiency			Airtightness	According to EnEV 2016
										According to passive house
								Ambitious Renovations	Insulation Approaches, Window Replacement and Airtightness	Building envelope insulation according to EnEV2016
										Building envelope insulation according to passive house
								Supply Temperatures	Control	Six supply temperatures for radiant warm ceiling
[43]	Scotland	–	Tenement flat	Typical 20th century	Functionality	Energy Efficiency Material & Waste	8 scenarios with four renovation cases and two heating systems	Case 1	As built condition	No renovations
								Case 2	Window Replacement	Improving existing windows to DGU
								Case 3	Insulation Approaches	Insulating the wall only
						Quality-of-Service		Case 4	Window Replacement and Insulation Approaches	Insulating walls and windows both
								Heating Systems	HVAC (heating systems)	Two heating systems if the house could not be connected to DH
[19]	Latvia	–	Town house		Functionality	Indoor Comfort	3 scenarios	No Renovation	As built condition	No renovations
								No Renovation with the reduced supply temperature	Control (supply temperature)	Reducing the supply temperature to 55/35
								Renovations with reduced supply temperatures	Insulation approaches, window replacements, airtightness, HVAC (V)	Improving overall building envelope
									Control (supply temperature)	Reducing the supply temperature to 55/35 °C
[20]	Sweden	MFH		1965–1974	Functionality	Energy Efficiency	Five scenarios	As built	As built condition	No renovations
								A	Insulation approaches	Wall and roof insulation
									Window replacement	High-performance glazing
									HVAC system	MVHR
						Quality-of-Service		B: A + radiator	HVAC (SH)	Ventilation radiators
								C: B+ primary heating system	HVAC (primary heating system)	District heating + Exhaust air heat pump for space heating only
								D: C + Primary heating system for DHW	HVAC (primary heating system)	District heating + Exhaust air heat pump for Space heating and hot water.

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