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CENTRE FOR
HOUSING EVIDENCE

Reviewing Residential Retrofitting Literature

An Explorative Mapping Study

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CaCHE has been conducting two major studies on residential retrofitting: Retrofit of Pre-1919 Glasgow Tenement Housing Demonstration Project and Flexible Air Source Heat Pump for Domestic Heating Decarbonisation (funded by EPSRC). This mapping study aims to set the scene for contemporary residential retrofitting literature as part of this research agenda. The wider funding for the housing evidence programme is by the ESRC, AHRC and the Joseph Rowntree Foundation through the UK Collaborative Centre for Housing Evidence.

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Executive Summary

UK housing has been bearing a bundle of long-standing problems such as affordability, access to decent housing, and the construction and distribution of new stock in the country. The climate emergency has brought another challenge to these long-standing problems. It requires an urgent response to reduce carbon emissions in the built environment. Dwelling on this urgent need, this mapping study explores the scope of the residential retrofitting literature internationally.

This study mapped contemporary residential retrofitting literature published in the last two decades in English. It reviewed 299 papers (abstracts only) which are published in 87 journals and six edited (and indexed) books. The study inductively found out that contemporary residential retrofitting literature highlights key themes as individuals' role in residential retrofitting; retrofit policy and planning; projections, simulations and models; life cycle assessment of the buildings; thermal comfort studies; and studies about heating-cooling-ventilation aspects as well as including residential retrofit studies engaging with multiple themes.

The key findings of the mapping study are as follows:

- The literature is thematically and geographically diverse.
- The Global North countries are represented more than the Global South countries in the literature.
- The literature is rich with increasing diversity in disciplines showing interests in residential retrofitting as well as the approaches to residential retrofitting analysis.
- Studies looking at multiple aspects of residential retrofitting comprise a substantial number of papers.
- Studies aiming to measure the effectiveness or efficiency of retrofitting practices and policies are highlighted in the literature.
- Among new technologies, heat pumps are identified as an area of interest in the literature.
- Thermal comfort and ventilation systems are underrepresented topics in the literature.



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Introduction

Climate emergency and built environment

Climate Emergency mandates a substantial change in the production and consumption relations. This includes how we produce and experience cities and built environment. The Intergovernmental Panel on Climate Change (IPCC) stress that cities and human settlements are key to delivering urgent climate action (IPCC, 2022a). While cities are the areas to be hit greatly by climate change, according to the IPCC report, they also are places for solutions (IPCC, 2022a). The cities and urban areas can provide these solutions through ambitious mitigation efforts for “(i) reducing or changing energy and material consumption, (ii) electrification, and (iii) enhancing carbon uptake and storage in the urban environment” (IPCC, 2022b, p. 33).

Following these mitigation efforts, various countries and cities across the world have pledged to achieve net zero targets. The building sector is responsible for 30% of total final energy use globally while 28% of global energy-related carbon emissions are attributed to buildings (UN-Environment, 2017). In the EU, the buildings are responsible for approximately 40% of total energy consumption and 36% of the energy-related greenhouse gas emissions (European-Comission, 2021). In the UK, buildings are the second largest source of emissions (HM-Government, 2020). Therefore, in addition to city-wide and neighbourhood-scale design solutions, building-level interventions are needed, if these targets regarding the extensive amount of energy used in the buildings are to be achieved.

Retrofit matters: Retrofitting housing stock for carbon reduction

Retrofitting existing buildings emerges as a key way of reducing carbon emissions in buildings. Even partial improvements can reduce energy consumption in buildings. The Department for Business, Energy & Industrial Strategy (BEIS) analysis reports 18% median energy savings in homes in England and Wales as a result of improving buildings with solid wall insulation (BEIS, 2021). According to IPCC (2022b), it is possible to reach net zero by 2050, if existing buildings are retrofitted and new builds follow net zero policies (IPCC, 2022b); however, “the low renovation rates and low ambition of retrofitted buildings have hindered the decrease of emissions” (IPCC, 2022b, p.35).

Dwelling on this urgent need for retrofitting for carbon reduction in buildings, CaCHE is conducting two major studies: [Retrofit of Pre-1919 Glasgow Tenement Housing Demonstration Project](#) and [Flexible Air Source Heat Pump for Domestic Heating Decarbonisation](#) (an EPSRC project concerned with engineering innovation but also investigating air source heat pumps market potential in the UK). This mapping study aims to set the scene for contemporary residential retrofitting literature as part of this wider research agenda.

Reviewing residential retrofitting literature

This study mapped contemporary residential retrofitting literature published in the last two decades in English. It reviewed 299 papers (abstracts only) published in 87 journals and six edited (and indexed) books. The study inductively found out that contemporary residential retrofitting literature highlights key themes as individuals’ role in residential retrofitting; retrofit policy and planning; projections, simulations and models; life cycle assessment of the buildings; thermal comfort studies; and studies about heating-cooling-ventilation aspects as well as including residential retrofit studies engaging with multiple themes.

The following sections present the methodology applied in this study in detail, set the scene for the academic literature for residential retrofitting regarding leading journals in this area of study, the temporal and geographical

distribution of the studies, and key themes in the residential retrofitting literature. The report concludes with a summary of mapping analysis for residential retrofitting literature and proposes areas for research to contribute to this literature in future.

Methodology

This research employs a literature mapping exercise (Soaita et al., 2020), an exploratory method developed by researchers at the UK Collaborative Centre for Housing Evidence (CaCHE) (see Serin, 2018a, 2018b; Soaita, 2018a, 2018b). The aim of this mapping exercise is to explore the scope of international residential retrofitting literature that has developed in the last two decades. The findings of the mapping revealed recent trends in residential retrofitting literature while signalling likely gaps in the literature and future areas of research. Although the review covers key studies in this area, this is not an exhaustive list of studies. Rather, this mapping exercise shows emerging themes in residential retrofitting and presents the scope of this field of research which has been expanded over the last decade substantially.

Thematic focus and scope: Key inclusion-exclusion criteria were developed before starting the review. These were decided based on the thematic focus of the exercise (residential retrofitting), timeframe (last 20 years), and geographical focus (international-no country-specific focus). The review specifically excludes studies focusing exclusively on technical issues about retrofitting such as technological advances, building materials and architectural design aspects. These all shape the keywords and queries run on the indices (see Appendices for the list of keywords/queries as part of the inclusion-exclusion criteria table).

Search media and publication category: The main search media to be used to map the literature were selected as Scopus and Web of Science due to the extensive coverage of these indices (Serin, 2018a). The review focused on scholarly publications (academic journal articles, reviews and indexed book chapters) and excluded grey literature (e.g. policy documents, reports, briefs). This is mainly mandated by the nature of a mapping exercise which is based on reviewing the abstracts of the documents rapidly to set the scene for published research (Soaita et al., 2020). Moreover, grey literature documents are usually published in the native language of the country of publication. While this is an international mapping exercise, only publications published in English are covered. Therefore, only grey literature pieces published in English could have been included in the review, which would have resulted in strengthening language bias. Thereby it would hamper to map the literature's geographical distribution correctly, therefore, it was avoided.

The review steps below were followed for this mapping study:

Step 1: The queries as combinations of selected keywords were run on the selected indices (on the title, abstract, stated keywords of journal articles, reviews and indexed book chapters). This step resulted in 587 returns (of journal articles, reviews and indexed book chapters). These returns formed the main database. For the sake of consistency, these journal articles, reviews and indexed book chapters will be referred to as 'papers' thereafter.

Step 2: The abstracts of all 587 papers were reviewed according to the inclusion-exclusion criteria. Irrelevant papers (n=288) were identified and then excluded. A core database with the remaining papers was created (n=299). The purpose of this round of inclusion-exclusion was to identify studies that were likely to engage with residential retrofitting and filter out studies which are out of scope (e.g. studies about materials, technical studies about new technologies, studies about engineering).

Step 3: The abstracts of the papers in the core database (n=299) were read through, and their content was analysed to identify themes and geographical engagement. This is the final number of papers contributing to the mapping review. The themes were explored inductively, and seven key themes were identified. The papers in the core database were categorised according to these key themes.

Step 4: The distribution of the papers in the core database was analysed regarding their publication year, clustering according to the themes, and publication outlets (journals and indexed edited books).

Step 5: The analysis results were synthesized to produce the mapping of residential retrofit literature.

Mapping the Residential Retrofitting Literature

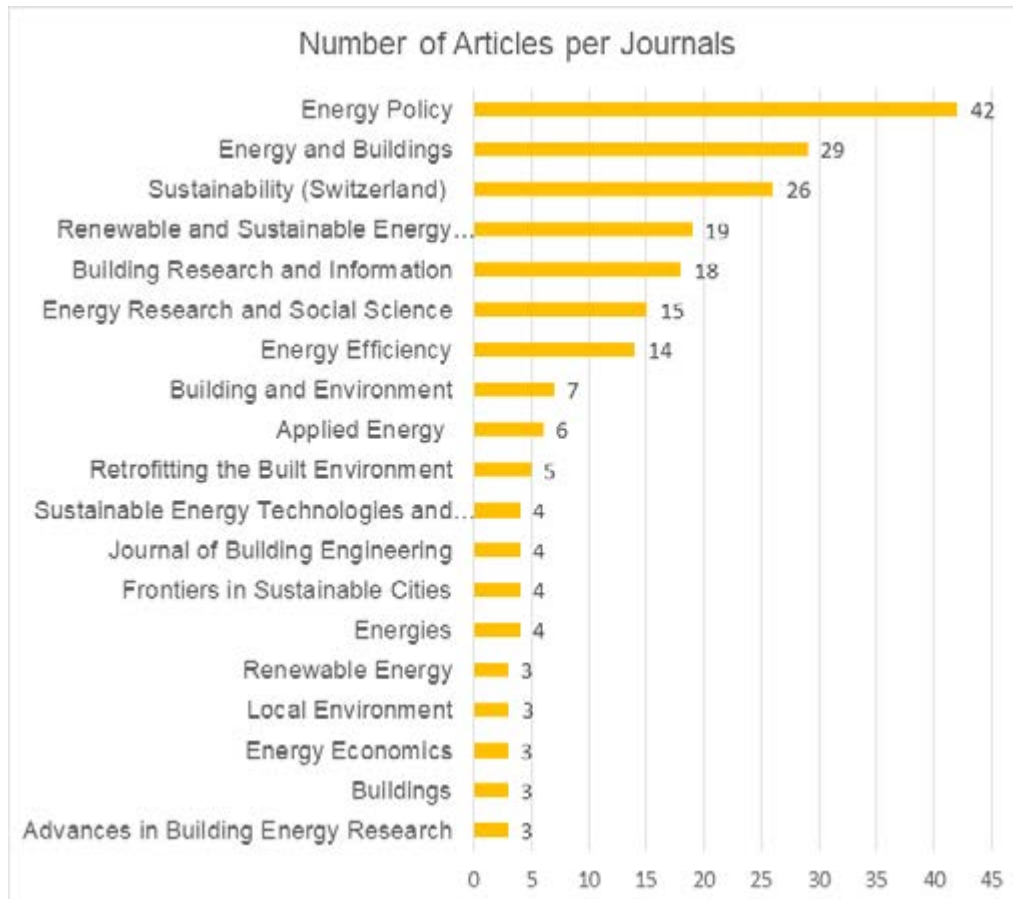
This section sets out the 'scene' for the residential retrofit literature. It presents the results of the literature mapping exercise for leading publication outlets, temporal distribution and trends, and geographical distribution.

Leading Journals for Residential Retrofitting

The mapping exercise shows that the distribution of papers among journals is uneven. Figure 1 shows the journals which published three or more articles in the core database of this review. Three-quarters of all papers (n=229) are published in 19 journals (Figure 1). The main journals are: Energy Policy (n=42), Energy and Buildings (n=29), Sustainability (Switzerland) (n=26), Renewable and Sustainable Energy Reviews (n=19), Building Research and Information (n=18), Energy Research and Social Science (n=15), and Energy Efficiency (n=14). These seven main journals published more than half of the articles in the core database. The remaining articles are published by other journals as per one or two articles per journal.

The results clearly show that a few journals lead the literature on residential retrofit. A closer look at the last five years also proves the dominance of these leading journals in the literature further (shown in Figure 1). On the other hand, there is an increasing diversity in the outlets publishing on the topics of residential retrofit (e.g. European Journal of Interdisciplinary Studies; Housing, Theory and Society; Geoforum; Policy Studies Journal; Urban Studies). This may be a result of increased interest in retrofitting buildings following its key role in responding to climate emergency. Thus, residential retrofitting has been attracting the attention of researchers from various disciplines in addition to the ones that are 'traditionally' interested in energy, carbon emissions and new energy-saving technologies. The disciplines that show relatively new interest in this topic can be named Urban Studies, Geography, Political Science and Housing, according to the distribution of journals.

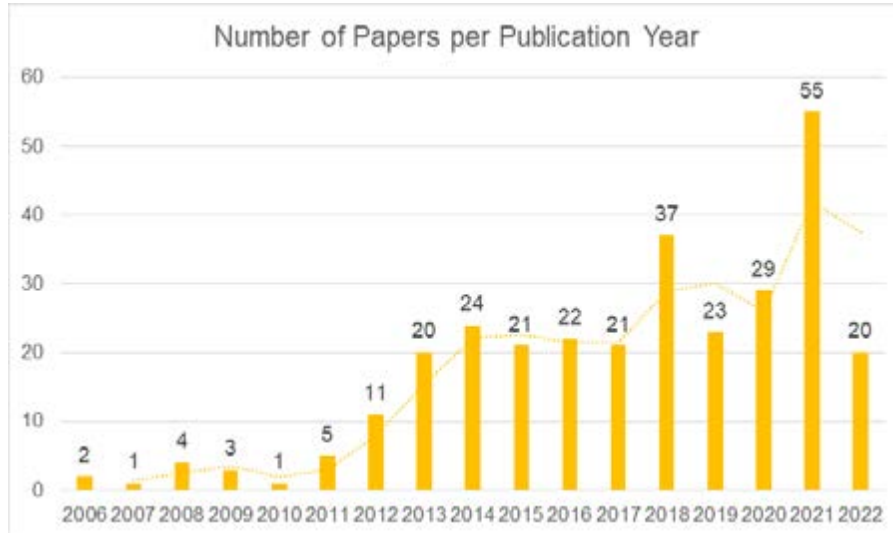
Figure 1: Number of articles per journals



Temporal Distribution and Trends

The mapping study covers the last two decades (2002-2022 inclusive). Figure 2 shows the distribution of the studies over these twenty years. The findings show a clear increase in the volume of publications over the years, especially after 2010. More than 50% of the studies were published in the last five years, while 90% of all papers in the database were published in the last decade (Figure 2).

Figure 2: Number of papers per publication year



This increase in the volume of publications about residential retrofit is consistent with the years of declarations of climate emergency by countries across the globe, increasing attention to issues about climate change and warnings about the role of the built environment in carbon emissions by institutions (IPCC, 2022a). Previous mapping studies (see Serin, 2018a, 2018b; Soaita, 2018a, 2018b) also show an increasing volume of publications on any topic in the academic literature in the last decade. Although this overall increase in the volume of academic publications should also be taken into account while interpreting the rise in the number of publications about residential retrofitting, it still signals an increase in the interest in the residential retrofitting by the academic community. The jump in the number of publications between the years 2010 and 2013, and the consistent trend afterwards clearly show the expansion of this area of research.

Geographical Distribution

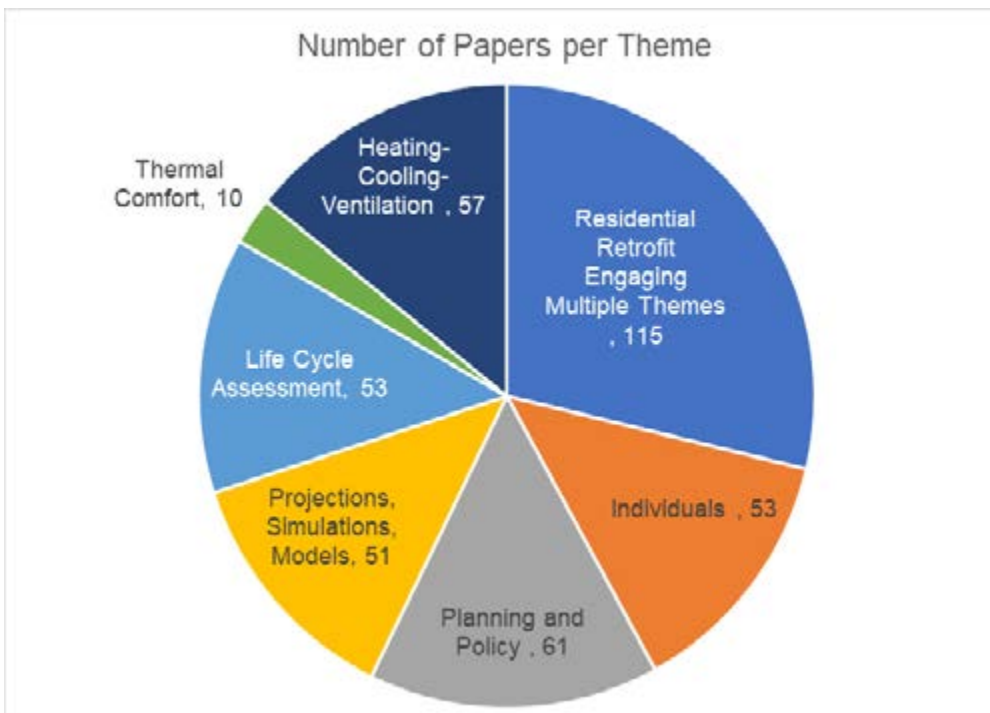
The mapping review shows that the literature about residential retrofit is geographically diverse. It includes studies from various countries, to name a few: China, Brazil, Germany, France, Spain, Italy, Portugal, Slovenia, Sweden, Cyprus, Poland, Canada, UK, US, Australia, and New Zealand, Uruguay. The distribution of studies among countries, on the other hand, is observed to be uneven. One-third of all papers included in the database mention the UK in their abstracts. Most of these papers study the UK residential retrofit practice as a single case study or a comparative one. This finding should be read together with the language bias of this review. However, it should also be acknowledged that the UK has the oldest housing stock in Europe (BRE, 2015) and poorly insulated housing stock. Therefore, the country faces a greater challenge and needs extensive retrofitting programmes. To illustrate, the percentage of buildings with disrepair to critical elements in Scotland is at 52% in 2019 while almost one-fifth of all dwellings require urgent disrepair to critical elements (Scottish-Government, 2019).

The clusters of papers about other countries are not as dominating as in the UK case. There are more than ten studies each in the database for Germany, Canada, the US, Spain, Italy, and Australia. This shows an obvious weight in the literature on the Global North while showing diversity in climatic conditions in these countries. It should be noted that this analysis is based on the abstracts which mention the country of the selected case study. Not all abstracts contain this data. This is a shortcoming of the mapping methodology that needs to be taken into account while evaluating the results about the geographical distribution of the studies.

Key Themes in the Residential Retrofitting Literature

The mapping analysis revealed seven emerging research areas within the academic residential retrofitting literature: studies about (1) residential retrofit engaging multiple themes (not focused on one specific aspect), (2) the role of individuals in residential retrofitting (residents, users, homeowners, renters), (3) planning and residential retrofitting policy, (4) projections, simulations and models, (5) the 'life cycle analysis', (6) thermal comfort issues in relation to residential retrofitting, and (7) heating-cooling-ventilation systems in residential retrofits.

Figure 3: Number of papers per theme



The mapping analysis resulted in some expected and unexpected findings regarding the themes within the residential retrofit literature. The analysis presented a balanced distribution among emerging themes across the studies in the review database. The studies engaging with multiple aspects take the lead, and thermal comfort studies form the smallest category of the studies. Considering the multifaceted nature of home upgrades, a relatively larger cluster engaging with multiple aspects of residential retrofitting would have been expected.

The remaining five groups are almost evenly distributed among the themes of the role of individuals in residential retrofitting; planning and residential retrofitting policy; the projections, simulations and models; life cycle assessment

and heating-cooling-ventilation systems. These groups each comprise one-sixth or one-fifth of all the studies covered in the mapping review. The studies about the role of individual actors such as residents, users, homeowners and renters and the studies about planning and policy for residential retrofitting are not unexpected groups regarding the stakeholders that take the role in the retrofitting processes as well as groups that are affected by these improvements. The limited engagement with thermal comfort, which is a key social and individual aspect of residential retrofitting, on the other hand, demonstrates a gap in the literature. This should not be read as a deficit in the literature, but as a sign of relatively low engagement on this topic. Therefore, it emerges as an area of exploration for future research.

The following sections map out the emerging themes in the literature. It should be noted that, as this is a mapping study, the analysis of these studies falling into these categories would not be exhaustive of the literature about these themes. Rather, this is a representation of the thematic engagement of the residential retrofit literature overall.

Residential Retrofit Studies Engaging Multiple Themes

The mapping analysis revealed that although there have been studies specialising in one aspect of residential retrofitting, more than one-third of the studies, which are mapped in this report, explore the residential retrofit engaging multiple themes. This may be a reflection of the complexity of the issue of retrofitting homes where everyday life takes place. It is also a reflection of the fact that retrofitting is a multifaceted process that includes many actors in place.

Almost 10% of the studies in this category are reviews (of literature or policy) about residential retrofitting (e.g. the studies by Hurst and O'Donovan (2019), Iralde et al. (2021), Alabid et al. (2022)). The reviews provide a good array of analyses on the case studies and policy implications on residential retrofitting across countries. These reviews should be utilised by any studies focusing on residential retrofitting while setting the scene.

The literature in this category is multiscale, although residential retrofitting as a topic and policy area bears a risk of being perceived as a building scale intervention. To illustrate with a few cases from the mapped literature, Häkkinen et al. (2019) discuss the drivers and benefits of district-scale energy refurbishment; Barbosa et al. (2022) focus on the environmental performance of cost-effective energy renovation at the neighbourhood scale in Portugal; and Williams et al. (2013) explore residential retrofitting in the suburban areas in England to respond to the climate emergency, while the studies by Feitosa and Wilkinson (2018) and Wilkinson and Feitosa (2015) focuses on green roof adaptations for retrofitting. These show quite a vast array of scales of interventions for residential retrofitting policy and practice.

The literature in this category also presents a diverse geographical distribution, albeit that most of the studies cluster in the Global North countries. It should be noted that this geographical distribution analysis is based on the abstracts of the studies only. It is not always possible to identify the case study countries via the abstract. This hinders the capacity of the mapping study to truly reveal the geographical distribution of the papers included in this review, although it still gives a fair idea about it. Therefore, while interpreting the geographical distribution of the studies for this category and the rest of the categories thereafter, this caution should be taken into account.

Individuals' Role in Residential Retrofitting

The mapping analysis showed that nearly one-fifth of the studies focus on the individuals' role in residential retrofitting whether as residents, occupants, end users, homeowners or renters. By definition, the relationships of these different groups of individuals with residential retrofit are fundamentally different. While the homeowners have control over the decision-making processes for retrofitting their homes, the renters and/or occupiers have no or little control over these decisions. This was reflected in the mapped studies' thematic engagement.

The subgroups of studies focusing on homeowners investigate homeowners' perception of carbon reduction and

retrofit (e.g. the studies by Barry (2015), Galvin (2014)), homeowners' retrofit experience (e.g. the studies by Bobrova et al. (2021), de Wilde and Spaargaren (2019)), the ways of how homeowners are informed about retrofit technologies (e.g. the studies by Bobrova et al. (2021), de Wilde and Spaargaren (2019)), the role of standards and intermediaries shaping homeowners' decision-making process (e.g. the studies by de Wilde and Spaargaren (2019), de Wilde and Spaargaren (2019)), the dynamics behind homeowners decision-making processes to retrofit their homes (e.g. the studies by de Wilde and Spaargaren (2019), Abreu et al. (2019)).

While the studies focusing on homeowners predominantly discuss factors behind decision-making processes for retrofitting, when it comes to residents, users or occupiers, the studies discuss the behavioural aspects in relation to and attitudes towards retrofits. This is a key area of study that expands residential retrofitting literature to social aspects further such as everyday life in retrofitted buildings, as well as behaviours, values and perspectives. Wise et al. (2021), for example, discuss the importance of residents' views, values and behaviours for retrofitting historic buildings while Bal et al. (2021) explore social housing residents' attitudes and behaviours toward sustainability and residential retrofit.

The studies about social housing residents predominantly focus on behavioural aspects and perceptions of the residents. This may be related to the social housing residents' limited role in the decision-making processes of their home retrofitting processes. Therefore, the studies ought to be limited to the topics of their everyday experience.

The analysis also revealed that there are a very limited number of studies that particularly focus on retrofitting privately rented homes, tenant-landlord relations regarding home improvement for carbon reduction and the ways of sharing the cost of retrofitting privately rented homes. This presents a gap in the literature while also signalling a possible gap in the residential retrofit practice of retrofitting privately rented homes internationally.

Studies about Retrofit Policy and Planning

The mapping analysis revealed that one-fifth of the studies covered in the review address issues related to retrofit policies and planning such as policies to facilitate and encourage residential retrofits, measures taken for carbon reduction and adapting homes for climate change, and strategies (e.g. reward-penalty schemes) for reducing energy consumption in homes (e.g. the studies by Laes et al. (2018), Amoruso et al. (2018), Galvin and Sunikka-Blank (2017), De Laurentis et al. (2017), Liu et al. (2020)). Considering the role of policy-making and planning in shaping the built environment, including housing, this category is an expected theme to find in the contemporary residential retrofit literature.

Many studies in this category discuss the residential retrofit policies as part of a larger policy landscape of energy efficiency in buildings, carbon reduction and climate adaptation in the built environment. Therefore, their direct engagement with residential retrofitting varies – from major engagements to minor ones - depending on the context and adopted policies in the case study countries.

The studies which aim to analyse the effectiveness of existing policies for residential retrofit or energy efficiency in buildings form a large number within this category and show potential impact on developing an improved policy landscape. Laes et al. (2018) study, for example, reviews the effectiveness of policies or policy packages in the EU for their role in the uptake of carbon mitigation measures or energy reduction in the existing residential buildings.

Besides the obvious weight of analysing the effectiveness of policy interventions, the literature goes beyond these assessments. Kerr et al. (2017), for example, analyse the 'rationale' for energy-efficient retrofit policy in four countries - the UK, Germany, New Zealand and Ireland – comparatively. Eckersley (2017), on the other hand, focuses on the role of the path-dependent characteristics of local governments in England and Germany, which they claim to have a significant impact on their carbon reduction and retrofitting policy-making in the present day. Such studies expand the understanding of policy-making and draw attention to other aspects of decision-making in addition to evidence.

These additional aspects should not be ignored for understanding the residential retrofit landscape fully.

While many studies in this category focus on one region or country, the category also includes studies on comparative analysis of policies across countries. Following this trait, Amoruso et al. (2018) look at efficiency policies, measure and tools in Germany and Norway comparatively. Similar to single case study studies, some papers in this category focus on one particular policy intervention or a particular policy package such as policies related to investment for residential retrofit (Kerr and Winskel, 2020), use of the pilot projects as a policy tool for climate adaptation in urban space and residential retrofit (Hughes et al., 2020), mitigating financial risks for retrofit investments (Ahlrichs et al., 2020).

The largest geographical cluster in this category is the studies about the UK. This is followed by Germany. The cluster of these two countries – either as single case studies or comparative studies that also include either the UK or Germany - comprise around one-third of the studies in this category. This clearly signals a weight in the literature on the policy practice in these two countries.

Studies about Projections, Simulations and Models

The mapping analysis shows that the studies about projections, simulations and models about residential retrofitting comprise a substantial ratio - one-sixth of the studies mapped in this review. This category presents the studies which are based on estimates and calculations. The studies conduct various projection methods. Most of the studies in this category are concerned with energy usage projections, estimating the impact of retrofitting on carbon reduction, and the impact of residential carbon reduction strategies. However, the literature is not exclusively about energy use and/or carbon reduction strategies and methods. A few studies are concerned with the social and personal impact of these strategies. For example, Taylor et al. (2021) investigate the connection between future heat and cold temperatures to mortality rates and model energy consumption across various scenarios such as demolition, construction and alternative energy efficiency retrofits. Monzón-Chavarrías et al. (2021), on the other hand, look at the relationship between changing everyday life habits and residential retrofits.

The methods used to estimate the impacts of residential retrofitting and carbon reduction technologies in residential buildings are found out extensively diverse. Many studies develop novel approaches to make estimations for the impact of residential retrofits or carbon reduction in buildings. Some studies utilise automated tools and machine learning (e.g. the studies by Foda et al. (2020) Fathi et al. (2020)), which may be expected to be used more widely in future. A few studies in this category are observed using 'life-cycle assessment' for their modelling (e.g. the studies by Vavanou et al. (2021), Monzón-Chavarrías et al. (2021), Mastrucci et al. (2020)). In fact, the mapping study revealed that 'life-cycle assessment' is widely used in the studies of residential retrofitting, and this will be discussed in the next sections (Studies about Life Cycle Assessment) further.

The studies in this category also show a diverse geographical coverage with a Global North weight. A few studies focus on the UK practice and UK regions, while the cases from mainland Europe are also highlighted in this category, followed by the studies about China practice.

Studies about Life Cycle Assessment of the Buildings

The mapping analysis found that one-sixth of the studies mapped for this review is concerned with a kind of Life Cycle Assessment of the buildings (e.g. Vavanou et al. (2021)), parts of the buildings (e.g. Zhang et al. (2021)) or a particular type of the building (e.g. Rivera et al. (2021)). Life Cycle Assessment is an established method in the literature. It is a "tool used for the quantitative assessment of a material used, energy flows and environmental impacts of products" (Sharma et al, 2011, p. 872). It assesses "various aspects associated with the development of a product and its potential impact throughout a product's life (i.e. cradle to grave) from raw material acquisition, processing, manufacturing, use

and finally its disposal" (Sharma et al, 2011, p. 872).

A few studies in this category look specifically at the performance of retrofit interventions and aim to assess the performance of these retrofit interventions (e.g. the studies by Barbosa et al. (2022), Balasbaneh et al. (2022), Zhang et al. (2021)) through the life cycle of the buildings.

The studies in this category are multiscale regarding the scale of intervention whether it is building scale, focusing on particular parts (e.g. walls) or materials (e.g. cladding) of the buildings or beyond building scale. The studies concerning building scale aim to assess the overall impact of retrofit (e.g. the studies by Sartori and Calmon (2019) and Bingham et al. (2019)). Many studies, however, focus on assessing an intervention that concerns one particular part of the building or building material that is used for retrofitting homes to reduce energy consumption. The intervention scale is not limited to buildings and their parts. It may even be a neighbourhood-level intervention, as in the study by Lausset et al. (2020) that looks at "scenarios with different levels of decarbonization of the electricity mix over a period of 60 years" (p.500) in a particular neighbourhood.

The category also shows a diverse geographical coverage. Again, with a weight on Global North countries, the literature presents cases from around the world. Many studies are based on the cases from Europe while a few studies focus on the China and Malaysia practice. The cases from North and South America (Canada and Brazil) are also identified in this category. This diversity is critical regarding the different climatic conditions of these countries.

Thermal Comfort Studies

The category for the studies about thermal comfort comprises the smallest group of publications within the mapped literature (n=10). This limited engagement was not an expected result of the mapping study considering the extensive thermal comfort literature. This may be due to the limitations of the mapping study methodology (e.g. reviewing only the abstracts, not full texts of the papers), and the ways of indexing and abstract writing in this area of study.

The studies in this category touch on various topics in relation to thermal comfort such as social housing residents' thermal comfort, historic buildings and their residents' experience, testing thermal comfort guidelines, older people's experience in retrofitted homes, and so on. It represents a fair distribution among relatively warmer countries (e.g. the studies about Spain and Portugal by Caro and Jose Sendra (2021) and Brandao and Lanzinha (2021)) and colder climate countries (e.g. the study about Scotland by Ellsworth-Krebs et al. (2021)).

However, the analysis results for this category do not present any meaningful generalisations or subgroups of themes due to the limited number of papers. These findings, therefore, should be evaluated together with overall thermal comfort literature in order to make a full evaluation of the studies exploring thermal comfort in retrofitted homes. This evaluation, however, is beyond the remit of this mapping analysis.

Studies about Heating-Cooling-Ventilation Aspects

The mapping analysis revealed that almost one-fifth of the reviewed studies are about heating, cooling and ventilation systems. Known as HVAC systems, they are an important part of retrofit applications. Heating-cooling and ventilation are designed as connected systems since ventilation is the key area where heat loss occurs (e.g. natural ventilation vs mechanical ventilation in retrofitted homes). Thus, the studies usually refer to heating-cooling and ventilation aspects together. Due to this overlap, the mapping analysis explored these under one category, rather than having multiple categories for parts of the same system.

Some studies in this category refer to the heating, cooling and ventilation systems without specifying the retrofit implications in their abstracts. Therefore, their direct engagement with residential retrofitting varies – from major

engagements to minor ones - depending on the context and adopted policies in the case study countries. However, due to the keywords used to collate these in the main database, the studies are expected to provide this engagement to a degree, therefore, not excluded from the review.

Many studies in this category aim to analyse the efficiency of new low carbon heating, cooling and ventilation systems adopted in homes such as heat pumps (e.g. the studies by Abid et al. (2021a), Abid et al. (2021b), Pallonetto et al. (2022), Michopoulos et al. (2016)). These studies present a diverse picture regarding the selection of new technologies and geography of focus (e.g. studies focusing on the cases from the UK, US, Mediterranean region (as a regional case study), Germany or Uruguay).

Most of these studies focus on one particular technology or system. More than half of the studies in this category are about heat pumps (e.g. the studies by Kelly and Cockroft (2011), Carroll et al. (2020), Walker et al. (2022), Judson et al. (2015)). The studies are diverse regarding the type of heat pumps. Heat pumps emerge as alternative tools to hydrocarbon fuel systems (e.g. gas boilers) which are currently extensively used to heat homes across countries. The interest in alternative technologies to hydrocarbon fuel systems further has increased with climate emergency declarations by the cities and ongoing policy interventions for carbon reduction in buildings. Therefore, the cluster of studies about heat pumps in this category reflects this known interest.

The studies that focus on ventilation form a smaller subgroup under this category. Only one-fifth of the studies under this category discuss ventilation (e.g. the studies by Giama (2022), Pereira-Ruchansky and Pérez-Fargallo (2020)). Regarding the importance of efficient ventilation for a successful residential retrofit and the health of the occupants of retrofitted buildings, this limited engagement in the mapped literature should be addressed as a warning.

The literature goes beyond technical or policy discussions about heating, cooling and ventilation systems for carbon reduction in buildings. A few studies explore the role of the user or consumer (Parrish et al., 2021), the demand side (Vijay and Hawkes, 2019) or the role of homeowners' preferences in (Michelsen and Madlener, 2012) adopting new low-carbon heating, cooling and ventilation systems.

The studies in this category also show a diverse geographical coverage including the studies from different climatic conditions (e.g. Ghana, Sweden, Finland, Denmark, US, UK). It is the most diverse category compared with the others. This may be a result of the fact that different climatic conditions require varied heating, cooling and ventilation systems. Therefore, the literature has to respond to these local conditions and requirements.

Conclusion

Climate emergency requires urgent response and reduction of carbon emissions. The cities and human settlements are key to delivering urgent climate action (IPCC, 2022a), and can offer solutions (IPCC, 2022a) by fundamentally changing how we produce cities and urban areas. Among various ambitious mitigation interventions for climate emergency, retrofitting existing buildings became a key response to the number of carbon emissions originating from buildings.

Dwelling on this, this mapping study explored the scope of the residential retrofitting literature internationally. It focuses on the academic literature published in the last two decades. The mapping study identified key themes as residential retrofit studies engaging multiple themes; individuals' role in residential retrofitting; retrofit policy and planning; projections, simulations and models; life cycle assessment of the buildings; thermal comfort studies; and studies about heating-cooling-ventilation aspects.

The mapping analysis of the literature presents thematic and geographic diversity, although the Global North countries are represented unevenly in the literature. This may be a result of the language limitation of this mapping study (i.e. it only covers papers published in English). However, this doesn't change this uneven representation of the Global South in the literature published in English on this topic.

The literature is rich with increasing diversity in disciplines showing interests in residential retrofitting as well as the approaches to residential retrofitting analysis. Some topics are highlighted more than others in the literature. Studies looking at multiple aspects of residential retrofitting comprise a substantial number of papers. This may be a reflection of the complex nature of retrofitting practice since it requires multiple level interventions and various stakeholders to involve in the process. Moreover, the studies aiming to measure the effectiveness or efficiency of retrofitting practices and policies are highlighted in the literature. Among new technologies, heat pumps are observed to be a wider area of interest in the literature.

Lastly, a few areas are underrepresented compared with others. Highlighted two underrepresented topics are thermal comfort and ventilation systems. Both topics are critical for successful retrofitting practice, and therefore require attention for future research.

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Appendices

Appendix A: Mapping review guidance

Defining the review	
<p>Review's aim/purpose:</p> <p>To review international literature about residential retrofit.</p> <p>Specific objectives</p> <ul style="list-style-type: none"> - To identify the scope of the literature developed in the last two decades on the residential retrofit, - To reveal emerging themes in the residential retrofit literature, - To identify likely research gaps in the residential retrofit literature. 	
<p>Search terms / Keywords and Queries:</p> <p>First level</p> <p>"low carbon" OR "zero carbon" OR "net zero" OR "climate change" OR "climate emergency" OR "climate responsive" OR "carbon reduction" OR "carbon emission" OR "carbon footprint" OR decarbonisation OR decarbonization</p> <p>AND</p> <p>residential OR housing OR house OR home</p> <p>Second level</p> <p>retrofit OR refurbish OR upgrade</p>	
Search strategy	Criteria / approach
<p>Search Medium: Where to look?</p> <p>Broad index search using Scopus and Web of Science.</p>	<p>Broad</p>

<p>Type of the Sources: What to review?</p> <p>Peer reviewed journal articles and indexed book chapters (using above key word searches)</p> <p>Excluded type of the sources - What NOT to review</p> <ul style="list-style-type: none"> • PhD thesis and dissertations • Books • Conference papers • Non-peer reviewed academic papers • Working papers – (unless peer reviewed) • Government reports 	<p>Inclusive</p>
<p>Creating a mapping database</p>	
<p>In this phase, the sources coming through the search queries put together and a main database is created before the review is started.</p> <p>Tool/Software: Endnote</p> <p>The two-phase-method:</p> <p>Phase 1 - Downloading and recording the sources with their abstracts and keywords, merging the query results into a main database compiled by using Endnote, and eliminating overlapping results</p> <p>Phase 2 – Reviewing the titles (firstly) and abstracts (secondly) of the sources in the database in order to exclude unrelated sources according to the first-round inclusion exclusion criteria (below).</p>	<p>Focused, but comprehensive</p>
<p>Mapping analysis</p>	
<p>In this phase, the abstracts of the sources in the database are reviewed in order to identify the themes and thematic categories.</p> <p>Tool/Software: Endnote</p>	<p>Systematic and informed</p>
<p>Synthesizing the evidence</p>	
<p>Synthesizing the mapping and reporting</p> <ul style="list-style-type: none"> • Review, compare and contrast data • Examine data on relevant outcomes as well as supporting and contradictory • Identify gaps, disputes, discussion points, major criticism areas and consensus (if any) <p>Written output</p> <ul style="list-style-type: none"> • Mapping report 	<p>Systematic and informed</p>

Appendix B: Inclusion-Exclusion Criteria

Inclusion-Exclusion Criteria
To be applied on the initial database which is compiled by title/ abstract/keyword queries on the search mediums
Publication date range: 2002 (inclusive) – 2022 (inclusive)
Language: English
Country / geographical focus: No geographical criteria to be adopted/ international
Thematic fit/relevance : Sources directly engaging with the residential retrofit
Participants characteristics: Not Applicable (no exclusion based on participant characteristics)
Methods: Not Applicable (no exclusion based on participant characteristics)
Quality Appraisal: Not Applicable (no exclusion based on participant characteristics)