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A review on the energy retrofit policies and improvements of the UK existing buildings, challenges and benefits

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ABSTRACT

There are inherited challenges and barriers the UK government faces in meeting the 80% carbon reduction target by 2050 compared to 1990 baseline. Technically research shows great opportunity to achieve this target through strategic mass-scale plan to include new and retrofit building schemes. This study aims at reviewing the current retrofit schemes and policies UK adopted since committed to reduce carbon emissions, with an emphasis on existing challenges and potential benefits brought to the construction industry. This will help identifying the gap performance between legislations, standards, and actual/anticipated deliverables. The review adopted secondary research method to allocate scientific research data published in journals and reports on building retrofits. Literature indicated insufficient guidance and information on existing UK housing stock to enable the decision-makers to implement realistic and achievable plans for reducing carbon emissions. The study signifies the understanding and dealing with individual cases as generic retrofitting packages will likely fail to address the complexity of the UK context. Great attention should be paid to some other factors such as social sustainability with great emphasis on using low embodied carbon and energy products. The review will be useful for home-owners and other stakeholders involved in decision-making or people interested in building retrofits.

1. Introduction

There are entailed challenges and barriers to improve the thermal and energy performance of the UK existing housing stock to meet the new ambitious target to reduce the country's emissions by at least 68% by 2030 [1]. Wheeler et al. [2],stated that carbon emission reduction of existing homes appears to be the biggest challenge for the UK government in meeting the net zero target. Up to 90% of people's time is spent indoors in the developed world and 69% of this time is being at homes [3,4]. As a result, buildings are responsible for over 40% of energy use in Europe [5] and in the UK even more, so improving its energy efficiency became essential to truly address the carbon reduction target to make the dream happen.

These figures indicate that homes are big contributor to carbon emissions and count for over 30% towards this. There is an agreement in literature on the potential contribution to reducing the national carbon emissions by supporting building retrofit schemes and incentives, through improving the thermal and energy performance of buildings [6]. This means the country should set a realistic target and strategic incentive schemes to carry out a holistic fabric and energy retrofitting to achieve the national CO_2 reduction plan.

However, building retrofits can be also challenging for the UK construction industry, considering the scale and complexity of housing and process. On the other hand, it is an important step to achieve the intended carbon reduction and should be done in a sustainable construction and maintenance manner. Jagarajan et al. [7], believed that current research lacks systematic review of knowledge on sustainable retrofitting. The 'Committee 2020 renewable heat and transport targets' [8] stated that our priority is to urgently invest an innovative retrofit program for over 20 million dwellings in the UK to meet the reduction target of carbon emissions of existing fossil fuel heating system. Pardo-Bosch et al. [9], addressed energy poverty as a big problem in our society and essential to tackle through strategic building retrofit plans targeting low-income households. Regrettably, millions of buildings in the UK are not cost-effective to treat their solid walls or improve glazing as majority of its residents are in low-income category or buildings are in poor conditions.

Roberts [10] studied the most common building elements that makes millions of UK existing housing perform poorly including single glazed windows, solid walls and less insulation in roofs and floors particularly in social housing. The fabric incentive schemes are yet to target the full

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List of abbreviations

PAS2035	Publicly Available Specification
NZEB	Nearly Zero Energy Buildings
WGBG	Welsh Government Building Regulation
EnerPHit	Passivhaus Standard for retrofitting
AECB	Association for Environment Conscious Building
BS	British Standards
EN	European Norm
CIS	construction information services
CSIC	Construction Scotland Innovation Centre
CIAT	Chartered Institute of Architectural technologist
SMEs	Small and medium enterprises
EPC	Energy performance certificate
VCL	Vapor control layer
PSCF	Passivhaus Sustainable Construction Future
BER	Building Emission Rate
DER	Dwelling Emission Rate
EES	Energy Efficiency Scotland
BRE	British Research Establishment
CEO	Company energy Obligation
UKAS	United Kingdom Accreditation Services
EPS	Expanded polystyrene
XPS	extruded polystyrene
BBA	British Board of Agreement
HIS	Health Information service
MVHR	Mechanical Ventilation and Heat Recovery System
RdSAP	Reduced Data Standard Assessment Procedure
BSI	British Standard Institute
BRE	British Research Establishment
EHC	Each Home Counts
VOCs	Volatile organic compounds
LZC	Low or zero carbon
LCA	Life Cycle Analysis
DEA	Domestic Energy Assessor
SAP	the Standard Assessment Procedure
PHPP	Passive House Planning Package
ASHREA	the American Society of Heating, Refrigerating and Air-Conditioning Engineers
BREEAM	Building Research Establishment's Environmental Assessment Method
LEED	Leadership in Energy and Environmental Design
PH	Standard Passivhaus standard
CIC	Community Interest Company

range of private and social housing [11]. The study claimed that retrofit measures might not be as effective as anticipated due to many reasons including poor quality of building components installation, lack of monitoring and may be increased use of heating after being refurbished. Despite that, building retrofit has been claimed to be a key strategy towards achieving the energy efficient policy with considerable energy-saving potentials especially in residential sector [12].

In developed countries like US 60% of existing construction industry projects focus on building retrofits [13], and EU around 70% of construction schemes targeting building retrofits [14] in the attempt to achieve the global carbon reduction aim by 2050. In the UK nearly all residential buildings require an improvement either in building envelope or energy systems to achieve the NZEB national target [15]. Hence, it becomes obvious for the UK government to invest on retrofit schemes and identify the most effective methods to implement the appropriate improvements for achieving the intended outcomes. Building regulation in any country has been regularly amended depending on each country vision, potential, and capability to implement such changes as well as how complex the architectural detailing and conditions of its building stock. WGBG [16], p.4 stated that "building regulations greatly influence how our buildings are constructed and used". In the UK building regulation Part L last amended 2016 but has not made any changes to retrofit of buildings, even though current performance requirements are relatively low and ineffective to meet the national carbon reduction target [17]. It is believed that UK current building regulation technically challenging and not on track to tackle the 80% emission ambitious reduction by 2050 [18].

PAS2035 published by the British Standard Institute BSI becomes the UK domestic retrofit standard for the future [19]. This standard is a Trust-Mark for energy retrofit of domestic buildings in the UK towards the government intended carbon reduction target by 2050 [20]. This review also provides an insight on the implications of the PAS2035 on the retrofit industry alongside with current UK and international standards such as EnerPHit and AECB Standard. This specification guidance has been basically developed and designed around Passive House Standard, comparing several key assessed factors including space heating demand, thermal performance, and airtightness. As retrofitting is an option not a must for building owners and other stakeholders, the forefront question would be posed is determining the effectiveness of the retrofitting, what benefits it may bring to them, and whether shallow or deep retrofitting would be appropriate solution to decide on [21].

Thermal retrofit is usually resulting in higher costs compared to saved energy costs, hence such schemes might focus on deep thermal retrofit to fully address the economic visibility of any project [22]. Thus, this paper seeks the knowledge on current building retrofit schemes to identify the challenges and barriers to which best can be overridden through a holistic retrofitting approach, that consider not only economic and technical barriers but also social and environmental challenges and some other co-benefits. The review intends to study the benefits of adopting innovative and low embodied carbon materials to the retrofitting construction industry in the UK. This would provide future research directions on the huge benefits and impact of these products may have on successful retrofitting and the whole construction industry. The main driving question for this study that ties its objectives together and lead the research methodology to valid discussion and contribution is: What building retrofit's approach works most for UK existing homes leading to achieve low carbon emission target and overcome current challenges and barriers?

Therefore, the review will investigate current retrofitting approaches and associated measures with the following objectives:

- Identifying the barriers facing the energy efficiency improvements in the existing UK housing stock targeted for retrofitting.
- Decision making on what and how building retrofits would have been carried out and which most cost-effective, practical, and beneficial approach could be adopted.
- Exploring options for enhancing building fabric as a first approach and what criteria should be considered when deciding on enhancing the building fabric alongside the thermal performance.

Discussing current building retrofit standards, measures and initiatives in the UK and the way forward to respond to the climate emergency act by 2050. Understanding building retrofit benefits and co-benefits on individuals, companies, national economy, communities, and local authorities as well as on a global vision.2. Research Methodology and rationale.

The research reviewed existing work on building retrofit challenges and benefits to provide first-hand insight on different issues identified in literature. This is achieved through thorough investigation on construction issues raised by practitioners, academics and decision makers that holds back UK refurbishment schemes from achieving anticipated building performance targets stated in building regulations and policy makers. According to a study investigated 80,000 homes in eleven European countries by Tado° the European Leader in Intelligent Home Climate Management [23] that UK homes found to be performing far worse, losing heat three times faster than some other European housing. This is one reason behind this study to focus on UK housing stock as represents the worst case, meanwhile lessons and successful experience in different context would help overriding some duplicated building retrofit problems.

The research focus is on how to overcome UK existing buildings' economic and environmental challenges, and how current incentives, standards and retrofitting schemes overlooking the co-benefits of enhancing the indoor living conditions and social values. This has been developed through:

- Gathering data from scholarly peer reviewed articles, building regulations and policies to compare current retrofitting schemes and standards in the UK in terms of requirements, possibilities and barriers. A searching mechanism is used through using terms such as energy policy, retrofitting, building regulation and standards provided by British Standards and guidance BS or EN European Norms. This review paper also employed other terms as synonyms like renovation and refurbishment to address any related work to improve the performance of existing buildings. CIS was explored to retrieve about 68 official reports and documents for building regulations, guidance and standards, whilst ScienceDirect and Scopus are the search engine to retrieve 94 peer reviewed journal articles published until 2021 using key search words such as environmental/health challenges in retrofitting, economic challenges and benefits, deep retrofitting, improving fabric in existing buildings, technical and social barriers in building retrofits, energy policy and retrofitting schemes … etc.

Regarding the scope of this review paper, number of research papers were excluded that may discuss non-residential buildings or had no clear methodological description. The review is only limited to original research articles published in English and more to the UK context apart from few studies that discuss very related issues and share similar climate or social context. Another criterion for selection is that the review is restricted to the context where building retrofits is a priority and housing stock comprises majority of relatively old buildings and expected to last for years to come like countries in central Europe. In the UK for example, about 80% of 2050 houses are already built according to many studies including IET [24]. It might be noted that not all articles selected are cited here in this study as only most recent or directly associated with current retrofitting issues are referenced.

Mendeley software is used, firstly as a referencing tool but also organizing literature by defining and structuring the source of data and inserting resources according to the identification process as demonstrated below in Fig. 1. Similar to reviews in other studies such as Lai and Man [25] classifying and mapping reviewed literature through the

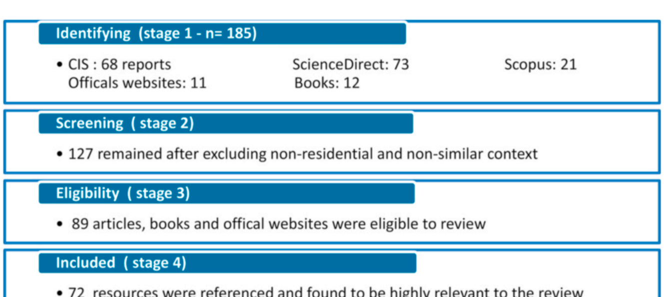

Fig. 1. Flowchart for filtering used resources and database.

intended database to use for extracting pertinent literature through screening irrelevant resources, followed by all eligible articles for review then finally included all resources cited in this study. The study focused on reviewing literature published in the period between 2006 and 2021 when Climate Change act was first planned to cut carbon emissions at COP12 followed by the UK action plan in 2008 to cut 80% of its carbon emissions by 2050.

- Discussing academic and professional views and opinions on which options and levels to approach and carry out building retrofits. This is achieved through gathering primary data from well-established organizations and associations in the field of building construction and technology in the UK. Section 5 in this review paper highlighted some professional and academic views regarding energy efficient retrofits and construction methods commonly practiced in building retrofits in the UK. CSIC, CIAT East Region Scotland, Retrofit Academy and AECB are among those organizations were consulted in this review paper. All data in this review was gathered in person through either participating or attending events, meetings and trainings related to building construction technology and methods in retrofitting.
- Comparing various options on enhancing the thermal envelope with more sustainable materials considering embodied carbon reduction approach based on published scientific data for some common construction products. This method relied on both research data gathered from journal articles and some other information retrieved from official websites for manufacturers and construction companies for instance US Department of Energy, Incynene Innovation, uk.gov, JSJ Foam Insulation, Energy-Trust, Scottish Government Officials … etc.

In addition, to identify any concerns around the UK ambitious environmental goals set by 2050, that may make them not truly net zero carbon targets. The research identifies the gap in knowledge on many obstacles and lack of strategic and realistic step-by-step policy in building retrofits that ensures UK ambitious targets are met by the committed timescale.

2. Literature

According to a number of researchers cited in Regnier et al. [6], there are many inherited challenges to improve energy efficiency in buildings including financial barriers, lack of awareness on the availability of various energy efficient options. In addition, there seems no sufficient information, robust database available to support retrofitters and the decision-making process might be complicated or there could be an interruption to the operation process. There are some other economic barriers facing both government incentive programs as well as building owners such as cost-effectiveness of retrofitting hard-to-treat homes. Wheeler et al. [2], identified key retrofitting barriers in the UK that led to systematic failure in tackling various challenges and difficulties including finance, technical, lack of awareness and information among householders about the retrofit benefits. The study realized that national challenges are of importance such as Brexit uncertainty and inadequacy of current building regulation in addressing retrofit policies. This study discusses number of economic, environmental, and technical barriers to adopt retrofit schemes for existing homes in the UK.

2.1. Economic challenges

Jagarajan et al. [7], addressed number of economic values of carrying out retrofit projects; including the benefit of not having a construction phase, property value will be increased, in many retrofitting cases legislation requirements were more surpassed compared to new built properties. Studies in literature including Regnier et al. [6], paid great attention to the importance of project life cycle cost as an indicator of cost-effectiveness of any investment or upgrading energy systems.

However, the challenges are to get a comprehensive energy data for embodied energy and transportation as well as economic evaluation using more reliable cost evaluation methods, for instance discounted cash flow rates and present/future net value of investment. The study highlighted number of barriers for deep retrofits including the high upfront cost and long payback period as well as the process complexity and lack of experience in the industry to implement a holistic retrofitting approach. It has been noted that building's market value has not been much increased after the retrofitting, which in turn discourages building owners and landlords to adopt such programs.

The European Parliament [26] produced a cost-effective strategy to identify the retrofit measures that contemplate to achieve great energy savings at low cost, although it failed to support low-income households. The energy retrofitting of buildings highly influenced by the cost so that millions of people who are in fuel poverty may not be able to afford such schemes, therefore it affects their buildings' thermal comfort conditions [27].

The Scottish Government [28] addressed further economic challenges to include households fuel poverty as a significant factor. The Government stated that around 649,00 households in fuel poverty in 2016, suggesting removing constraints and support vulnerable households with more flexible funding allocations. The report discusses ways of allowing a holistic improvement to reach EPC targets, referring to the Green Deal program limitation of not supporting low-income households and hard-to-treat homes. The report also highlighted the wide range of financial incentives available for small and medium enterprises SMEs and local communities, however less awareness and understanding of their benefits among those groups. James [17] found that many clients are not able to afford the cost of deep retrofitting unless a long-term plan is allowed for refurbishing their buildings. In addition, the building retrofit may become more complex and expensive while occupants remain using their homes during the refurbishment work.

2.2. Environmental, social, and technical challenges

In practice, building retrofits may develop new indoor environmental issues at inappropriate measures and implementation particularly in shallow retrofitting. Passive House UK [29] revealed a study that showed a high potential risk of radon levels in poorly ventilated retrofitting buildings to more than double, owing to highly air tightening structures to focus on achieving required thermal performance. Among the environmental issues in building retrofits is the increased risk of interstitial condensation in some cases, where there is not enough space to install insulation material especially in roofs [30]. Ortiz et al. [4], studied the potential indoor environmental risk over retrofitted homes and found that higher humidity problems and overheating risk occurred in retrofitted buildings. This risk is assigned to the enhancement of the envelope airtightness and thermal insulation with little attention paid to ventilating the envelope. The study addressed the issue disregarded by many retrofitting measures and schemes related to indoor environmental quality and occupant's health as most of current retrofitting approaches focus on energy-savings and improving the thermal performance of building envelopes.

Moses et al. [3], stated that people in developed countries tend to spend most of their time indoors with increased exposure to indoor air pollutants i.e. around 4.3 million people in the UK suffer from asthma due to associated problems with indoor dampness, fungal contaminants and other chemical agents. In addition, increased risk of moisture in the building envelope particularly in the insulation layers may lead to deteriorating the effectiveness of the thermal conductivity of the material [31]. Studies such as [32] concluded that a moisture risk can be mitigated by leaving a cavity gap of at least 200 mm especially in timber frames. The study also identified the decrease in heating savings from 66% to 54% when a cavity gap is applied, and the extremer the winter the higher the effect.

However, UK building regulation encourages the use of VCL to avoid accumulative moisture presence in most types of building construction. Zhang et al. [33], studied the behavior of moisture in porous insulation materials and found that the thinner the insulation layer the higher the over-measured moisture content is. This study has been overridden by current research that recommended the use of breathable insulation materials such as Icynene open-cell spray foam which diffuses through the foam enabling the moisture to dry and evaporated out which is known as bi-directional drying nature [34].

Siyu and Duan [35] pointed out several design and technical challenges such as the UK housing diversity regarding age, typology, function, location and occupancy patterns, which made it difficult to agree on an energy retrofit package that fits all solutions. Furthermore, internal, and external wall insulation can be a big issue particularly for solid walls that found to be responsible for over 35% heat loss [11]. Other studies addressed some technical challenges and gap between the theoretical design approach in retrofit schemes. Warm Front Scheme for example retrofitted 1372 properties claiming to achieve about 50% in energy consumption, whereas actual monitoring showed about 15% energy savings [11]. The Scottish Government Report [28] discusses the necessity of developing specific actions to target different stakeholders including homeowners, and landlords appropriate to different archetypes as one may not fit to all, bringing different opportunities and barriers to building retrofits.

Besides the technical and economic challenges that face retrofit schemes either the government or landlords there are some other social aspects should be considered. Palmer et al. [36], interviewed 40 social housing landlords and 8 retrofit suppliers to discuss the barriers face landlords, supply chains and the government to improve energy efficiency in social housing. Palmer's study found that majority of landlords are not putting health issues of concern to carry out retrofitting, but they also find it a challenging to educate tenants on how to maintain changes to their homes after improvements made. In addition, some other common barriers for homeowners and tenants are the lack of understanding of the whole benefits of retrofit, the perceived value against cost, the untrust of tradespeople and national government in getting high quality of work as well as concerning with cleaning space after renovation [2]. However, current incentive schemes for building retrofits in the UK such as Green Deal does not target low-income households, whilst hard-to-treat homes are still out of their scope [11]. Hence, social sustainability has not been appropriately addressed in building retrofit schemes, which plays a pivotal role in the success of achieving the country intended carbon off-set target.

2.3. Shallow or deep retrofitting

The decision on carrying out or selecting a building retrofit scheme can be determined by many factors including the building condition, budget and cost-effectiveness of the plan, value brought to the property and owners' preference. The awareness of the benefits and national impact as well as the availability of retrofitting schemes might have an implication on decisions to carry out such plans. It depends on individual cases, how significant and possible to retrofit a building and whether to decide on shallow or deep retrofitting work as well as the architectural detailing of buildings. Felius et al. [12], study showed that building form factor plays a significant role in low energy building retrofits as flats found to be cheaper to retrofit, concluded that improving the U-value of external walls and roofs has higher impact in energy efficiency compared to other building elements such as windows and floors. Hence, the decision on carrying out shallow or deep retrofits seem to be not forthright as building form, condition, typology, and other factors highly influence on this decision.

2.3.1. Shallow building retrofits

Basic or traditional building retrofits in literature refers to an alteration to an existing building to improve the energy efficiency of a system usually end-user or reduce the energy demand. Regnier et al. [6], discussed the most common and basic building retrofits is to upgrade an existing system or equipment, typically changing an old boiler or lights often at end-of-life replacement to increase the energy saving potentials. Studies like [11] revealed that conventional retrofitting shows greater energy savings in some cases for example insulating solid wall in comparison of cavity walls as for the later installing insulation can be restricted to the cavity width. Another study by Roberts [10] showed 50–80% of heat loss reduction when insulation was installed in a cavity wall and roof at the same time, whereas about 40% energy savings found when insulation was added only to the cavity walls.

This indicated that basic retrofitting by simply adding wall insulation can be effective in many cases depending on the amount of heat loss the fabric is being responsible for [11]. The study also found that traditional retrofitting showed great return of investment with a payback period of around 3 years for installing loft insulation compared to other deep retrofitting methods. Fig. 2 shows step-by-step energy savings with great reduction through simply improving the thermal envelop towards achieving the 22 kWh/m2/a target.

As mentioned earlier in the methodology that this article mainly focuses on the UK context, but important measures can be taken on how the country will be dealing with this and how significant on an international scale to retrofit housing. In a country like U.S. over 60% of current construction projects focus on retrofitting schemes [13]. Likewise, in EU about 70% of existing building stock estimated to be energy retrofitted to meet the low energy target by 2050 [14]. In the UK almost all 27 million existing homes need energy improvements [15], whereas 38% of those existing housing stocks are hard-to-treat homes and require major retrofitting to meet the national target by 2050 [35]. Regnier et al. [6], stated that retrofitting existing buildings using an integrated system has great potentials to save up 84% energy consumption compared to traditional building retrofits. However, others like Osmani and Davies [37] believed that the most successful design approach for low energy retrofit for the UK housing is to improve the envelope thermal insulation.

Daly in PSCF [38] agrees with some other researchers such as Power in Ref. [35] that75-85% of UK existing homes will still be in use by 2050, considering the poor thermal and energy performance of such dwellings. This implies how significant the contribution of retrofitting projects on achieving the reduction target of carbon emissions in the next 30 years. Retrofit solutions should consider various building aspects with different scopes such as the building age and size, function and social value of the building stock and whether there will be different needs and expectations for homeowners and tenants [11].

2.3.2. Deep building retrofits

Deep building retrofit has been defined in literature as a holistic approach to upgrade multiple energy improvements typically to reduce heat losses through building envelope or enhancing the efficiency of a system to achieve a BER or A-rating. A robust and reliable approach to achieve an explicable retrofitting system is to use a dynamic and

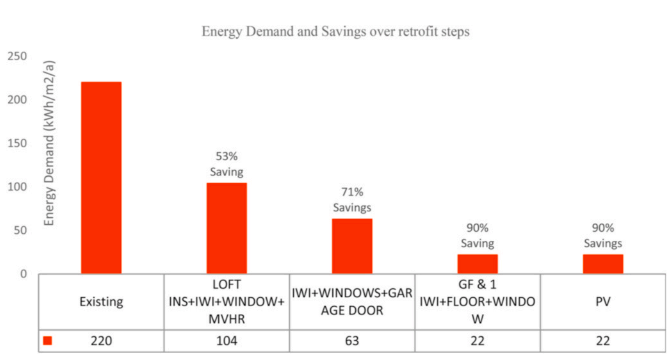

Fig. 2. Step-by-step to 90% savings, Bowman's Lea residential buildings in London: Source author based @Harry Paticas 2018.

detailed building energy simulation in order to comprehensively evaluate improvements in an integrated method [6]. The research concluded that achieving net zero annual consumption become only possible with deep level of energy improvements and fabric retrofits. AECB [39] stated that about 27 million UK homes need deep retrofitting to meet the government carbon reduction target by 2050, as shallow retrofits have been often counterproductive. Number of researchers share very similar views that one-step approach in deep retrofitting is cost-effective and technically more efficient and feasible in the next few decades [24].

The Scottish Government [28] published a report to explore how best to oversee the delivery of the country Energy Efficient Scotland (EES) program to improve energy and carbon performance of Scotland homes. The report stated that the majority of Scotland non-domestic buildings have no EPC ratings and only 5% for those hold certificates have a rating of EPC B+, whereas 73% are EPC E or worse. It is also noted that social rented homes achieved higher EPC compared to owned or privately rented homes. The Scottish government report indicated that deep building retrofits are required to achieve the EES (EPC C+) targets to include not only building envelope improvements but also installation of renewable energy and upgrading building services and systems with low carbon technologies. The Scottish Government report urges actions to be taken on a significant scale to install around 66,000 measures per year up to 2040 to meet the EES targets across all Scotland's housing stock. whilst improving an average of 17,500 buildings' EPC to C+ by 2030.

2.3.2.1. Fabric and thermal improvement. Across literature the thermal performance of building envelope has been the key aspect and focus of many new and retrofit suppliers and developers. Warming homes became a fundamental need for both individuals and government to achieve healthy and low energy homes. On the other hand, uninsulated homes have a potential risk of dampness and mold growth which can lead to health conditions. The development of external thermal insulation system with the technique of reducing thermal bridges within the external envelope has been a common practice and first step to achieve low energy buildings [40,41]. James [17] considers improving the building fabric the biggest factor in determining the ultimate outcomes of retrofitting a building. Among various types of conventional and composites insulation including EPS and XPS, an aerogel blanket type of open cell porous insulation seems to be an optimal solution to improve the optics, acoustic, thermal and fire resistance of building envelopes [42]. Professor Sarshar co-author of scaling up retrofit 2050 [24] stated that "throwing a duvet over the building is the simplest approach" and first step for UK's retrofit for the future. This statement simply refers to fabric first approach for either deep or shallow building retrofits, however authors of this report highly support the one-step deep retrofitting approach without considering the high cost, scale, capacity, and capability of the industry to deal with and implement this approach.

As the fabric first approach seems to be investable and inevitable for all intended UK housing to retrofit, there are number of manufacturers have developed and introduced insulation materials to the UK market. Aerogel for instance has been classified as a novel insulation material and applicable to most building components including roofs and windows, which is among the very few insulation materials categorized as a fire retardant (Class A1) with porosity of 95% and thermal conductivity below 0.025 W/m K [31], Meanwhile, other studies reported upper respiratory tract irritation as particulates of aerogel can be deeply inhaled into lungs during handling [43]. However, aerogel is not a vapor permeable but has a relatively high embodied energy value at 55.10 MJ/kg compared to Icynene with only 0.91 MJ/kG as Table 1 shows.

Icynene open-cell spray foam insulation has been approved and certified by the BBA and by the European Technical Standard as a safe insulation material to be used in construction. Icynene Europe S.P.R.L [44]. carried out a laboratory and in-situ tests and investigations to certify an Icynene H2 foam lite plus insulation for suspended floor application. The Agreement certificate identified key performance

Table 1
Comparison between thermal and environmental performance of some thermal insulation materials.

Type of insulation/key factors	Density/rigidness Kg/m3	Thermal yj conductivity (W/m.K)	vapor permeable	Specific Heat Capacity J/(Kg.K)	Behaviour in relation to fire	Embodied Energy MJ/kg
Extruded polystyrene XPS	Rigid/170	0.033–0.035	Yes, 50–250	850	Class E	8.5
Expanded Polystyrene EPS	Rigid & tough/ 15–30	0.034–0.038	No, 20–70	1300	Class D-E	88.60
Icynene H2Foam Lite LD-C-50	Semi-rigid/ 7.5–8.3	0.039	No: 3.3 μ	1.47	Class E	0.91
Aerogel porous ultralight	Rigid/150	0.014	No: 5 μ	1000	Class A	5.4 kg s/m^2 = 55.1 MJ/kg
Mineral-wool	Rigid/70-150	0.034–0.044	No: 1–2 μ	n/a	Class A1	22.4
Polyisocyanurate/Polyurethane foam PIR/PUR	Rigid/30–40	0.023–0.026	No: BBA Cert says (2–5)	1958 to 2076	Class D	101
Glass-wool	Rigid/circa 20	0.035	Yes: 5–7 μ	1030	Class A	26

Source: BBA Cert 08/4598, EN12086, BS EN 13501–1:2018, ICE Database 2011, Building Green, Eco-merchant and BRE.

factors where the product was declared to have a thermal conductivity of 0.037 W/mK, and high durability factor. However, the product has been classified to Class E with regard to its behavior to fire according to EN 13501-1: 2007 and also has water vapor resistance factor of 2μ which is quite low value according to HIS [45] makes it breathable material. The Icynene open-cell spray foam is 100% water-blown and available in low and high density, semi-rigid, flexible and can be applied to most building components including roof, floors, walls, and openings. It also provides continuous insulation over all surfaces which improves thermal bridges in building envelopes. Table 1 shows a comparison of some common thermal insulation materials in terms of their physical and thermal performance. An interesting fact that Icynene open-cell spray foam has high vapor permeability at low density and has the lowest embodied energy rate among those most common insulation materials.

Number of studies including [32] investigated the impact of applying wall-thermal insulation on the total energy use, for example 54% possible reduction can be achieved by simply applying this solution. Further investigation and intensive research might be undertaken to study the environmental behavior and the implication of Icynene open-cell spray foam on the future of UK building retrofits, especially for stone-timber cavity walls as very limited information on this application is found in literature. In addition, considerable number of houses in the UK constructed with cavity walls and conventional insulation could result in high cost due to disassembling internal wall layers. Hence, injecting pourable foam insulation would be a good option which can save time and cost, yet to officially approve its thermal and hygro-thermal performance though.

2.3.2.2. Window installation in deep building retrofits. The window is an essential component in the building envelope which responsible for ventilation, daylighting, connection to the outdoor environment and significantly contributes to the occupants' health and wellbeing [46]. On the other hand, windows are responsible for the greatest among of heat loss among other building components [46]. A poor window performance can lead to a major source of unwanted heat loss in the building envelope. Urbikain [47] studied the behavior of windows and their impact on thermal energy loss in buildings and found that windows are responsible for greater amount of heat loss up to 48% in cases of single glazed compared to opaque surfaces, although windows' areas so often less than external walls. The study concluded that up 66% heat reduction is possible to achieve by upgrading to triple-glazed with the use of low-E argon or krypton filled gases in windows.

Gangolells et al. [5], agreed that replacing windows found to be the most effective strategy to reduce a building energy in use. Windows count for about 35% of heat escaping for building envelopes which higher than any building components as demonstrated in Passive House Design guide whilst the U.S. Department of Energy [48] believes windows are responsible for 25–30% of heating and cooling energy use in dwellings. Peter Fay in Ref. [29] explained the necessity of upgrading windows and doors in building refurbishment which helps improve the envelope thermal performance reducing great amount of heat loss and mitigate the risk of condensation. However, upgrading windows for example from single to double glazing might show poor return of investment with long payback periods for up to 98 years which exceeds the estimated lifespan of most construction products and buildings themselves [11].

However, an appraisal is to the advance of technology that enabled the industry to provide high-performance and efficient windows with various glazing options and made-up materials [46]. Although, selecting a specific type of window will be determined by many factors to include cost, material availability, required performance and aesthetic preference. High-efficient window does not refer to only its high thermal performance but also minimize condensation and air leakage as well as increase visual and acoustic comfort. Window material is of important too as it determines how sustainable the window is, by determining the embodied energy associated with production and throughout its life-cycle, cost, durability and even its behavior to fire. Kubba [46] discussed another two important factors when it comes to select the window material in retrofitting, referring to renewable and non-renewable materials and how toxic during manufacturing, use, recycling, and end-of-life.

2.3.2.3. System upgrading. The existing UK building stock must significantly improve its thermal performance to meet the government's commitment to reduce the carbon emissions by 80% by 2050 [49]. Felius et al., [12]. stated that improving the building envelope to reduce heat losses might not be always the best solution in retrofitting, as greater energy-savings could be achieved by simply installing air source heat pump instead. Most of energy efficiency schemes in retrofitted buildings are focusing on improving the building envelope particularly in cold climates. There is a sense of agreement within literature that cost is the most notable challenge for retrofit programs to existing buildings especially deep retrofits in the UK. This implies not only the cost of envelope renovation but also high cost of microgeneration technologies and system upgrading of existing UK housing [37].

Felius et al. [35], also considered installing air source heat pump as an effective solution that would achieve similar energy savings to the reduced operational costs. Olgyay and Seruto [50] studied the whole building retrofit including architectural, electrical, and mechanical systems which have huge implications on achieving the potential carbon emission reduction. They encourage investors to use the whole life-cycle cost analysis to demonstrate the long-term benefits. Figures in their study indicated that a 100% deep retrofit demand has been reached by 2020, meanwhile the US has only 25% deep retrofit capacity at the same time to meet the carbon savings by 2030. Upgrading building services should be considered earlier in any retrofit project particularly using an energy efficient technology that reduces energy consumption, enhance the indoor thermal and environmental conditions e.g., MVHR system.

Regnier et al. [6], stated that upgrading existing system or equipment at its end-use is the most common and simplest way of improving energy savings, but not much attention paid to how this isolated replacement could be optimized and integrated into the whole building system. A significant gap between predicted and actual energy savings in building retrofits owes to not considering the user's behavior and control over the indoor thermal environment [4].

A great energy savings that most of building retrofit schemes seem to neglect is improving the users' control over their indoor environment, appliances and installation of renewable energy resources. Osser et al., [51]. said that usually energy savings in retrofits defined by the dwelling emission rate DER which focuses on heating/cooling loads, building fabric and lighting. The study stated that implementing new systems, appliances or lighting can be different from new to existing buildings as building owners would rather upgrading them at their end of life. Paridari et al. [52], proposed a smart approach to schedule home appliances through a multi-objective algorithm-based system known as MILP to reduce energy and associated CO_2 emissions as well as controlling the user's behavior particularly at peak periods. Habibi [53] discussed the smart management system which has great potential to save energy, improve indoor environmental quality but unfortunately it has not been fully addressed in buildings. Research revealed a lack of energy awareness among building users on the control of their high energy consumption by home appliances [54].

Lighting plays an important role on occupants' health and wellbeing, visual comfort, productivity and performance. It contributes to considerable amount of energy and carbon emissions produced by buildings; hence it should be considered for any retrofitting plans [55]. Dubois et al. [56], stated that lighting accounts for about 19% of the global energy usage that can be significantly reduced by improving the control of system and occupants' behavior and by utilizing daylight system. The study covered over 160 research articles and found very limited knowledge about existing lighting retrofits and lack of actual energy performance data and information related to lighting in existing buildings.

Literature discussion: This section discussed number of environmental, social, and technical challenges faces UK existing retrofitting schemes, with an insight into the causes and available building retrofit options to cope with such challenges. There is a sense of agreement in literature that cost is the biggest challenge for homeowners, policy makers and retrofitters. The cost effectiveness of retrofitting in literature referred to the upfront and payback period indication. Hence, many studies in literature claimed that retrofitting schemes lack experience in the industry to implement a holistic approach with reliable cost evaluation and to include project lifecycle cost (operation, maintenance, and product end-use). In addition, retrofitting schemes may have disregarded the environmental and social values consequences of any project, whereas user's health and social sustainability are key indicators for successful retrofitting measures.

This section also drew a debate in literature on some decision-making regarding the depth of building retrofits. As cited in this article, a clear disagreement on whether deep retrofitting would always be a good solution and results in more energy and carbon savings. However, the majority are agreed on the fabric first approach at all retrofitting levels to be an important step towards great energy savings. Therefore, this review emphasizes on the importance of considering product embodied carbon emission method rather than only looking at the energy in use and thermal performance. Installing thermal insulation commonly seems to be the first option and step in retrofitting. Thus, by investigating the most common insulation materials, we found Icynene H2F Foam has the lowest embodied carbon value despite its being less used in the industry as stated by the U.S. Department of Energy [57] owning to the high upfront cost compared to traditional batt insulation. It can be concluded that decision-making process is quite complex in a measure and depends on individual cases. Therefore, understanding each case, existing conditions, available resources, and potential outcomes could result in more reliable retrofitting measures and cost evaluation.

3. Building retrofit measures, standards, and initiatives in the UK

The UK introduced the first energy certificates (EPCs) earlier in the second millennium following by the European Performance of Buildings certification scheme in 2002. Later, a new target for energy efficiency has been introduced by the Living Housing Association following the Clean Growth Strategy by 2030 which aims at building stock above EPC C-rating [36]. James [17] also commented on both EU and UK policies in addressing carbon emissions in existing buildings being relatively ineffective. He stated that the UK Government recently shifted towards using the RdSAP to test the thermal performance of existing buildings. However, the procedure is not enforcing domestic dwellings to act upon this, which is a big consumer counts for over 40% of the total energy usage in the UK. Yet, the UK building regulation for retrofitting (Part L2B) brings relatively low standards to meet the country carbon emissions target for 2050 according to Ref. [17].

UKAS is one among several accredited bodies in the UK that certifies building products and systems. However, the BBA currently is the largest testing services in the UK awarding an agreement certificates to products or systems, that successfully passes all laboratory assessments and tests as well as on-site evaluation and inspections [30]. Recently, there has been a call to review current governmental and non-governmental policies and standards for building refurbishment in cooperation with third party accredited associations to implement clear roadmap for the future of the UK energy retrofit schemes.

The Department for Business, Energy and Industrial Strategy (BEIS) sponsored the retrofitting dwellings for improved energy efficiency specification and guidance known as PAS 2035:2019, a document that has been reviewed every two years published by the BSI. This specification guidance for energy retrofits in the UK domestic projects was developed by joined organizations including AECB, BBA, BRE and EHC. BSI [15] stated that PAS supports the EU and UK objectives to achieve nearly zero energy buildings and national targets to reduce carbon emissions through a whole-domestic building retrofit work. The specification guidance ensures high-quality work in terms of functionality, durability and usability. It is looking at improving the health and wellbeing of occupants, enhancing the efficiency of energy in construction and use as well as minimizing the environmental and carbon footprint of buildings. BSI [15] identified several energy efficiency measures and improvement options to retrofit buildings that PAS2035 intends to improve the building performance including:

- The thermal insulation of building elements,
- The airtightness of the envelope
- A safe moisture content of the building fabric
- Enhancing the water penetration and resistance of the building envelope
- Ensuring good level of indoor air quality and reduce risk of condensation
- Minimize the risk of releasing VOCs in the building as a result of improving the airtightness
- Ensuring that efficiency in heating and cooling is provided and promoting the smart control of systems with minimum associated risk of overheating
- Provide an efficient domestic hot/cold water with the use of LZC technologies
- Promote the energy efficient lighting and appliances
- The provision of locally generated renewable energy and on-site energy storage with appropriate metering and monitoring systems to enhance the efficiency of systems

The energy and thermal modelling design and analysis tools such as

SAP and PHPP software highly support the application of PAS2035 and retrofit designer, assessors and coordinators should be familiar with such design and simulation tools [15]. PAS2035 qualified retrofit assessors must hold a DEA certificate which requires a deep understanding and knowledge on building energy, risk assessment and management procedure [19]. The AECB launched a new AECB Retrofit Standard which is apparently based on Passive House Standard that aims at achieving 50 kWh/m^2/yr for space heating with a maximum of 2 ach @50 Pa [58]. Andy Simmonds at AECB CEO stated "we must prioritize the retrofitting of existing buildings at scale to meet 2050 environmental targets, as outlined in the Paris Agreement" [55, p.13]. However, number of professionals and authors including Dr Price author of the British Standards Institute believes that the EnerPHit Standard is a concise but too strict approach to be adopted for UK retrofit buildings to meet 25 kWh/m^2/yr. It can be said that AECB Retrofit Standard focuses on managing and dealing with moisture, floor, radon, and fire risk with setting an excellent retrofit survey in the first place to ensure the building is in an appropriate condition for retrofit Dr Price said.

Despite AECB Retrofit Standard the UK adopted guide to meet the emission target for 2030 the standard compliance relied deeply on using PHPP as a modelling tool especially for minimizing thermal bridging occurrence and airtightness design and testing protocol. In Denmark, the LCA introduced a policy for reducing the construction emissions in accordance with the country commitment to meet the 70% reduction of CO_2e by 2030, focusing on embodied energy and retrofit buildings [29]. As such UK retrofit schemes should include the lifecycle assessment of a building and adopted into the retrofitting standard. Duncan Smith in Ref. [29] discussed the EnerPHit Retrofit standard in the UK market in which regarded to be an expensive approach to implement in many cases, however it still offers a great opportunity for improving the building envelope and use of renewables. In addition, and more important it brings long-term benefits for the society and economy of the whole country as well as addressing climate change and tackling fuel poverty.

Kubba [59] stated that American Recovery and Reinvestment Act of 2009 extended a tax reduction of up to $1.80/ft2 in retrofitted buildings that achieve ASHRAE Standard 90.1–2001 requirements for heating and cooling, with investment tax credits of up to 30%. Such investment tax credit can be reviewed by UK retrofit incentives to support and motivate low-income households to adopt more affordable retrofit plans. As Fig. 3 shows, EnerPHit Standard requires the building to deliver less space heating demand at 25 kWh/m^2/a than Passive house classic with similar primary renewable and non-renewable energy at 120 kWh/m^2/a. It is well documented that UK existing housing stocks are mostly hard to treat and comply with Passive House standard as underlined by AECB and Part L1A retrofitting targets.

In addition, Table 2 compares the UK existing retrofit standards (AECB and UK Part L1A) compliance to the envelope airtightness at rates of 1.5 and 5.0 n50 1/h respectively. The table shows that envelope

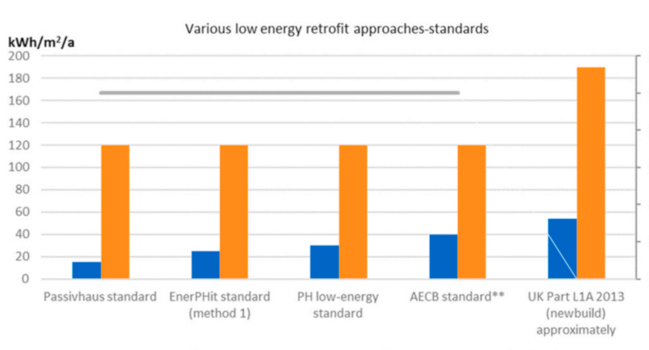

Fig. 3. Comparison of low energy retrofit standards. Source @Author based on [57].

Table 2
Comparison of thermal envelope requirements for low energy retrofit building standards.

	Passivhaus standard	EnerPHit standard (method 1)	PH low-energy standard	AECB standard**	UK Part L1A 2013 (newbuild)
Airtightness	<0.6 n50 1/h	<1.0n50 1/h < 120	1.0 n50 1/h	1.5 n50 1/h	5.0 n50 1/h
Thermal bridges	0.01 W/MK	0.01 W/MK	0.01 W/MK	0.01 W/MK	NA

Source [57].

airtightness in UK building regulation relatively high and thermal bridging is not part of the design requirements. Currently there is no UK Standard for Net Zero Carbon Buildings since the Code for Sustainable Homes was withdrawn [17]. The AECB has adopted the Passive House Standard to be a Gold Standard for both newbuild and retrofits with less restrictions in airtightness and space heating requirements as Table 2 illustrates.

Other building retrofit guides in the UK is the BREEAM UK Domestic Refurbishment (2014) and BREEAM UK Non-Domestic Refurbishment and Fit-Out (2014). These documents are more assessment and rating systems rather than design approach likewise LEED and other sustainability rating systems. BRE [61] defined the BREEAM UK scope and use as an international and local certification scheme for domestic and non-domestic buildings since launched in 1990, assessing buildings across lifecycle with reference to the environmental, social and economic sustainability rating benchmark. The standard assesses new and refurbished constructions encouraging all stakeholders to achieve high and continuous building performance and improvements that go beyond current required building regulation and practice. BRE Group is an independent approval body that provide certification to the international market for the use of fire, security and other sustainability products and services [62].

There are number of governmental funded schemes which are targeting social and private housing in the UK mostly those were rated under band D in SAP such as Warm Front in England, Home Energy Efficiency Scheme (HEES) in Wales and Warm Deal in Scotland [11]. Green Deal program is supported by UK government since 2012 through the Green Investment Bank to financially support low-income households and those hard-to-treat homes to obtain energy efficiency improvements. Although the scheme provides no upfront costs of retrofit works as well as opens thousands of jobs in the insulation industry, but highly believed meeting the scheme requirements is quite hard especially considering those in fuel poverty or others with multiple occupied buildings with an issues of low consumer appeal and investor incentives [63].

4. Professional and academic views on building retrofit challenges

This review paper also derived information from primary source of data through participating and attending seven professional, academic events and webinars organized by different organizations in the UK construction industry. Information discussed here were either presented by participants or directly posed and acquired by authors to serve the purpose of the article. In addition, all source of information and events are cited here in this section.

4.1. The Retrofit Academy CIC event

The CSIC hosted a webinar discussion on retrofit challenges Episode 5 podcast inviting members from Retrofit Academy CIC Smith and Peerpoint [64] the CEO managing director of Parity projects. Smith stated that professionals believe that 50% of the retrofit challenges related to cost and EnerPHit standard is far too expensive to achieve, whilst the second most common challenge is the one size retrofitting solution that does not suits UK existing housing stock. What can be derived from this discussion is that cost perceived to be the major challenge for achieving net zero buildings particularly for existing housing stock. However, those views may lack of understanding of co-benefits associated with improving the energy performance of existing buildings including enhancing health and wellbeing of occupants, employability, and social justice in local communities.

4.2. ResiBuild in residential sector

I was invited to attend an interview and leading a live webinar on Construction Carbon Dilemma by ResiBuild on May 26, 2021. The event brought an academic and professional community from around the world (Past Events| Resibuild) in the field of sustainable architecture and technology from UK, Canada, US and other countries such as Dr Syeda Zainab the sustainable Technology Services Manager at Wates Group. The event discussed the UK decarbonization plans, affordability, embodied carbon in UK construction, and whether the UK is on track to meet the government carbon reduction targets by 2025,2030 and 2050. There was a sense of agreement that cost of decarbonization is the major challenge and low energy and carbon materials are key in retrofitting. The ResiBuild community shared a common view that UK yet to be on track to meet carbon reduction target by 2025. The main topic discussed either in the interview or during the live event was decarbonizing our construction through an affordable approach. It was great to hear and learn from others experience in this mater like in Canada and US, but the challenge seems relatively greater in the UK as considerable part of its existing homes is hard-to-treat and much worse in energy performance.

4.3. Chartered institute of architectural technologists (CIAT) Scotland East Region

As a member of CIAT Scotland East Region there has been a series of retrofit knowledge exchange sessions organized which hosted in collaboration with the Scottish Ecological Design Association through virtual meetings [65]. The events discussed various subjects related to methods for sustainable energy efficiency retrofit including EnerPHit, circular economy and future of building standards in Scotland. Rupert Daly answered one of my questions regarding the use of PH standard for retrofitting compared to AECB standard in the UK, stating that AECB uses PHPP as a design tool whilst the standard may be unachievable aspiration for some but the quality assurance of applying the methodology and verification is key. Tibo Bandula commented on section 7 sustainability the gold and platinum level in the standard saying it may currently seem a visionary to many in the industry as PH was in 90s in Europe. Bandula posed good question, why are we not promoting and building our own regulations? Allowing for more flexible approach and resulting in solutions that are kinder to the environment.

It can be understood that Part L building regulation no longer meets the rapid transformation in the built environment and the national inspiration for cutting down carbon emissions without phase-change in the standard. However, duplicating some international standards might not be very good solution without understanding the nature and complexity of the local built environment to avoid unattended consequences. Professionals who attended these meetings highly support the use of PH retrofitting methodology rather than the standard itself and therefore adoption of EnerPHit standard for UK retrofitting stock would not achieve similar results.

4.4. The construction scotland innovation centre CSIC

Two full-days AECB Carbon Lite Passivhaus Contractor training were attended provided by CSIC in 11th-13th May 2021 and followed by a practical one full-day Passivhaus in Practice on June 23, 2021 [66]. The sessions covered all essential aspects of Passivhaus construction on-site including installing thermal insulation, thermal bridges concept with airtightness taping, airtightness test, building services and systems presenting some case studies achieved Passivhaus standard in Scotland. The center provided a case-show for several PH rigs to demonstrate the detailing and methods of construction. There was a discussion around PH and EnerPHit standards for new build and retrofits with Dr Julio Bros-Williamson the Energy and Building Consultant in the Institute for Sustainable Construction-Scottish Energy Centre. He believed that PH Standard is the way forward for Scotland new construction industry and the standard provides creative methods for low energy design. However, Williamson also stated that AECB Standard is a softer version of EnerPHit for UK construction which would be more flexible and achievable for most existing building. The event demonstrated the possibility of applying PH design methods in the UK without underpinning the challenges and barriers may face existing buildings particularly pre 1939 housing with solid wall construction, listed and historic sites considering that almost all certified PH components and materials are imported. Therefore, the argument yet to be valid without addressing these issues and whether the country is capable to locally source materials and produce construction products that meets certification approval.

5. Building retrofit scheme benefits

Siyu and Duan [35] highlighted number of advantages for retrofitting existing buildings, including the great savings in construction materials, contributing to reduce the embodied energy of the lifecycle of a project and retaining the sense of community, cultural and historical reservation. Although it is essential to improve the energy performance of existing housing stock in the UK to tackle the climate change problem, over 70% of those homes are classified as Hart-to-Treat properties [67,68]. According to the energy efficiency rating EER, majority of homes over 75% in the UK in 2014 were in band C and D [69]. Studies such as IPCC [70,71] revealed that, there are huge benefits of building retrofits on reducing global carbon and greenhouse gas emissions. Dong et al. [72], mentioned another advantage of building retrofits which is reducing the landfill waste resulted from building demolitions that saves the environment alongside with other economic and social benefits.

AECB [66] has identified who could benefit from building retrofits in the UK specifying all stakeholders to include homeowners, tenants, landlords and government. The AECB Association summarized the multiple benefits of getting buildings retrofitted such as increasing the indoor level of comfort and quality of indoor air and environment, less health issues, cutting down energy bills, and low maintenance, low risk of overheating and fuel poverty. In addition, there are wide scale governmental benefits such as achieving the carbon reduction targets, improving the public health which in turn reduces the NHS costs, flourishing the country economy through improving employability and tax revenue. AECB [66] stated that one of the greatest benefits of retrofits are the improvements of indoor thermal and air quality conditions but unfortunately this is not widely known or understood by residents.

Section 4 and 5 brought an overview on current legislation and public energy programs that support national retrofitting schemes and home users' welfare. It is noted that existing UK carbon emission policies and regulations are inadequate to deal with the country ambitious target and ineffective in addressing carbon reduction through retrofitting existing buildings. Products and systems accreditation services are equally important to building legislation and standards as they provide a quality assurance and implementation of high performance to comply with current regulations.

Complexity of UK building stocks alongside with other factors made it relatively challenging for the country to adopt existing European retrofit standards such as EnerPHit. Some construction professionals and engineers considered PH retrofit standard to be a visionary to certain extend, whilst other newly developed guides like AECB standard are still far superior to achieve for many in a cost-effective approach. This review believes further steps should be taken by UK policy makers in implementing successful retrofitting plans such as considering tax reduction and credits as well as going beyond regulation compliance when possible and rewards for doing so. It is found that educating building users and all stakeholders on the importance of understanding the co-benefits of building retrofits is a key element and motivator for achieving the intended retrofitting target by 2030 in the UK.

6. Discussion

This study reviewed number of research articles, government reports and standards on current challenges, benefits, approaches, and movements on the UK existing retrofit plans to meet the intended carbon reduction target by 2050. The study aimed at providing an overview of existing research on retrofitting to draw an attention to related issues to energy and carbon reduction policies in building retrofits, meanwhile seeking possible future research directions on the role of innovative construction products that contribute to reduce carbon emissions in the construction industry. The objective of the review is to provide an insight on the performance gap of UK existing retrofitting schemes and incentives.

Although the EU and UK retrofit initiatives encourage building owners and local communities to support the national target of carbon emission reduction as discussed in section 3 literature and section 4 retrofitting measures and incentives, research showed ineffectiveness of application, public unawareness of those incentives in the market and lack of sufficient data and information to suppliers and retrofitters. As cited here in this study various challenges and barriers currently facing the UK retrofit projects including cost, complexity of buildings' architectural design, social value and availability of accurate data and information on UK existing housing stock. However, there are potential co-benefits building retrofits may offer to users, contractors and government that contribute to improve the thermal and energy performance of buildings and enhance the indoor environmental quality.

Installing ground/air source heat pumps and mechanical ventilation with heat recovery systems (MVHR) have been leading the market in the last decade or so for new build or upgrading heating systems. However, homeowners and retrofitters would simply need substantial grants to help implementing non-profitable investment with over 60 years back return money. To validate this argument authors made simple calculation for installing domestic heat pump based on annual home energy consumption and savings.

12 months heating consumption for two-bedroom semi-detached house 22,352 kWh until October 2021.

85% heat and hot water = 19,000 @ 2.9p/gas = £551.

Equivalent heat pump @ 4:1 = 4750 kWh @ 4.7p/Elect kWh = £224.

Annual savings = £327.

An average air source heat pump capital cost = £12,000 Payback period 37 years.

Considering 50% increase in gas prices annual savings would be only £817 which means delivering a 23 years payback period. This simple mathematical calculation applies also to MVHR systems, and the question posed here for UK government is how possible for homeowners to invest in these systems without substantial and subsidized grants available to public interest.

IET report [24] for example highly support and encourage the whole-house approach in deep and one-retrofitting step. The report claimed that bite-sized approach could result in higher cost and may need to be re-retrofitted by the next few decades, also urging actions to start retrofitting social housing and the use of energy efficient systems like heat pumps. This report may support the view of number of studies cited here in this article for adopting the whole-deep retrofitting approach including [6,50], whilst upfront cost and understanding the complexity of the UK housing stock may seem to be neglected in most of these studies. The IET report itself admitted that deep retrofitting currently is very expensive suggesting cutting down the cost to an affordable level through public subsidies.

There is no agreement in literature that retrofitting social housing is priority and how significant its proportion to the whole UK housing market. The Scottish Government report [28] for instance stated that social housing found to be more energy and thermal efficient achieving higher EPC ratings, whilst other official reports like IET and other studies such as [10,36] have pointed out the poor performance of social housing in the country with the need of a whole retrofit plan to include upgrading windows, systems and fabric insulation. The disagreement on which type of housing stock urgently requiring actions, scale, time and cost of each housing typology either privately owned or socially rented is owing to the lack of accurate and publicly available source of data on existing housing performance according to the different housing categories. Therefore, this review article supports the call for robust and reliable information at a scale prior to any actions on retrofitting plans. Literature revealed that UK building regulation and retrofit programs might not be congruent to meet the potential decarbonization policy committed by the UK government for 2050 target, without special carefulness to the details and step-by-step holistic approach. There is a big debate as cited here in this article on the acceptance of retrofitting guidance and standard that works for UK context as many support the adoption of EnerPHit standards, whilst others believe such standard is way far to achieve for most UK housing stock. On the other hand, the UK based and developed standards such as PAS2035 and AECB do not demonstrate as clear methodology as EnerPHit considering the pre-existing of the later in the construction industry. Furthermore, the review showed that retrofit plans and packages do not address the diversity in needs and requirements of UK housing stocks. Thus, an urgent call to review existing policies and standards is needed to consider more holistic retrofitting approach in the UK supporting some emerging policies like PAS2035 standard to cope with current challenges.

As stated earlier in the methodology that our review scope and context is UK housing, although it took into consideration successful experience of building retrofits of other context such as central Europe and US that may share similar housing stock, building typology or retrofitting policies. For example, tax credit and tax reduction applied in US might be a good driver for those willing to apply for building retrofit loans. It has been noted that fuel poverty and social sustainability have not been fully addressed as an essential ingredient in building retrofits. It is also found that involvement of some stakeholders like building users and suppliers is neglected at early design stages of retrofit packages. Moreover, there has not been enough data and information publicly available for decision makers to understand the benefits/co-benefits and cost-effectiveness of retrofitting schemes on the long-term. Deciding on the level of retrofitting can be a bit complicated, so the process should be carefully dealt with beyond cost evaluation. It can be understood that existing UK building retrofit plans may need to adopt and develop a renovation framework with various motivations to meet the needs of different groups and local authorities across the whole country. This can be achieved through addressing key aspects and differences among those devolved nations regarding their different resources, capacity and social values and priorities to implement such framework.

UKAS and other accredited associations are equally important and would play a significant role in the process of cutting down carbon emissions in the built environment. Studies and professional views discussed here in this article consensually agreed that fabric insulation is an essential and first step in building retrofits. Despite the tremendous amount of insulation materials needed to insulate millions of homes to reduce energy being used for space heating and carbon emission associated with, embodied carbon of materials clearly neglected by most of retrofitting policies and guidance. This study underpinned the significance of considering the embodied carbon emissions in construction products as a key indicator for carbon and energy savings in retrofitting programs. Energy and carbon lifecycle analysis for building construction products and systems is still not fully considered in UKAS approvals such as BBA certificates, beyond solely assessing the physical and thermal performance.

7. Conclusion

This research developed its argument around the future of the UK building retrofits through looking at current challenges and possibilities to achieve the 2050 net zero building target. Thus, objectives were set to understand what kind of technical and non-technical retrofitting challenges UK housing is facing including economic and environmental barriers. Having understood these challenges and the approach followed to carry out retrofit work the study tended to define the most practical and cost-effective retrofitting approach for the benefits of all stakeholders including occupants, homeowners and to serve the national target the country committed to. Legislation and building regulation are critical part in the process not only for retrofitters to comply with by also for the government to ensure incentives and retrofitting schemes are achieved at anticipated deliverables. Therefore, the article reviewed current and most practiced building measures, standards, and guidance in retrofitting, discussing the capability and technical capacity in the UK context.

It is pivotal to understand and cope with those environmental and social challenges discussed in this article to achieve sustainable retrofitting successfully and realistically, and to avoid generalizing any case study whatever the retrofitting approach applied as individual cases may have assessed and represented differently. This review thoroughly evaluating the common retrofitting approaches to underline any barriers and overlooked benefits in retrofit measures. It scrutinized different building retrofit options at either deep or shallow levels discussing the pros and cons and opinions of advocates in literature and industry in order to draw a conclusion on which way faced challenges can be tackled through strategic plan that may support different retrofitting approaches. The UK has launched the climate act in 2008 to tackle fossil fuel emissions and yet to agree on specific and legal document that defines the level and minimum requirements to retrofit existing housing stock leading to the optimum deliverables. The conclusion of this review can be summarized with the following:

- Deep retrofitting will be needed for most UK existing housing stock with both options step-by-step and whole-house renovation to bring more flexible financing schemes at long-term strategic plan.
- An emphasis on the environmental and health benefits on retrofitting instead of focusing on cost-effectiveness and investment returns solely.
- Raising the public awareness on the significance of the national scheme to cut down carbon emissions, engaging end-users in the process and build a trust between all stakeholders including supply chains and investors.
- The ideal approach is to start with the most vulnerable groups (users and buildings) to tackle fuel poverty, health and wellbeing of users and work on energy and carbon savings simultaneously.
- There is a need for a holistic retrofitting strategy that considers abandoning fossil fuel and reducing heating demand, and equally invest in sustainable construction materials and technologies.
- It is vital to Invest on research and innovative technologies, develop and publicize mass-resource data on retrofitting strategies and schemes at national scale.
- Innovation centers, local governments and authorities should introduce more events, workshops and training programs on sustainable building retrofits that bring all stakeholders together including policy makers and end-users to be part of the decision-making process.

Further scientific and experimental research on existing retrofitting schemes with evaluation/monitoring of pre and post renovation work on large-scale is recommended and would support this review discussion and assumptions.

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Data availability statement

Publicly available datasets were analyzed in this study and all links are provided in references accordingly.

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.

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