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Li, X. and Densley Tingley, D. (2021) Solid wall insulation of the Victorian house stock in England : a whole life carbon perspective. Building and Environment, 191. 107595. ISSN 0360-1323

https://doi.org/10.1016/j.buildenv.2021.107595

Solid wall insulation of the Victorian house stock in England: a whole life carbon perspective

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Abstract: Solid walls are a common feature of the pre-1919 Victorian housing stock in England, however their construction results in considerable heat loss, and thus large heating requirements. Solid wall insulation of these walls would improve energy efficiency, and in turn should reduce greenhouse gas emissions. However, the additional insulation needed comes with an embodied carbon cost. Current studies about whole life performance of solid wall insulation focus on a single building or building type only, without considering the diversity of building types in the pre-1919 Victorian house stock. This study fills this gap by investigating the whole life carbon performance of eight current market available insulation materials. The insulation materials studied include vacuuminsulated panels (VIPs), aerogel, phenolic foam, polyurethane (PUR), polyisocyanurate (PIR), expanded polystyrene (EPS), glass wool and wood fibre. The results show that solid wall insulation reduces whole life carbon emissions up to 1654 $kgCO_2e$ per m^2, with the carbon payback time of all eight insulation materials being less than 23 years in the worst case scenario, and less than one year in the best case scenario. Both are considerably shorter than the service life of the insulation materials. More actions should be taken to promote the installation of solid wall insulation in the pre-1919 Victorian house stock as this work shows that the accumulated carbon reduction potential reached 268 $MtCO_2e$ from 2021 to 2050.

Keywords: Solid wall insulation, Whole life carbon analysis, Carbon emissions, Retrofit, Victorian house stock

1. Introduction and literature review

Materials are one of the fundamental pillars of our society, as primary resources extracted from the natural environment, they are used to fuel and sustain national economies [1, 2]. The construction sector and the built environment are major drivers of materials consumption [3], with the residential building sector alone accounting for 30-50% of the material consumption [4]. The selection of building materials is of vital importance, as an example, a study by González and García Navarro [5] shows that selecting low environmental impact construction materials can reduce 27% of carbon dioxide emissions in the construction phase. Building materials also contribute considerably to various impact categories including human toxicity, fossil depletion, and global warming [6].

The UK government is committed to bring all greenhouse gas emissions to net zero by 2050 [7]. There are 28.7 million homes in the UK [8], and domestic energy consumption emits 20% of the UK GHGs [9], this makes them a critical area to target in the pursuit of zero carbon. Specifically, retrofit of existing buildings has the potential to cut down both global energy consumption and greenhouse gas emissions at relatively low cost and high uptake rates [10]. Although life cycle assessment of different refurbishment strategies for individual buildings has been widely studied, the urban or larger scale life cycle assessment of different refurbishment strategies for building stock has attracted much less research interest [11]. Currently the majority of UK domestic stock retrofit studies focus on operational impacts [12-17], largely excluding embodied impacts. However, sometimes the increase of embodied impact leads to diminishing operational energy savings during retrofit, as shown in this roof retrofit example [18], beyond a certain insulation thickness, the energy efficiency benefit stabilizes with increasing thickness of insulation. This emphasises the need to extend UK domestic stock retrofit studies to include whole life cycle assessment.

1.1 Solid wall insulation in pre-1919 Victorian house stock

As a result of the UK's extremely low demolition rate of the housing stock [13], pre-1919 Victorian dwellings, with comparable poorer thermo-physical characteristics and higher energy demand to maintain indoor thermal comfort [19], still account for 20.8% of the English stock (*calculated based on the number of dwellings*) [20]. Solid walls are commonly used in the pre-1919 house in the UK [21], and these walls are responsible for 35% of the heat-loss for these building types [22]. Whilst there was a national goal to insulate 2 million solid walls by 2030 [23, 24], progress has been slow [23-26], and low installation in recent years means there is significant work to be done to meet this target. This is mainly due to the fact that adding insulation to solid walls is more expensive and intrusive compared to other forms of insulation, it thus remains less attractive and challenging for energy efficiency policy [27]. Only

9% of the properties with solid walls in Great Britain had already installed wall insulation at the end of 2019 [28].

Adding insulation to solid walls brings various benefits to the stock, including improving energy efficiency, improving comfort, health and wellbeing, as well as supporting fuel security and addressing fuel poverty [29]. However, it also increases the material demand and comes with an embodied carbon price. Insulation is not normally a low environmental embodied impact material due to the energy and resources used during manufacture, the use of blowing agents and the lack of reuse/recycling at the end of life [30]. Therefore, a whole life analysis of insulation is needed to evaluate its overall performance. Currently, limited studies have evaluated the life cycle performance of solid wall insulation during building retrofit. Moncaster, et al. [31] analysed the cradle to grave carbon emissions from applying four types of insulation material in a traditional masonry semi-detached 2 storey house with solid walls. Their results show the embodied carbon from insulation is very low compared with operational carbon saving, which led to a very short carbon payback of around one year. Densley Tingley, et al. [32] compared cradle to gate environmental impacts (including greenhouse gases) of three insulation materials, namely EPS, mineral wool and phenolic foam. Their environmental payback periods in the external wall insulation system for a mid-terrace house with solid walls is calculated and compared. These studies only consider a single building or building type, making their conclusions limited when trying to scale to an age cohort, e.g. the pre-1919 Victorian house stock, due to the inherent diversity that exists within the stock in practice.

1.2 Archetype approach in building stock modelling

Building stock modelling is commonly used to quantify the potential for reducing energy and environmental impact [33], with two main approaches, namely the *top-down* approach and the *bottom-up* approach [34-36]. The bottom-up approach bridges the gap between a building oriented model and an aggregated stock model [37], therefore, it is capable of providing a more detailed inner structure of the building stock [38].

The archetype approach, which identifies archetype buildings to represent the studied stock, is widely applied to support bottom-up models. It has previously been utilized for residential stock energy modelling in the UK [16], the USA [39], China [40], Japan [41] and various EU countries [42-46]. The archetype approach has also been used in building material stock modelling and building stock retrofit life cycle impact analysis. Wiedenhofer, et al. [47] modelled non-metallic minerals material stocks and flows for residential buildings in the EU25 from 2004 to 2009 using 72 archetype buildings generated by Nemry, et al. [48] and Nemry, et al. [49]. Stephan and Athanassiadis [50] applied a bottom-up approach to spatially model building material stocks and quantify their embodied environmental requirements in the City of Melbourne, Australia. 48 building archetypes are generated based on land use, construction year and height, their construction assemblies are defined using expert knowledge in construction and architectural history. Those 48 building archetypes have also been used in their further study to quantify, spatialise and estimate both current material stock and future material replacement flows for all buildings in the City of Melbourne, Australia [3]. Nemry, et al. [49] selected 72 representative building types to study the life cycle impact of different building improvement options at EU-25 level. The building retrofit measures included additional roof insulation, additional facade insulation and new sealing to reduce ventilation losses. Famuyibo, et al. [51] used archetypes to evaluate the life cycle energy and GHG emissions of retrofitting existing Irish housing stocks, although the life cycle assessment has been done for each of the archetypes without scaling up to the whole stock level. Allacker, et al. [52] studied the EU housing stock by using 24 reference residential buildings, with different eco-innovation measures being evaluated by life cycle assessment. Murray, et al. [53] adapted clustering analysis to generate 145 archetypes for residential and non-residential building stock of Switzerland. Those archetypes are further used in multi-objective optimization to identify the optimal building retrofit measures to reduce costs and life cycle CO_2 emissions. Drouilles, et al. [54] used four archetypes to represent the Swiss residential building stock, and evaluated the whole life environmental impacts, including non-renewable primary energy and global warming potential, for archetypes to achieve four different building energy performances. The results from archetypes can be used for strategic planning, with the potential to extend life cycle assessment to neighbourhood or city scale.

1.3 Aim and objectives

In the UK, the current rate of solid wall insulation installations are much slower than desired. Higher rates are likely required to improve the energy efficiency of the stock if the UK is to meet its 2050 net zero ambitions. Given the scale of installation required (7.7 million uninsulated solid wall properties at the end of December 2019 [28]), the choice of material could play an important role in the whole life carbon impacts, in addition to the cost, and installation methods. This study will use an archetype approach to investigate the solid wall insulation of the pre-1919 Victorian house stock in England. The potential insulation material demand is evaluated and whole life analysis of the retrofit is considered for the whole pre-1919 house stock instead of only considering a single building type. This study also compares various types of solid wall insulation material, assessing their whole life carbon emissions. The results from this study are useful when considering material selection for solid wall retrofit treatments. Moreover, the stock level analysis will offer an overview about the total amount of material needed for solid wall whole life treatment, and their corresponding carbon impact. Both results are beneficial to policy making to effectively promote solid wall insulation.

2. Methodology

The methodology applied in this study can be subdivided into four sections, as presented in Figure 1. 1) Identify solid wall insulation material options, together with the respective material characteristics, and thus calculate the required insulation thickness for the different insulation materials. 2) The whole life carbon emissions per unit area of the solid wall is analysed to compare the environmental impact of different insulation materials. The whole life boundary of solid wall insulation goes beyond cradle to gate [55] embodied carbon, it includes the carbon emissions from the product stage, construction process stage, use stage and end of life stage in BS EN 15978 [56]. The carbon payback time has also been calculated to indicate the whole life carbon performance. Depending on the service life of the insulation material (which is taken from literature), the replacement of the insulation layer might happen during the buildings' continuing lifespan, the replacement is assumed to use exactly the same material to achieve identical performance. 3) By considering the on-site U-value range of solid walls, uncertainty analysis has been carried out, including the worst case scenario. 4) The whole life performance of solid wall insulation in pre-1919 Victorian house stock is evaluated using building archetypes and stock characteristics. The detailed implications of these steps are explained in the following sections.

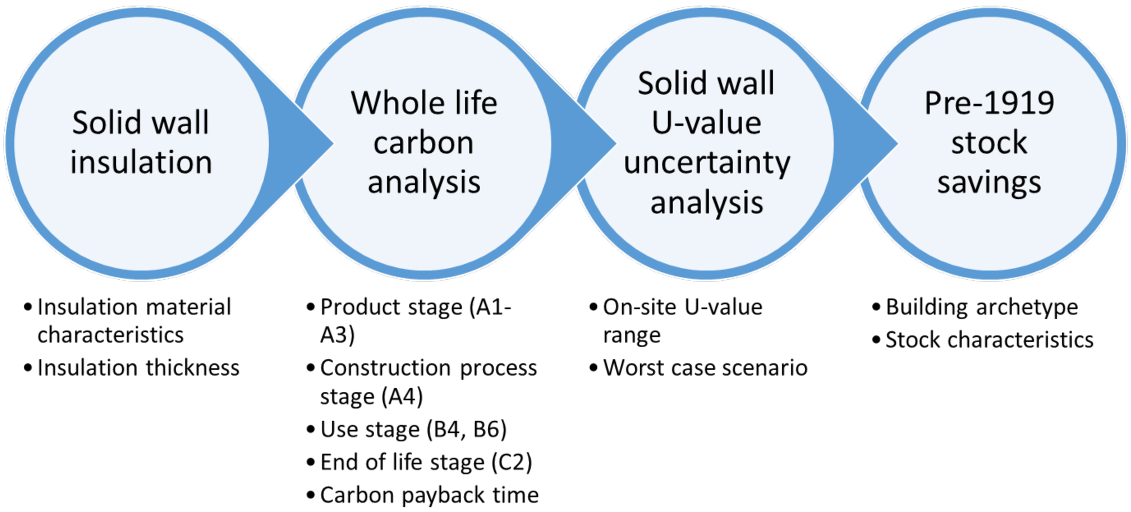

Figure 1: The framework of methodology

2.1 Solid wall insulation

In this paper, eight types of insulation materials that are currently available on the market for solid wall insulation are compared, including vacuum insulated panels (VIPs), aerogel, phenolic foam, polyurethane (PUR), polyisocyanurate (PIR), expanded polystyrene (EPS), glass wool and wood fibre. While the phenolic foam, PUR, PIR, and expanded polystyrene are commonly used for retrofit wall insulation in UK, the other four materials are less common, with VIPs and aerogel typically being more expensive [57]. Their corresponding characteristics, including thermal conductivity, density, cradle to gate embodied carbon and service life are presented in Table 1. For the embodied carbon factors for different insulation materials, the Inventory of Carbon and Energy (ICE) database [58] provides the core of the data used, but as not every insulation material is included yet, data from published journal papers and EPDs have supplemented this to compare a wider range of insulation materials, while maintaining the attributional system modelling approach taken in the ICE [59].

Table 1: The characteristics of different insulation materials

Insulation material	Thermal conductivity (W/(m·K))	Density (kg/m^3)	Cradle to gate embodied carbon factor ($kgCO_2e/kg$)	Service life (year)
Vacuuminsulated panels (VIPs)	0.003 [60]	190 [60]	8.3* [61]	40 [60]
Aerogel	0.015 [62]	150 [62]	8.2 [62]	50 [63]
Phenolic foam	0.022 [57]	40.5 [64]	7.021 [64]	60 [65]
Polyurethane (PUR)	0.025 [66]	30 [66]	4.26 [58]	50 [60]
Polyisocyanurate (PIR)	0.0236 [67]	29 [67]	3.68 [67]	50 [68]
Expanded polystyrene (EPS)	0.04 [66]	15 [66]	3.29 [58]	50 [3]
Glass wool	0.032 [66]	32 [66]	1.35# [58]	60 [69]
Wood fibre	0.038 [70]	40 [70]	0.98# [58]	80 [71]

Note: * The mean of cradle to gate embodied carbon factor of VIP from four different sources in [61];
This cradle to gate embodied carbon factor only covers CO_2 emission.

The typical wall construction for pre-1919 residential buildings is solid walls at least one brick thick with lime mortar [21], with an assumed U-value of 2.1 W/(m²·K) to match with both TABULA typology [72] and SAP [73]. In this study, all eight insulation materials are considered to reduce the U-value of solid wall to meet the UK building regulations, part L1B requirement of maximum 0.3 W/(m²·K) [74], and the higher passivehaus standard requirement of maximum 0.15 W/(m²·K) [75]. Part L1B is the statutory guidance set by building regulation in England for the energy performance of existing dwellings, the target post-retrofit U-value of wall is 0.3 W/(m²·K) when upgrading through external or internal insulation.

The U-value of the wall is calculated using the following equation 1 [76],

$$U = \frac{1}{\mathrm{R}_{si} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \cdots + \frac{d_x}{\lambda_x} + \mathrm{R}_{se}} \quad (1)$$

Where

U is the thermal transmittance of the wall, unit: W/(m²·K);

R_{si} is the internal surface resistance, unit: (m²·K)/W;

$\mathrm{d}_1, \mathrm{d}_2, \cdots, \mathrm{d}_x$ are thickness of the material layer 1,2,x, unit: m;

$\lambda_1, \lambda_2, \cdots, \lambda_x$ are thermal conductivity of material used in layer 1,2,x, unit: W/(m·K);

R_{se} is the external surface resistance, unit: (m²·K)/W.

The thickness of insulation layer added to reduce the U-value of solid wall to meet the aforementioned requirements is calculated following equation 2,

$$T = \lambda \times (1/U_b - 1/U_a) \quad (2)$$

Where U_b and U_a are the thermal transmittance of the wall before and after the retrofit [W/(m²·K)]; T is the thickness of the insulation material [m]; λ is the thermal conductivity of insulation material [W/(m·K)].

2.2 Whole life carbon analysis

The modular structure of a building life cycle in BS EN 15978 [56] has been adopted in this study. Building renovations are generally accompanied with long-term benefits/impacts and these are typically assessed considering a 20-50 years' time period [77]. In this study, 3 life spans will be considered, including 1) 30 years, to match with UK's carbon reduction target in 2050; 2) 50 years, as it's the most commonly used life cycle assessment lifespan value [78, 79]; and 3) 80 years, to evaluate the long term impact until the next century. The whole life carbon analysis in this study considered the following BS EN 15978 life cycle stages: the product stage (A1-A3), construction process stage (A4 transport to project site), use stage (B4 replacement and B6 operational energy use) and end of life stage (C2 transport to disposal facility).

The material consumed for the building life cycle covers both the quantities of building material in-place and those wasted during the construction, as suggested by [80], the material needed from the manufacture process is increased by 5% to account for the construction waste [81, 82]. Moreover, as the service life of insulation materials might be shorter than the life span suggested for the building, insulation will be replaced when it reaches the end of its service life. The mass of insulation material needed per unit of wall area is calculated in equation 3, their corresponding cradle to gate embodied carbon C_P is calculated via the following equation 4.

$$m = \rho \times T \times ceil(L_h / L_i) \times (100\% + r) \quad (3)$$

$$C_P = D \times m \quad (4)$$

Where m is the mass of the insulation material per unit area needed [kg]; ρ is the density of the insulation material [kg/m^3]; L_h is the assumed life span of the house after retrofit [year]; L_i is the service life of the insulation material [year]; r is the construction waste rate [/], which is 5% as discussed above; D is the embodied carbon factor during the production stage [kgCO_2e/kg].

According to the study of Cuéllar-Franca and Azapagic [83] on the life cycle assessment of the UK residential sector, 22t trucks are assumed as the method to transport insulation material. The following assumptions are made in line with Cuéllar-Franca and Azapagic [83], manufacturers' gate to site distance of 50km and the building to demolition waste destination of 30km. For the transportation process, an empty return journey is assumed, this agrees with Babaizadeh, et al. [84] and Moncaster and Symons [85], which results in a total journey load of 50%. The carbon emission factor corresponding to it is 0.20598 kg CO_2e/tonne.km (diesel rigid HGV) [86]. The embodied carbon from transportation per unit area are calculated via the following equation 5-6.

$$C_T = m \times 10^{-3} \times J \times 0.20598 \quad (5)$$

$$C'_T = m \times 10^{-3} \times J' \times 0.20598 \quad (6)$$

Where C_T and C'_T are the embodied carbon per unit area from gate to site and house to demolition waste destination transportation [kg CO_2e/tonne.km]; J and J' are the gate to site and house to demolition waste destination transportation distance [km], which is 50km and 30km respectively.

The installation of insulation on the solid wall will reduce the operational energy needed for indoor thermal comfort control as a lower U-value is achieved. In this study, only heating energy need is considered as majority of household in England do not have an air conditioning units for summer cooling [87]. A simplified heating estimation method using degree days for energy estimation has been applied to calculate the avoided heat flux during the in-use phase, using the following equation 7 [88]:

$$\Delta E = HDD \times (U_b - U_a) \times 24 \frac{hours}{day} /1000 \quad (7)$$

Where ΔE is the annual reduction in energy flow through a unit area [kWh/m^2], the HDD is the annual heating design day [K·day], which has a long term mean of 2175.8 for Great Britain [89], the U_b and U_a are the U-values of the solid wall before and after the installation of insulation [W/(m^2·K)].

To offset the heat loss through the wall and maintain a comfortable internal environment, energy is consumed by heating system, which leads to operational carbon emissions. The corresponding operational carbon emissions avoided per unit area can be calculated in equation 8-9 [88]

$$\Delta C_{annual} = \frac{\Delta E}{\eta} \times F \quad (8)$$

$$\Delta C_{total} = \Delta C_{annual} \times L_h \quad (9)$$

Where ΔC_{annual} and ΔC_{total} are the annual and total operational carbon emission reduction per unit area from solid wall insulation [kg CO_2e], η is the efficiency of the heating system [/]. As the most common form of space heating in the UK [90], gas central heating was assumed to use a natural gas condensing boiler with a efficiency of 90% [91], F is the carbon conversion factor of natural gas, which is 0.18385 kg CO_2e/kWh [86].

The whole life net carbon emission per unit area C_{Net} is calculated to evaluate the overall impact from adapting solid wall insulation, and it is calculated using equation 10.

$$C_{Net} = C_P + C_T + C'_T - \Delta C_{\ total} \quad (10)$$

The carbon payback time (PT) of retrofitting solid walls in the pre-1919 Victorian house stock using various insulation materials is calculated as the ratio between the additional embodied carbon emission from insulation material and the annual operational carbon emission avoided, shown in equation 11. The cradle to gate product and transportation embodied carbon exclude the replacement of insulation material to identify the payback time of a single application of insulation.

$$\mathrm{PT} = \frac{C_P + C_T + C_T'}{\Delta C_{annual}} \quad (11)$$

2.3 Solid wall U-value uncertainty analysis

Although the commonly assumed U-value for solid wall is 2.1 W/(m²·K), the on-site U-value varies from building to building. After measuring 87 solid wall homes in England, Stevens, et al. [92] found that the on-site U-value of solid walls varies between 0.64 W/(m²·K) to 2.52 W/(m²·K). To understand the carbon payback of different insulation materials in real solid walls, whole life carbon analysis has been conducted considering the pre-retrofit U-value of 2.52 W/(m²·K) and 0.64 W/(m²·K). The carbon payback times of insulating the solid walls to meet the after retrofit U-value of 0.3 W/(m²·K) and 0.15 W/(m²·K) are calculated using the same approach illustrated in section 2.1 and 2.2. Moreover, as a lower solid wall U-value both before and after retrofit resulted in a longer carbon payback time, the likely worst case scenario in solid wall insulation carbon payback time is also calculated. It is if a ‘typical’ U-value of 2.1 W/(m²·K) is assumed, but the actual solid wall has a U-value of 0.64 W/(m²·K), the amount of insulation applied to achieve a post-retrofit U-value of 0.15 W/(m²·K) will be calculated based on the higher U-value. Meaning more insulation will be applied than required to achieve the target U-value (although this will also result in a lower U-value).

2.4 Pre-1919 stock savings

An archetype approach is utilized to study the whole life performance of solid wall insulation in the pre-1919 Victorian house stock. During the TABULA project, BRE developed national building typologies representing the residential building stock of England based on dwelling age and built form type [72]. For the pre-1919 residential buildings, 3 typologies are identified, namely single family house pre 1919, terraced house pre 1919 and multifamily house pre 1919. 3 archetypes are identified based on these 3 typologies. The wall surface area of every archetype is the same as the wall surface area of their corresponding typologies in TABULA WebTool [93]. The English house survey 2013 [94] is referenced for the latest information about the dwelling type and their corresponding dwelling age, with the later surveys no longer publishing this breakdown. The pre 1919 dwellings are classified into four types, namely detached, terraced, semi-detached and flat. According to the original assignment of English dwelling types to TABULA built form types [72], detached and flat dwellings are represented by the single family house pre 1919 archetype and multifamily house pre 1919 archetype respectively, while terraced and semi-detached are represented by the terraced house pre 1919 archetype, as semi-detached houses are very similar to end of terrace houses with one shared wall and can be considered as a two-dwelling terrace. The number of pre-1919 dwellings for each archetype is presented in Table 2, the terraced house pre 1919 archetype accounted for 66.3% of the pre-1919 dwellings, followed by multifamily house pre 1919 archetype and single family house pre 1919 archetype. As the housing demolition rate in the UK is lower than 0.3% [13], the demolition of pre-1919 dwellings after 2013 are ignored. The ratio between number of buildings and number of dwellings from the TABULA project [95] has been used to calculate the number of buildings for each pre-1919 residential archetypes.

Table 2: The pre-1919 residential archetypes

Residential archetypes	 Single family house pre 1919	 Terraced house pre 1919	 Multifamily house pre 1919
Number of dwellings	592,000	3,082,000	974,000
Number of buildings	592,000	3,082,000	369,961
Wall surface area per building (m^2)	200.3	89.1	233.3

Note: images of archetypes from BRE typologies, their usage in this paper is approved by BRE

To evaluate the performance of installing solid wall insulation in the whole pre-1919 Victorian house stock until 2050 for the national carbon reduction target, this study considered six future scenarios, with six rates of retrofit, the detailed assumptions are as follows:

1) S1: The annual number of buildings insulated is 18,000. Based on the actual building solid wall insulation installations in 2018 [26].
2) S2: The annual number of buildings being insulated is 36,000, doubling the current solid wall insulation retrofit speed.
3) S3: The annual number of buildings being insulated is 54,000, tripling the current solid wall insulation retrofit speed.

4) S4: The annual number of buildings being insulated is 72,000, four times the current solid wall insulation retrofit speed.
5) S5: The annual number of building been insulated is 90,000, assumed based on the Committee on Climate Change's 2018 indicator in building solid wall insulation [26]
6) S6: As 9% of the properties with solid walls in Great Britain have already been insulated [28], this scenario assumes the rest of uninsulated 91% of pre-1919 Victorian houses are retrofit with solid wall insulation instantly in the first year, as all studied insulation materials have a service life longer than 30 years, no replacement of insulation material is considered before 2050.

For S1 to S5, a gross annual number of buildings being insulated is set, assuming that every residential archetype has an equal possibility of installing solid wall insulation. Thus, the number of buildings being retrofitted in each residential archetype is apportioned according to their ratio of the pre-1919 Victorian house stock. The number of buildings that have been retrofitted annually is calculated using equation 12 for each residential archetype.

$$n_j = N \times \left(\frac{B_j}{\sum_{i=1}^{3} B_j}\right) \quad (12)$$

Where n_j is the annual number of buildings that have had solid wall insulation installed for residential archetypes j [/], N is the gross annual number of buildings being insulated [/], B_j is the number of buildings in the pre-1919 Victorian house stock for residential archetypes j [/], the archetypes including all three shown in Table 2.

The annual wall surface area being retrofitted is calculated via equation 13.

$$A_k = \sum_{j=1}^{3}(n_j \times S_j) \quad (13)$$

Where A_k is the wall surface area being retrofitted annually at the kth year [m^2]; S_j is the wall surface area per building for archetype j [m^2].

For S6, the annual wall surface area being retrofitted is calculated via equation 14.

$$A_k = \begin{cases} \sum_{j=1}^{3}(91\% \times B_j \times S_j), when\ k = 1 \\ 0, when\ k > 1 \end{cases} \quad (14)$$

The carbon performance of solid wall insulation at the whole pre-1919 Victorian house stock level is evaluated annually from 2021 to 2050 considering the above mentioned six scenarios. At the kth year, the stock level annual cradle to gate production embodied carbon $S_{p,k}$ and gate to site transportation embodied carbon $S_{T,k}$ are calculated via equations 15 and 16, while the stock level operational carbon emissions avoided $\Delta S_{O,k}$ and annual net carbon emissions from insulation $S_{net,k}$ are calculated by equation 17 and 18. As the buildings' total wall surface area are used in equation 17, the results are likely to overestimate the operational carbon emissions avoided, as the reduction in heat loss will be less significant when insulating solid party wall compared to solid external wall.

$$S_{p,k} = C_P \times A_k \quad (15)$$

$$S_{T,k} = C_T \times A_k \quad (16)$$

$$\Delta S_{O,k} = \Delta C_{annual} \times \sum_{z=1}^{k} A_z \quad (17)$$

$$S_{net,k} = S_{p,k} + S_{T,k} - \Delta S_{O,k} \quad (18)$$

The accumulated carbon reduction R_k at the kth year is calculated use the following equation 19.

$$R_k = -\sum_{z=1}^{k} S_{net,z} \quad (19)$$

3. Results

3.1 The demand for insulation materials

With a known solid wall U-value before and after the installation of insulation, the thickness needed to achieve a U-value equal or less than 0.3 W/(m²·K) and 0.15 W/(m²·K) can be calculated, the results are presented in Table 3. The material thickness had been rounded up to ensure it meets the required U-value. The thickness of vacuuminsulated panels (VIPs) and aerogel is much thinner than the other insulation materials, which potentially leads to a space saving benefit when applied as internal wall insulation.

Table 3: The insulation material thickness to achieve required U-values

Insulation material	Material thickness [mm]	
	U-value=0.3 W/(m²·K)	U-value=0.15 W/(m²·K)
Vacuuminsulated panels (VIPs)	9	19
Aerogel	43	93
Phenolic foam	63	137

Polyurethane (PUR)	72	155
Polyisocyanurate (PIR)	68	147
Expanded polystyrene (EPS)	115	248
Glass wool	92	199
wood fibre	109	236

The mass of the insulation material needed per unit area to achieve the assumed U-value for brick solid wall is presented in Figure 2. Aiming to achieve a U-value of 0.3 W/(m²·K), when considering a building life extension (post-retrofit) of 30 years, the mass of insulation per unit area ranges from 1.80 kg for vacuum insulated panels to 6.77 kg for aerogel. When increasing the building life extension to 50 years, the mass of insulation per unit area ranges from 1.81 kg for expanded polystyrene to 6.77 kg for aerogel. In this scenario, expanded polystyrene has the lowest weight as the vacuum insulated panels will need to be replaced within the 50 years lifetime extension. Further increases in the building life extension to 80 years will result in a dramatic rise in material mass, from 3.59 kg for vacuum insulated panels to 13.55 kg for aerogel. All insulation materials require replacement once in the lifespan of the building, with the exception of wood fibre which has a service life of 80 years. Similar trends also appear when achieving a U-value of 0.15 W/(m²·K), insulation material mass increasing with a longer building lifetime extension – due to the replacement cycles of the insulation materials. It varies from 3.79 kg for vacuum insulated panels, with a building life extension of 30 years to 29.30 kg for aerogel with a building life extension of 80 years.

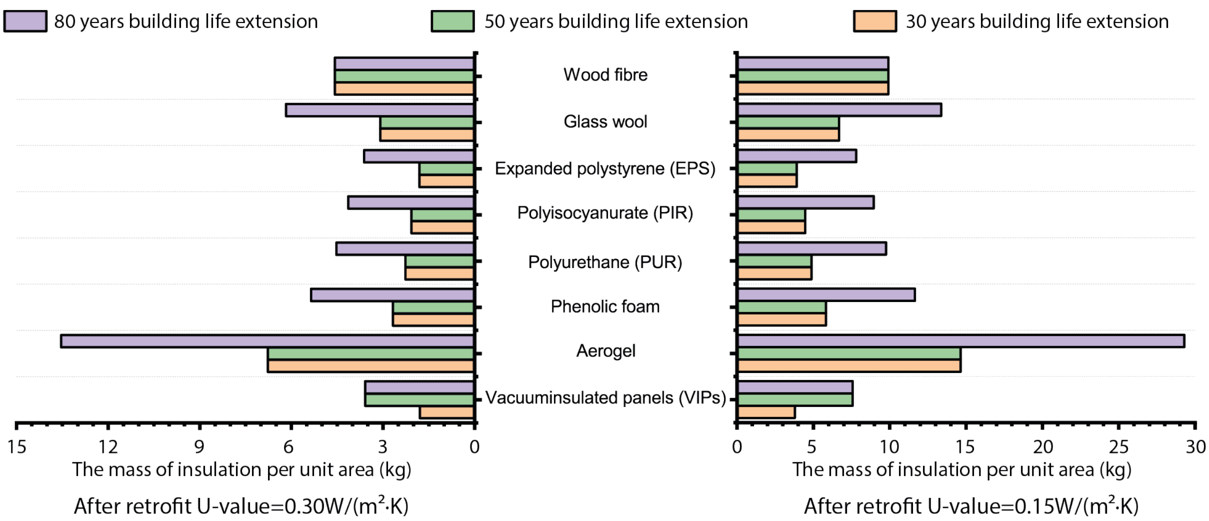

Figure 2 The mass of insulation material per unit area to achieve a post-retrofit U-value of 0.3 W/(m²·K) and 0.15 W/(m²·K)

3.2 The whole life carbon analysis results

The whole life carbon emissions per unit area results are presented in Table 4, including product stage carbon emissions, transportation carbon emissions and saved operational carbon emissions. Whole life net carbon emissions are also calculated to show the overall net carbon impact per unit area of using various insulation material to retrofit the solid walls of pre-1919 Victorian house stock in England.

Table 4: Whole life carbon emission per unit area results (Units: kgCO_2e)

Carbon emission	Post-retrofit		Vacuum insulated panels (VIPs)	Aerogel	Phenolic foam	Plyurethane (PUR)	Polyisocyanurate (PIR)	Expanded polystyrene (EPS)	Glass wool	Wood fibre
	U-value (W/(m²·K))	Building life extension (years)								
Product	0.3	30	14.90	55.53	18.81	9.66	7.62	5.96	4.17	4.49
		50	29.81	55.53	18.81	9.66	7.62	5.96	4.17	4.49
		80	29.81	111.07	37.62	19.32	15.24	11.92	8.35	4.49
Gate to site transportation		30	0.02	0.07	0.03	0.02	0.02	0.02	0.03	0.05
		50	0.04	0.07	0.03	0.02	0.02	0.02	0.03	0.05
		80	0.04	0.14	0.06	0.05	0.04	0.04	0.06	0.05
Saved operational		30	576.03	576.03	576.03	576.03	576.03	576.03	576.03	576.03
		50	960.05	960.05	960.05	960.05	960.05	960.05	960.05	960.05
		80	1536.08	1536.08	1536.08	1536.08	1536.08	1536.08	1536.08	1536.08
House to demolition waste destination transportation		30	0.01	0.04	0.02	0.01	0.01	0.01	0.02	0.03
		50	0.02	0.04	0.02	0.01	0.01	0.01	0.02	0.03
		80	0.02	0.08	0.03	0.03	0.03	0.02	0.04	0.03
Whole life net		30	-561.10	-520.38	-557.18	-566.33	-568.38	-570.04	-571.81	-571.47
		50	-930.19	-904.40	-941.20	-950.35	-952.40	-954.06	-955.83	-955.49
		80	-1506.22	-1424.79	-1498.37	-1516.68	-1520.77	-1524.10	-1527.63	-1531.52
Product	0.15	30	31.46	120.11	40.90	20.80	16.47	12.85	9.03	9.71
		50	62.92	120.11	40.90	20.80	16.47	12.85	9.03	9.71
		80	62.92	240.22	81.81	41.60	32.94	25.70	18.05	9.71
Gate to site transportation		30	0.04	0.15	0.06	0.05	0.05	0.04	0.07	0.10
		50	0.08	0.15	0.06	0.05	0.05	0.04	0.07	0.10
		80	0.08	0.30	0.12	0.10	0.09	0.08	0.14	0.10
Saved operational		30	624.03	624.03	624.03	624.03	624.03	624.03	624.03	624.03
		50	1040.05	1040.05	1040.05	1040.05	1040.05	1040.05	1040.05	1040.05
		80	1664.09	1664.09	1664.09	1664.09	1664.09	1664.09	1664.09	1664.09

House to demolition waste destination transportation		30	0.02	0.09	0.04	0.03	0.03	0.02	0.04	0.06
		50	0.05	0.09	0.04	0.03	0.03	0.02	0.04	0.06
		80	0.05	0.18	0.07	0.06	0.06	0.05	0.08	0.06
Whole life net		30	-592.51	-503.68	-583.03	-603.15	-607.49	-611.12	-614.90	-614.16
		50	-977.01	-919.70	-999.05	-1019.17	-1023.51	-1027.14	-1030.92	-1030.18
		80	-1601.04	-1423.38	-1582.09	-1622.33	-1630.99	-1638.26	-1645.81	-1654.21

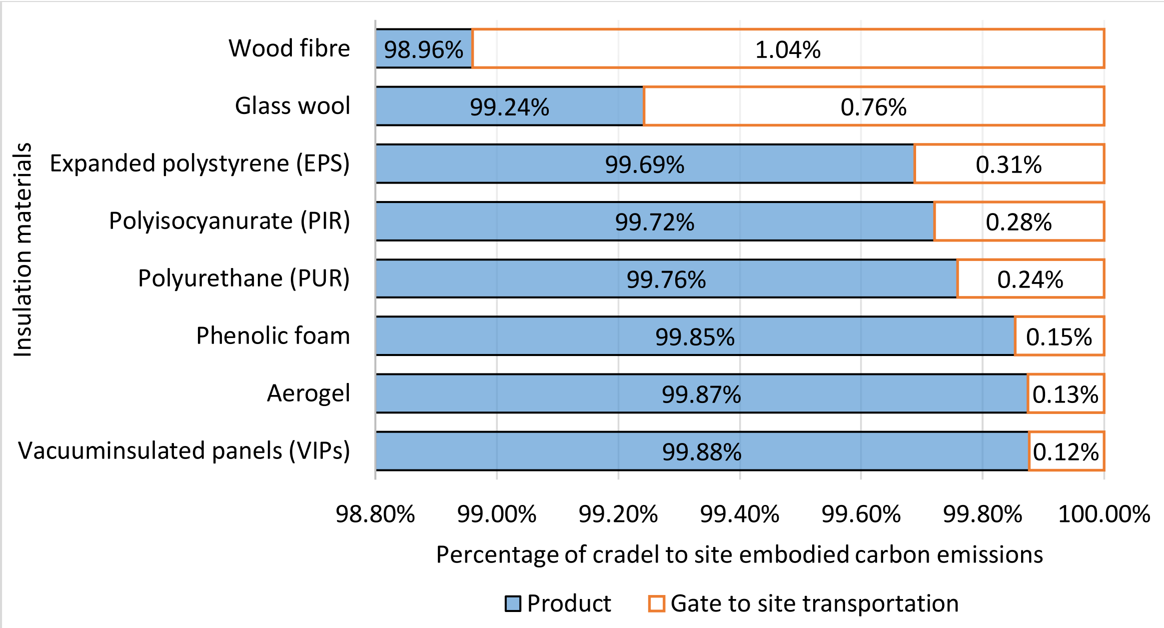

Figure 3 The breakdown of the cradle to site embodied carbon emissions

Looking at the breakdown of the embodied carbon emissions (as show in Figure 3), the gate to site transportation carbon emissions are almost negligible if compared with the cradle to gate product carbon emissions, for all the insulation materials, gate to site transport accounts for less than 1.1% of cradle to site carbon emissions. When the transport distance is increased to 100km and 200km, the carbon emissions from gate to site transportation will increase up to 2.1% and 4.0% of the cradle to site carbon emissions respectively. The cradle to gate product carbon emissions per unit area ranges from 4.17 $kgCO_2e$ (using glass wool to achieve U-value of $0.3W/(m^2{\cdot}K)$, considering a 30 years post-retrofit building life span) to 240.22 $kgCO_2e$ (using aerogel to achieve U-value of $0.15W/(m^2{\cdot}K)$, considering a 80 years post-retrofit building life span). Moreover, it's important to note that the cradle to gate embodied carbon intensity for glass wool and wood fibre only accounts CO_2 emissions, their evaluation of cradle to gate product carbon emission per unit area are thus underestimated.

As proved by calculation results shown in Table 4, although insulating solid walls brings extra embodied carbon emissions, the operational carbon emissions decrease so dramatically that it results in a gross carbon emission reduction considering the whole life cycle. Although the selection of insulation material has a great impact on the carbon emission during the cradle to gate product process and transportation process, their impact on the whole life carbon emissions is diluted due to the significant carbon emissions reduction from operational energy saving. For all scenarios considered above, with different U-values, insulation materials and building life extension times, the whole life carbon emission saving per unit area varies from 503.68 $kgCO_2e$ to 1654.21 $kgCO_2e$. Adding a thicker layer of insulation material to achieve a lower U-value is worthwhile for all materials studied in this study, apart from aerogel. As the whole life net carbon reduction per unit area is higher for a U-value of 0.15W/(m²·K) compared to 0.3W/(m²·K). Moreover, extending the building life span after retrofit should also be promoted as increasing building life extension reduces the whole life carbon emissions.

The carbon payback time of insulating the pre-1919 Victorian house stock using the different materials is presented in Figure 4. The carbon payback time for achieving a U-value of 0.3W/(m²·K) varies from 0.22 years for glass wool to 2.90 years for aerogel. Whilst pursuing a lower U-value of 0.15W/(m²·K) almost doubled the carbon payback time to range from 0.44 years for glass wool to 5.79 years for aerogel. Although lower post-retrofit U-value will have a longer carbon payback time, it is also able to achieve bigger whole life net carbon reduction for all materials except aerogel, as shown in Table 4. Under all scenarios considered in this study, the carbon payback time is less than 6 years. The short payback time of insulating the solid walls for pre-1919 Victorian house stock indicated that they started to reduce whole life carbon emissions very quickly.

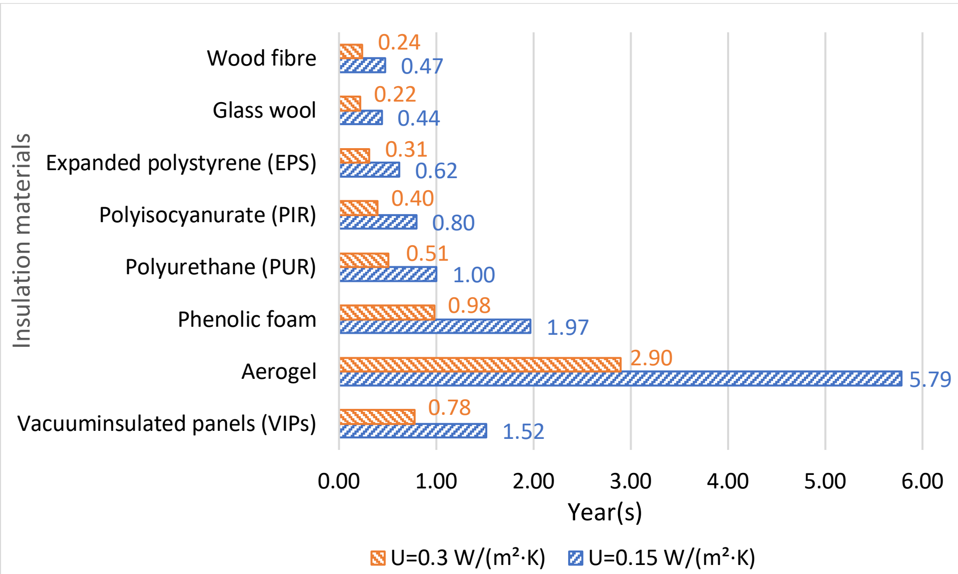

Figure 4 The carbon payback time of solid wall insulation (considering a pre-retrofit U-value of 2.1 W/(m²·K))

3.3 The solid wall U-value uncertainty analysis results

Considering the real solid wall U-value range, to analyse the uncertainty in the U-value assumption of 2.1 W/(m²·K), the carbon payback time range for achieving a post-retrofit U-value of 0.3 W/(m²·K) and 0.15 W/(m²·K) where the starting U-value ranges between 0.64 W/(m²·K) to 2.52 W/(m²·K) is shown in Figure 5. As expected, the solid wall insulation carbon payback times are increased when the solid wall pre-retrofit U-value decreases. However, considering the lowest pre-retrofit U-value, in the worse cases the carbon payback times to achieve an post-retrofit U-value of 0.3 W/(m²·K) and 0.15 W/(m²·K) are less than 10 years and 20 years respectively.

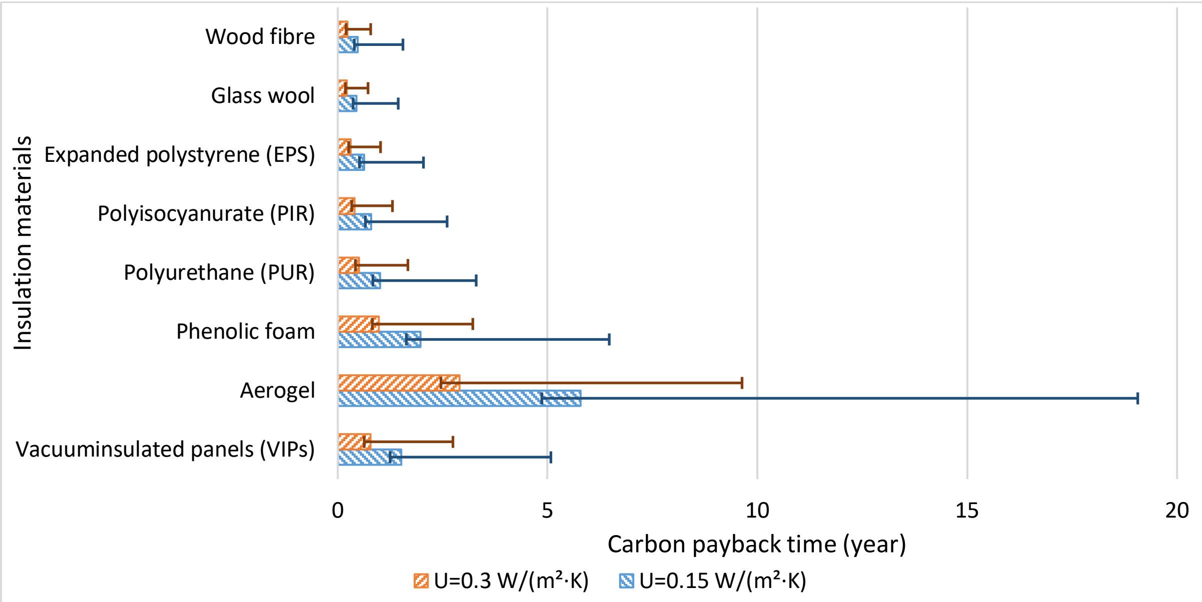

Figure 5 The carbon payback time range of different solid wall insulation materials, considering a pre-retrofit u-value range from 0.64 to 2.52 W/(m²·K)

This worst case carbon payback time of excessive insulation for a solid wall with pre-retrofit U-value of 0.64 W/(m²·K) is presented in Figure 6. This demonstrates that all the materials studied have a carbon payback time of less than 23 years, which is still considerably shorter than material service life.

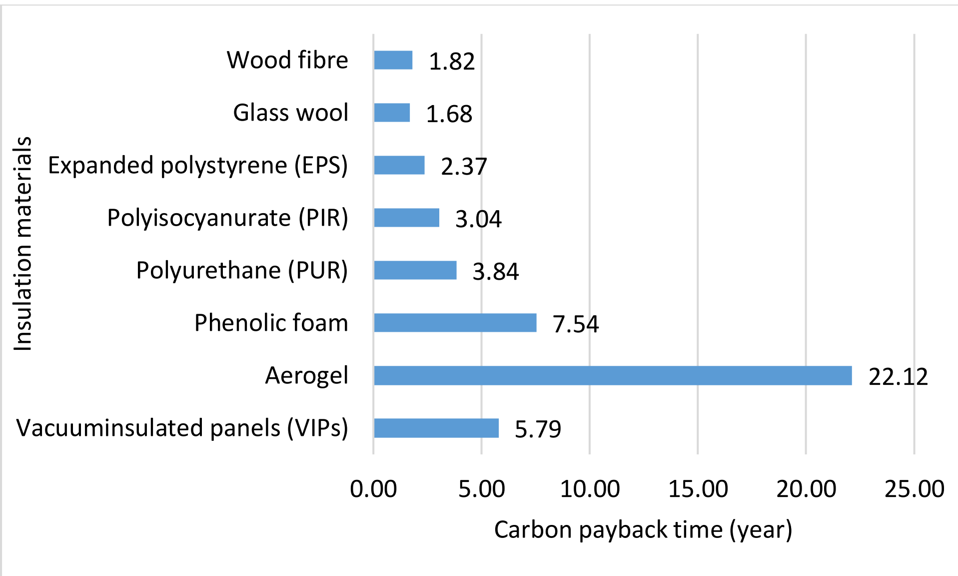

Figure 6 The carbon payback time of solid wall insulation (considering a pre-retrofit U-value of 0.64 W/(m²·K))

3.4 The stock carbon reduction from solid wall insulation

Glass wool is selected as an example to demonstrate the whole life carbon performance under various retrofit speeds for insulating the pre-1919 Victorian house stock with solid wall insulation, as it has the shortest carbon payback time in the eight types of insulation materials analysed in this study. Although, if carbon sequestration was included, wood fibre could be considered to have negative cradle to gate emissions, as for those products [96-98], due to the removal of CO_2 from the atmosphere during tree growth. In this case the end of life treatment is critical, as landfill, or incineration would result in release of greenhouse gases back into the atmosphere, whereas, reuse and then recycling of wood fibre (or indeed other products) would retain the material, and the carbon storage within it. Giving the importance of the end of life treatment on carbon storage, we have not included sequestration in our cradle to site assessment.

Considering the use of glass wool to insulate a solid wall to achieve an post-retrofit U-value of 0.15W/(m²·K) (from a pre-retrofit U-value of 2.1 W/(m²·K)), the annual net carbon emissions for pre-1919 Victorian house stock from 2021 to 2050 is presented in Figure 7. For six scenarios described in section 2.4, all scenarios achieve negative annual carbon emissions. Moreover, as expected, the faster the retrofit speed, the larger carbon reduction from solid wall insulation of pre-1919 Victorian house stock.

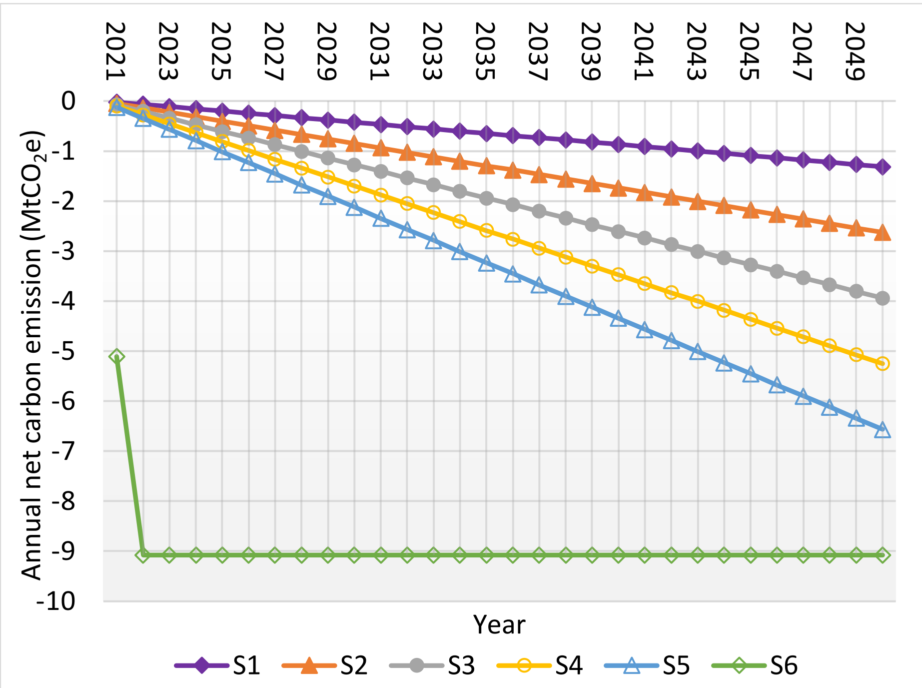

Figure 7 The annual net carbon emissions for the six different installation rate scenarios from insulation

The accumulated carbon reduction for all six scenarios is shown in Figure 8. Through 30 years of applying glass wool solid walls insulation in pre-1919 Victorian house stock, the accumulated carbon reduction in 2050 varies from 20.1 $MtCO_2e$ for S1 to 268.3 $MtCO_2e$ for S6.

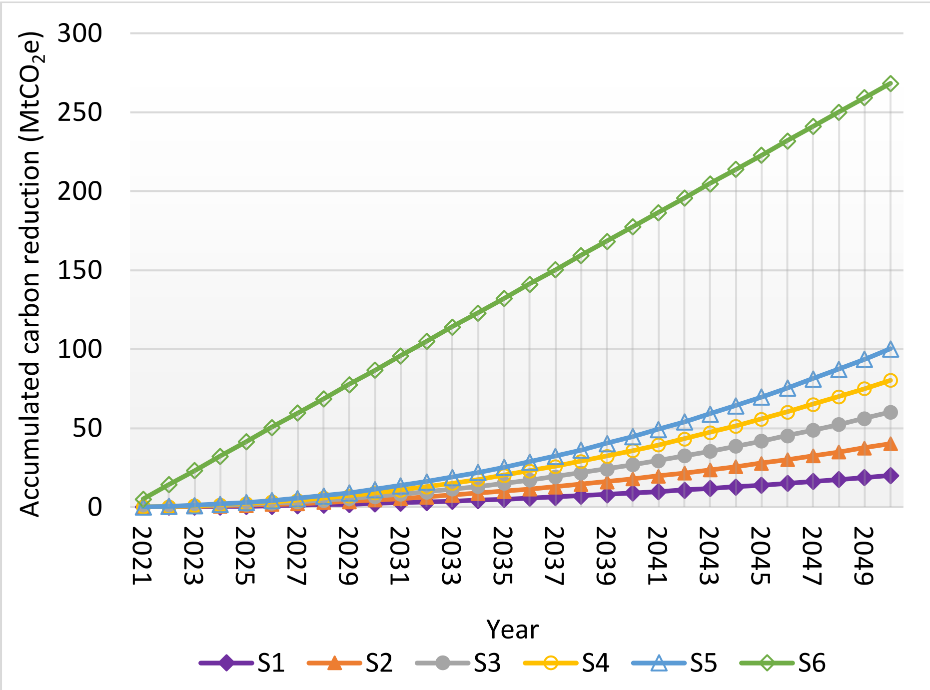

Figure 8 The accumulated carbon reduction for the six different installation rate scenarios

When taking the on-site pre-retrofit U-value ranges between 0.64 W/(m²·K) to 2.52 W/(m²·K) into account, the accumulated carbon reduction of insulating solid walls of pre-1919 Victorian stock to a post-retrofit U-value of 0.15 W/(m²·K) is presented in Figure 9, with two retrofit speeds (S1 and S6) present as examples. Depending on the real pre-retrofit U-value distribution of solid walls in pre-1919 Victorian house stock, the stock level accumulated carbon reduction till 2050 ranges from 4.7 to 24.5 $MtCO_2e$ for S1, and ranges from 65.2 to 326.9 $MtCO_2e$ for S6.

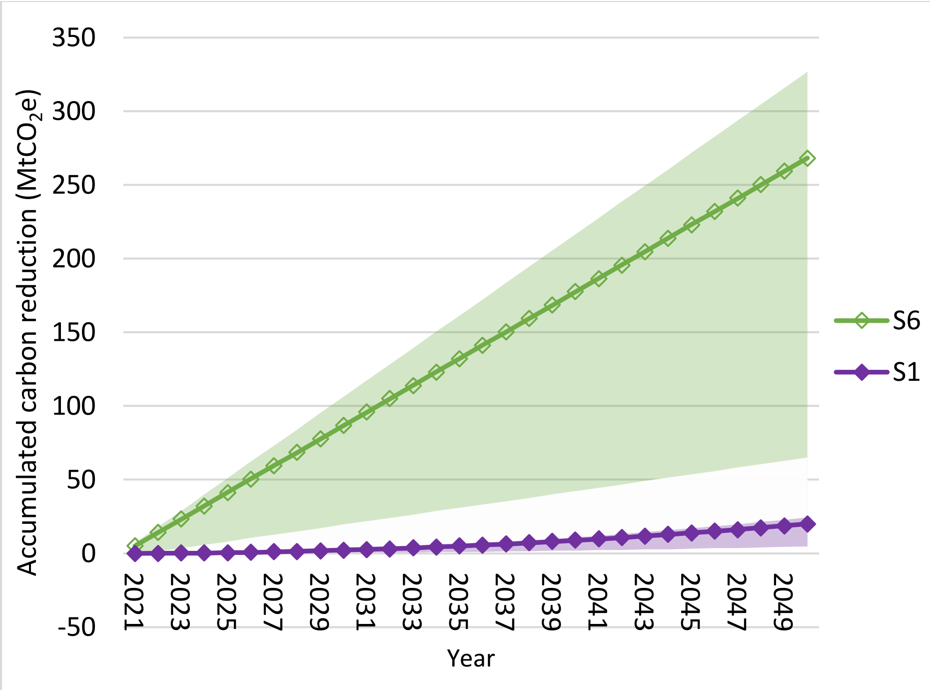

Figure 9 The accumulated carbon reduction range for S1 and S6 considering the pre-retrofit U-value ranges between 0.64 W/(m²·K) to 2.52 W/(m²·K), and post-retrofit U-value of 0.15 W/(m²·K), with the plotted line assumes the pre-retrofit U-value as 2.1 W/(m²·K)

S6 is the only future scenario to have retrofit all uninsulated pre-1919 Victorian houses by 2050, while the number of homes that still need to be retrofit for the other five future scenarios varies from 980,005 (S5) to 3,140,005 (S1) after 2050 .

4. Discussion

This study has analysed the whole life carbon emissions of solid wall insulation of the pre-1919 Victorian house stock in England. By using glass wool, the insulation material with the shortest carbon payback time, reducing the solid wall U-value from 2.1 W/(m²·K) to 0.15 W/(m²·K), the cradle to site embodied carbon emissions to retrofit all uninsulated pre-1919 Victorian house stock is around 4.0 $MtCO_2e$, 0.89% of the UK's 2018 GHG emissions (451.5 $MtCO_2e$ [99]). 30 years of building life extension with this additional insulation results in a maximum carbon reduction of 268.3 MtCO2e. This is equivalent to more than 3.8 times of the impact of the UK's residential direct GHG emissions in 2018 (69.1 $MtCO_2e$ [99]). Thus, insulating the solid walls of the pre-1919 Victorian housing stock has the potential for considerable carbon benefits, and should be considered a critical part of meeting the UK's 2050 net zero greenhouse gas ambitions. However, installation rates are still low, and as shown in our scenario modelling, installation rates need to be rapidly increased for significant carbon benefits to be achieved.

Considering the amount of properties that still have uninsulated solid walls, policy incentives, financial support and other promotion measures are likely to be needed to increase the uptake of solid wall insulation.

This study is based on the assumption of continuing use of natural gas condensing boiler for space heating. However, with the governmental renewable heat scheme like Domestic Renewable Heat Incentive (RHI) [100], biomass boilers, solar water heating and heat pumps could become more popular. A switch from natural gas boilers to other renewable heating sources would also reduce operational carbon emissions. Homes that install renewable heating sources in addition to solid wall insulation would have different embodied carbon payback times to those modelled in this paper, which assesses payback as a result of the reduction in the demand for gas for heating. However, reducing the heat demands of a home (through solid wall insulation) may make renewable heat alternatives more viable to provide comfortable internal temperatures, especially when low-temperature heating is adapted [101], and thus the two solutions would work well in tandem. Solid wall insulation is also likely to reduce fuel poverty and reduce the health impacts of cold homes [29].

4.1 Data availability

A detailed whole life carbon analysis is still challenging due to the limited information available, even for the cradle to gate embodied carbon emissions data. This study uses cradle to gate embodied carbon emission data from trustworthy sources, including the Inventory of Carbon & Energy databases, published journal papers and environmental product declarations. However, currently there are still issues such as non-unified embodied carbon reporting boundaries, the diversity of what types of gas are counted in the carbon emissions, e.g. all greenhouse gases or only carbon dioxide. All cradle to gate embodied carbon emissions of common insulation materials should be undertaken following a standard procedure, e.g. EN 15804 [102], with consensus on the system modelling approach and including all greenhouse gases. More consistent product/material studies of this type would assist in building level assessments. Although there are Environmental Product Declarations (EPD) available for those materials from manufacturer for glass wool [69, 103] and wood fibre [96-98], the cradle to gate varies depending on the manufacturers' detailed production process, e.g. glass wool 0.96 to 1.62 $kgCO_2e/kg$; and wood fibre -1.12 to -0.95 $kgCO_2e/kg$. Therefore, instead of selecting a single EPD value, representative general cradle to gate embodied carbon values from the ICE database have been used in this study. The embodied carbon of glass wool used in the analysis from ICE database is 1.35

kgCO2e/kg, although it's only covers CO_2, it sits nicely in the range of glass wool. The embodied carbon of wood fibre used in the analysis is positive, as carbon sequestration is not integrated into the data of ICE due to global tree populations decline and fail to reach a steady-state balance between consumption and replenishment [104]. Further development of comprehensive, consistent cradle to gate embodied carbon databases (e.g. the Inventory of Carbon and Energy [105]) for use in the built environment would assist wider uptake of embodied carbon calculations, and should ensure comparison studies of different materials are subject to less uncertainty. It is also worth noting that, life cycle assessment has various implicit uncertainties, including those from data variability and quality (parameter uncertainty), methodological choices (scenario uncertainty) and impact assessment methods (model uncertainty) [106]. Future studies could also examine these uncertainties in the context of national whole life carbon stock models. Besides, as large amount of electricity is used in the manufacture of insulation materials, their embodied carbon will likely decrease with the decarbonisation of electricity grid. Therefore, a frequent update of the embodied carbon databases will be beneficial to improve embodied carbon calculations accuracy.

4.2 Internal versus external insulation

In this study, the installation of insulation material on the solid walls is simplified without considering the placement of insulation layer. In real world applications, there are pros and cons for both external and internal wall insulation. Even though external wall insulation avoids the internal surface and space interruption, it can change the building's external aesthetic and thus may be unfavourable, particular for those buildings with facades of architectural and historical merit. The is significant for the pre-1919 Victorian housing stock, considering that a quarter of the dwellings built before 1919 are preserved, including 1.2 million dwellings in conservation areas and about 300,000 individual residential buildings listed as architecturally important [13]. Internal wall insulation is preferable to maintain buildings external appearances. However, there are cases where internal wall insulation might lead to moisture accumulation within the wall [107], which affects both the structural integrity and the health of occupants [108]. Therefore, the placement of insulation materials should be carefully evaluated at an individual building level.

4.3 Limitations of the study

This paper assumes that the thermal performance of insulation material is a constant during its service life, without considering the effect of aging. However, in reality aging will lead to a decrease in insulation thermal resistance [109]. Even for vacuum insulated panels (VIPs), which is commonly recognized as a high-performance thermal insulation solution, climate factors, including temperature, moisture, and pressure will downgrade its thermal performance [110].

With a focus on carbon emissions reduction, this study only considers the whole life carbon performance of the insulation material selection of the solid wall insulation, however, there are other layers in internal or external insulation treatments, e.g. a finish render/plaster, protective mesh, higher rise buildings may require structural support of external insulation. Where the scope is more detailed to the individual building level and considers either external or internal treatment, and building height these elements should be included. In addition, apart from the whole life carbon perspective investigated in this paper, other economical and construction factors, such as the material price, and installation ease will influence the decision making of the insulation material selection.

5. Conclusion

This study has adopted a whole life carbon analysis approach to investigate the solid wall insulation of the pre-1919 Victorian house stock in England. Eight types of insulation materials that are currently available on the market are studied, namely: vacuum insulated panels (VIPs), aerogel, phenolic foam, polyurethane (PUR), polyisocyanurate (PIR), expanded polystyrene (EPS), glass wool and wood fibre. Their whole life carbon emissions considering 30, 50 and 80 years of building life extension have been calculated. Moreover, the stock level carbon reduction performance of different future solid wall retrofit speeds is also compared. The main results from the analysis can be summarised as follows:

- To retrofit solid walls to meet the requirements of current UK building regulations, 1.80kg to 13.55 kg of insulation material is needed per unit area, depending on material used and building life extension; further retrofit to meet the higher passivehaus standard requires insulation material between 3.79kg to 29.30kg per unit area.
- Considering a manufactures' gate to site distance of 50km, the gate to site transport carbon emissions of insulation materials accounted for less than 1.1% of the cradle to site embodied carbon emissions.
- Solid wall insulation leads to a dramatic reduction in operational carbon emissions, which pays back extra embodied carbon emissions from insulation materials and achieves gross carbon emission reduction considering the whole life cycle. The whole life carbon emission saving

varies from 503.68 $kgCO_2e$ to 1654.21 $kgCO_2e$ per unit area considering three post-retrofit building life spans (30, 50 and 80 years) and two post-retrofit U-values (0.3 and 0.15W/(m^2·K).

- The carbon payback time of insulating the solid wall of pre-1919 Victorian house stock with a pre-retrofit U-value of 2.1W/(m^2·K) is very short, less than 6 years. With polyisocyanurate (PIR), expanded polystyrene (EPS), glass wool and wood fibre having a carbon payback time of less than one year.
- Retrofitting solid walls by adding glass wool insulation achieves negative annual carbon emissions. The faster retrofit speed is, the larger carbon reduction in the stock level. The accumulated carbon reduction varies from 20.1 $MtCO_2e$ to 268.3 $MtCO_2e$ when insulating solid walls in the pre-1919 Victorian house stock using glass wool.
- Considering the service life of insulation materials, solid wall insulation is shown to be a carbon efficient retrofit measure for the pre-1919 Victorian house stock in England.

The results from this study highlight the whole life carbon benefits from insulating the solid walls of pre-1919 Victorian house stock. More actions, e.g. policy incentives and financial support should be taken to promote the installation of solid wall insulation to support the UK national carbon reductions target. Furthermore, the results from this study will be applicable to buildings internationally with similar solid wall construction. The archetype whole life carbon method developed could also be applied to building stocks internationally.

Acknowledgment

This research is financially supported by EPSRC UKCRIC-CORONA: City Observatory Research Platform for Innovation and Analytics [Grant numbers: EP/R013411/1] and EPSRC Active Building Centre [Grant numbers: EP/S016627/1].

References

[1] M. Fischer-Kowalski, F. Krausmann, S. Giljum, S. Lutter, A. Mayer, S. Bringezu, Y. Moriguchi, H. Schütz, H. Schandl, H. Weisz, Methodology and Indicators of Economy-wide Material Flow Accounting, Journal of Industrial Ecology, 15 (6) (2011) 855-876.

[2] A. Miatto, H. Schandl, L. Forlin, F. Ronzani, P. Borin, A. Giordano, H. Tanikawa, A spatial analysis of material stock accumulation and demolition waste potential of buildings: A case study of Padua, Resources, Conservation and Recycling, 142 (2019) 245-256.

[3] A. Stephan, A. Athanassiadis, Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks, Resources, Conservation and Recycling, 129 (2018) 248-262.
[4] S. Marinova, S. Deetman, E. Van Der Voet, V. Daioglou, Global construction materials database and stock analysis of residential buildings between 1970-2050, Journal of Cleaner Production, (2019) 119146.
[5] M.J. González, J. García Navarro, Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact, Building and Environment, 41 (7) (2006) 902-909.
[6] B. Huang, F. Zhao, T. Fishman, W.Q. Chen, N. Heeren, E.G. Hertwich, Building Material Use and Associated Environmental Impacts in China 2000-2015, Environ Sci Technol, 52 (23) (2018) 14006-14014.
[7] GOV, (2019). "UK becomes first major economy to pass net zero emissions law." Retrieved 08.12, 2019, from https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law.
[8] NHBC, (2018). "40 facts Homes, housing and house building today." Retrieved 07.02, 2019, from https://www.nhbcfoundation.org/wp-content/uploads/2018/09/NF81-WEB.pdf.
[9] IET, (2018). "Scaling Up Retrofit 2050." from https://www.theiet.org/media/1675/retrofit.pdf.
[10] Z.J. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: Methodology and state-of-the-art, Energy and Buildings, 55 (2012) 889-902.
[11] A. Mastrucci, E. Popovici, A. Marvuglia, L. De Sousa, E. Benetto, U. Leopold, GIS-based Life Cycle Assessment of urban building stocks retrofitting- a bottom-up framework applied to Luxembourg, Atlantis Press, 2015.
[12] A. Mhalas, M. Kassem, T. Crosbie, N. Dawood, A visual energy performance assessment and decision support tool for dwellings, Visualization in Engineering, 1 (1) (2013) 7.
[13] B. Boardman, S. Darby, G. Killip, M. Hinnells, C. Jardine, J. Palmer, G. Sinden. (2005). "40% house. Environmental change institute."
[14] D. Johnston, A physically-based energy and carbon dioxide emission model of the UK housing stock, 2003.
[15] L.D. Shorrock, J.E. Dunster, The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock, Energy Policy, 25 (12) (1997) 1027-1037.
[16] S.K. Firth, K.J. Lomas, A.J. Wright, Targeting household energy-efficiency measures using sensitivity analysis, Building Research & Information, 38 (1) (2010) 25-41.
[17] V. Cheng, K. Steemers, Modelling domestic energy consumption at district scale: A tool to support national and local energy policies, Environmental Modelling & Software, 26 (10) (2011) 1186-1198.
[18] C. Rodrigues, F. Freire, Integrated life-cycle assessment and thermal dynamic simulation of alternative scenarios for the roof retrofit of a house, Building and Environment, 81 (2014) 204-215.
[19] B. Kaveh, M.U. Mazhar, B. Simmonite, M. Sarshar, B. Sertyesilisik, An investigation into retrofitting the pre-1919 owner-occupied UK housing stock to reduce carbon emissions, Energy and Buildings, 176 (2018) 33-44.
[20] MHCLG, (2019). "English Housing Survey data on stock profile." from https://www.gov.uk/government/statistical-data-sets/stock-profile.
[21] C. Turner, R. Partington, Homes through the decades. The making of modern housing, NHBC Foundation, 2015.
[22] CIOB. (2011). "Buildings under refurbishment and retrofit." Carbon Action 2050 White Papers from https://www.ciob.org/sites/default/files/Buildings%20under%20Refurb%20and%20Retrofit.pdf.
[23] CCC. (2018). "Reducing UK emissions 2018: Progress Report to Parliament." from https://www.theccc.org.uk/wp-content/uploads/2018/06/CCC-2018-Progress-Report-to-Parliament.pdf.
[24] CCC. (2017). "Meeting Carbon Budgets: Closing the policy gap 2017 Report to Parliament." from https://www.theccc.org.uk/wp-content/uploads/2017/06/2017-Report-to-Parliament-Meeting-Carbon-Budgets-Closing-the-policy-gap.pdf.
[25] CCC. (2020). "Reducing UK emissions: Progress Report to Parliament." from https://www.theccc.org.uk/publication/reducing-uk-emissions-2020-progress-report-to-parliament/.
[26] CCC. (2019). "Reducing UK emissions: 2019 Progress Report to Parliament." from https://www.theccc.org.uk/publication/reducing-uk-emissions-2019-progress-report-to-parliament.
[27] BRE. (2016). "Solid wall heat losses and the potential for energy saving: Classification of solid walls." from https://www.gov.uk/government/publications/solid-wall-heat-losses-and-the-potential-for-energy-saving.

[28] BEIS. (2020). "Household Energy Efficiency detailed release: Great Britain Data to December 2019." from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/873663/Detailed_Release_-_HEE_stats_19_March_2020.pdf.

[29] P. Hansford. (2015). "Solid Wall Insulations: Unlocking Demand and Driving Up Standards. A Report to the Green Construction Board and Government by the Chief Construction Adviser."

[30] K. Allbury, J. Anderson, Environmental impact of insulation, BRE Electronic Publications, 2011.

[31] A. Moncaster, E. Soulti, M. G, K. Symons, Retrofitting solid wall buildings: energy and carbon costs and savings, 2013.

[32] D. Densley Tingley, A. Hathway, B. Davison, An environmental impact comparison of external wall insulation types, Building and Environment, 85 (2015) 182-189.

[33] M. Österbring, É. Mata, L. Thuvander, H. Wallbaum, Explorative life-cycle assessment of renovating existing urban housing-stocks, Building and Environment, 165 (2019).

[34] M. Kavgic, A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, M. Djurovic-Petrovic, A review of bottom-up building stock models for energy consumption in the residential sector, Building and Environment, 45 (7) (2010) 1683-1697.

[35] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: A review of modeling techniques, Renewable and Sustainable Energy Reviews, 13 (8) (2009) 1819-1835.

[36] V. Augiseau, S. Barles, Studying construction materials flows and stock: A review, Resources, Conservation and Recycling, 123 (2017) 153-164.

[37] M.E. Muñoz Hidalgo, Construction of regional building typologies with a material catalog, Management of Environmental Quality: An International Journal, 27 (6) (2016) 663-680.

[38] T. Lichtensteiger, P. Baccini, Exploration of urban stocks, Journal of Environmental Economics and Management, 18 (1) (2008) 41-48.

[39] J. Sokol, C. Cerezo Davila, C.F. Reinhart, Validation of a Bayesian-based method for defining residential archetypes in urban building energy models, Energy and Buildings, 134 (2017) 11-24.

[40] X. Li, R. Yao, W. Yu, X. Meng, M. Liu, A. Short, B. Li, Low carbon heating and cooling of residential buildings in cities in the hot summer and cold winter zone - A bottom-up engineering stock modeling approach, Journal of Cleaner Production, 220 (2019) 271-288.

[41] Y. Shimoda, Y. Yamaguchi, T. Okamura, A. Taniguchi, Y. Yamaguchi, Prediction of greenhouse gas reduction potential in Japanese residential sector by residential energy end-use model, Applied Energy, 87 (6) (2010) 1944-1952.

[42] E.G. Dascalaki, K.G. Droutsa, C.A. Balaras, S. Kontoyiannidis, Building typologies as a tool for assessing the energy performance of residential buildings – A case study for the Hellenic building stock, Energy and Buildings, 43 (12) (2011) 3400-3409.

[43] I. Ballarini, S.P. Corgnati, V. Corrado, Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project, Energy Policy, 68 (2014) 273-284.

[44] J. Kragh, K.B. Wittchen, Development of two Danish building typologies for residential buildings, Energy and Buildings, 68, Part A (2014) 79-86.

[45] A. Mastrucci, P. Pérez-López, E. Benetto, U. Leopold, I. Blanc, Global sensitivity analysis as a support for the generation of simplified building stock energy models, Energy and Buildings, 149 (2017) 368-383.

[46] C.S. Monteiro, A. Pina, C. Cerezo, C. Reinhart, P. Ferrão, The Use of Multi-detail Building Archetypes in Urban Energy Modelling, Energy Procedia, 111 (2017) 817-825.

[47] D. Wiedenhofer, J.K. Steinberger, N. Eisenmenger, W. Haas, Maintenance and expansion: modeling material stocks and flows for residential buildings and transportation networks in the EU25, Journal of Industrial Ecology, 19 (4) (2015) 538-551.

[48] F. Nemry, A. Uihlein, C.M. Colodel, B. Wittstock, A. Braune, C. Wetzel, I. Hasan, S. Niemeier, Y. Frech, J. Kreißig, Environmental improvement potentials of residential buildings (IMPRO-building), JRC report (ftp. jrc. es/EURdoc/JRC46667. pdf), (2008).

[49] F. Nemry, A. Uihlein, C.M. Colodel, C. Wetzel, A. Braune, B. Wittstock, I. Hasan, J. Kreißig, N. Gallon, S. Niemeier, Y. Frech, Options to reduce the environmental impacts of residential buildings in the European Union—Potential and costs, Energy and Buildings, 42 (7) (2010) 976-984.

[50] A. Stephan, A. Athanassiadis, Quantifying and mapping embodied environmental requirements of urban building stocks, Building and Environment, 114 (2017) 187-202.

[51] A.A. Famuyibo, A. Duffy, P. Strachan, Achieving a holistic view of the life cycle performance of existing dwellings, Building and Environment, 70 (2013) 90-101.

[52] K. Allacker, V. Castellani, G. Baldinelli, F. Bianchi, C. Baldassarri, S. Sala, Energy simulation and LCA for macro-scale analysis of eco-innovations in the housing stock, The International Journal of Life Cycle Assessment, 24 (6) (2019) 989-1008.
[53] P. Murray, J. Marquant, M. Niffeler, G. Mavromatidis, K. Orehounig, Optimal transformation strategies for buildings, neighbourhoods and districts to reach CO2 emission reduction targets, Energy and Buildings, 207 (2020).
[54] J. Drouilles, S. Aguacil, E. Hoxha, T. Jusselme, S. Lufkin, E. Rey, Environmental impact assessment of Swiss residential archetypes: a comparison of construction and mobility scenarios, Energy Efficiency, 12 (6) (2019) 1661-1689.
[55] RICS, Whole life carbon assessment for the built environment, 2017.
[56] BSI, BS EN 15978: 2011, Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method, (2011).
[57] J. Palmer, N. Terry. (2017). "Solid Wall Insulation: Best Practice and Innovation." from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/658604/BEIS_-_SWI_Innovation_Final_Report_-_FINAL_Approved.pdf.
[58] C. Jones, G. Hammond, Inventory of carbon & energy (ICE) V3.0 - 7 Nov 2019, 2019.
[59] G. Hammond, C. Jones, Embodied Carbon: The Inventory of Carbon and Energy (ICE), BSRIA Guide BG 10/2011, Building Services Research and Information Association: Berkshire, (2011).
[60] J. Kono, Y. Goto, Y. Ostermeyer, R. Frischknecht, H. Wallbaum, Factors for Eco-Efficiency Improvement of Thermal Insulation Materials, Key Engineering Materials, 678 (2016) 1-13.
[61] P. Karami, N. Al-Ayish, K. Gudmundsson, A comparative study of the environmental impact of Swedish residential buildings with vacuum insulation panels, Energy and Buildings, 109 (2015) 183-194.
[62] Aspen Aerogels Inc., (2015). "Spaceloft® Aerogel Insulation Environmental Product Declaration." Retrieved 09.28, 2020, from https://www.environdec.com/Detail/?Epd=10953.
[63] S.S. Filate, Investigation of an energy refurbishment concept for office building using Nanogel® Aerogel insulation plaster and replaced windows by building simulation, Master Programme in Energy Technology, Uppsala Universitet, (2014).
[64] D.D. Tingley, A. Hathway, B. Davison, D. Allwood, The environmental impact of phenolic foam insulation boards, Proceedings of the Institution of Civil Engineers-Construction Materials, 170 (2) (2017) 91-103.
[65] BRE, (2018). "Environmental Product Declaration." from http://www.greenbooklive.com/filelibrary/EN_15804/EPD/BREGENEPD000200.pdf.
[66] CIBSE, CIBSE Guide A: Environmental design, The Chartered Institution of Building Services Engineering, 2019.
[67] K. Biswas, S.S. Shrestha, M.S. Bhandari, A.O. Desjarlais, Insulation materials for commercial buildings in North America: An assessment of lifetime energy and environmental impacts, Energy and Buildings, 112 (2016) 256-269.
[68] M. Gravit, A. Kuleshin, E. Khametgalieva, I. Karakozova, Technical characteristics of rigid sprayed PUR and PIR foams used in construction industry, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2017, pp. 012187.
[69] Saint-Gobain Denmark A/S ISOVER, (2016). "ENVIRONMENTAL PRODUCT DECLARATION." from https://www.glava.no/sitefiles/1/BREEAM/EPD_Lameltag_tilGlava.pdf.
[70] NATUFLEX. " NATURAL WOOD FIBRE INSULATION." from https://www.blackmountaininsulation.com/NatuFlex_Brochure.pdf.
[71] F. Werner, R. Taverna, P. Hofer, K. Richter, Carbon pool and substitution effects of an increased use of wood in buildings in Switzerland: first estimates, Annals of Forest Science, 62 (8) (2005) 889-902.
[72] BRE, (2014). "Building Typology Brochure England." from http://episcope.eu/fileadmin/tabula/public/docs/brochure/GB_TABULA_TypologyBrochure_BRE.pdf.
[73] BRE, (2012). "The government's standard assessment procedure for energy rating of dwellings." from https://www.bre.co.uk/filelibrary/SAP/2012/SAP-2012_9-92.pdf.
[74] HM Government, Approved Document L1B: conservation of fuel and power in existing dwellings, 2010 edition (incorporating 2010, 2011, 2013, 2016 and 2018 amendments), 2018.
[75] Passive House Institute, (2019). "Passive House requirements." from https://passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm.
[76] BSI, Building components and building elements–thermal resistance and thermal transmittance–calculation method [BS EN ISO 6946:2017], 2017.

[77] T. Häkkinen, A. Ruuska, S. Vares, S. Pulakka, I. Kouhia, R. Holopainen, Methods and concepts for sustainable renovation of buildings, VTT Technical Research Centre of Finland: Espoo, Finland, (2012).
[78] M. Beccali, M. Cellura, M. Fontana, S. Longo, M. Mistretta, Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits, Renewable and Sustainable Energy Reviews, 27 (2013) 283-293.
[79] B. Palacios-Munoz, B. Peuportier, L. Gracia-Villa, B. López-Mesa, Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach, Building and Environment, 160 (2019) 106203.
[80] C.K. Chau, T.M. Leung, W.Y. Ng, A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings, Applied Energy, 143 (2015) 395-413.
[81] A. Abd Rashid, J. Idris, S. Yusoff, Environmental Impact Analysis on Residential Building in Malaysia Using Life Cycle Assessment, Sustainability, 9 (3) (2017).
[82] B. Rossi, A.-F. Marique, M. Glaumann, S. Reiter, Life-cycle assessment of residential buildings in three different European locations, basic tool, Building and Environment, 51 (2012) 395-401.
[83] R.M. Cuéllar-Franca, A. Azapagic, Environmental impacts of the UK residential sector: Life cycle assessment of houses, Building and Environment, 54 (2012) 86-99.
[84] H. Babaizadeh, N. Haghighi, S. Asadi, R. Broun, D. Riley, Life cycle assessment of exterior window shadings in residential buildings in different climate zones, Building and Environment, 90 (0) (2015) 168-177.
[85] A.M. Moncaster, K.E. Symons, A method and tool for ‘cradle to grave’ embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards, Energy and Buildings, 66 (2013) 514-523.
[86] BEIS, (2019). "Greenhouse gas reporting: conversion factors 2019." from https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019.
[87] BRE. (2013). "Domestic appliances, cooking & cooling equipment." from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/274778/9_Domestic_appliances__cooking_and_cooling_equipment.pdf.
[88] M.H. Mazor, J.D. Mutton, D.A.M. Russell, G.A. Keoleian, Life Cycle Greenhouse Gas Emissions Reduction From Rigid Thermal Insulation Use in Buildings, Journal of Industrial Ecology, 15 (2) (2011) 284-299.
[89] BEIS, (2019). "Digest of UK Energy Statistics (DUKES): weather." GOV.UK, from https://www.gov.uk/government/statistics/weather-digest-of-united-kingdom-energy-statistics-dukes.
[90] MHCLG. (2018). "English Housing Survey Energy efficiency 2016." from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/724339/Energy_efficiency_2016.pdf.
[91] B. Greening, A. Azapagic, Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK, Energy, 39 (1) (2012) 205-217.
[92] G. Stevens, J. Bradford, U. Do, Do U-value insulation? England’s field trial of solid wall insulation, ECEEE Summer Study Proceedings, 2013, pp. 1269-1280.
[93] (2015). "TABULA WebTool." from http://webtool.building-typology.eu/#bm.
[94] DCLC. (2015). "English housing survey 2013: profile of English housing report." from https://www.gov.uk/government/statistics/english-housing-survey-2013-profile-of-english-housing-report.
[95] BRE, (2013). "Building Typolog GB Great Britain / England." Retrieved 02.05, 2020, from https://episcope.eu/building-typology/country/gb.
[96] GUTEX, (2015). "Wood Fibre Insulating Boards Environmental Product Declaration." Retrieved 09.28, 2020, from https://foursevenfive.com/content/product/thermal_insulation/thermowall/epd_declaration_gutex.pdf.
[97] STEICO SE, (2016). "Environmental Product Declaration." Retrieved 07.16, 2020, from https://www.steico.com/fileadmin/steico/content/pdf/Certificates_-_Documents/English__multiple_markets_/STEICO_EPD-STE-20150327-IBD1-EN.pdf.
[98] Holzwerk Gebr. Schneider GmbH, (2016). "Wood-fibre insulation boards best wood FLEX 50 Environmental Product Declaration." Retrieved 09.28, 2020, from https://www.schneider-holz.com/fileadmin/redaktion/pdf_FR/Actualit%C3%A9s/Wood-fibre_insulation_boards_best_wood_FLEX_50.pdf.
[99] BEIS, (2020). "2018 UK Greenhouse Gas Emissions, Final figures." Retrieved 07.14, 2020, from https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2018.

[100] GOV, (2015). "Domestic Renewable Heat Incentive (RHI)." GOV.UK Retrieved 07.16, 2020, from https://www.gov.uk/domestic-renewable-heat-incentive.

[101] Q. Wang, A. Ploskić, S. Holmberg, Retrofitting with low-temperature heating to achieve energy-demand savings and thermal comfort, Energy and Buildings, 109 (2015) 217-229.

[102] BSI, BS EN 15804:2012+A2:2019 Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products, British Standards Institute, London, 2012.

[103] Tasman Insulation, (2019). "Environmental Product Declaration for Tasman Insulation: Pink® Batts glass wool ® insulation: segments, blankets and boards." Retrieved 09.28, 2020, from https://www.environdec.com/Detail/?Epd=13363.

[104] G.P. Hammond, C.I. Jones, Embodied energy and carbon in construction materials, Proceedings of the Institution of Civil Engineers - Energy, 161 (2) (2008) 87-98.

[105] Circular Ecology, (2020). "Embodied Carbon - The ICE Database." Retrieved 08.06, 2020, from https://circularecology.com/embodied-carbon-footprint-database.html.

[106] N. Bamber, I. Turner, V. Arulnathan, Y. Li, S. Zargar Ershadi, A. Smart, N. Pelletier, Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment: review of current practice and recommendations, The International Journal of Life Cycle Assessment, 25 (1) (2020) 168-180.

[107] R. Walker, S. Pavía, Thermal and moisture monitoring of an internally insulated historic brick wall, Building and Environment, 133 (2018) 178-186.

[108] V. Marincioni, G. Marra, H. Altamirano-Medina, Development of predictive models for the probabilistic moisture risk assessment of internal wall insulation, Building and Environment, 137 (2018) 257-267.

[109] H.-J. Choi, J.-S. Kang, J.-H. Huh, A Study on Variation of Thermal Characteristics of Insulation Materials for Buildings According to Actual Long-Term Annual Aging Variation, International Journal of Thermophysics, 39 (1) (2017) 2.

[110] E. Wegger, B.P. Jelle, E. Sveipe, S. Grynning, A. Gustavsen, R. Baetens, J.V. Thue, Aging effects on thermal properties and service life of vacuum insulation panels, Journal of Building Physics, 35 (2) (2011) 128-167.