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Carbon evaluation considering a hygrothermal performance comparison of stone wall retrofits

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Abstract: Improving the thermal performance of walls by adding or increasing insulation is one of the first considerations for reducing heat loss in existing buildings. In most situations, the selection of materials is determined by the cost and reduction of thermal conductance, most likely choosing high embodied carbon materials used reduce becoming a counterintuitive process increasing the building's overall retrofit carbon intensity.

Through this research, hygrothermal performance for specific solid stone walls and the selection of insulation materials, whether they are synthetic or natural in their origin, were evaluated by comparing the embodied carbon of the products from cradle to grave boundary conditions. In addition, the research explores the potential benefits of using natural insulation products manufactured in the UK and the carbon intensity benefits it presents.

Two scenarios were evaluated involving a minor retrofit (MiR), with a U-value of 0.50 W/m²K and a major retrofit (MaR) with a U-value of 0.22 W/m²K. The distinction between the thermal improvements depended on the selected insulation type and the thickness required to meet the established U-values and hygrothermal considerations. The comparison included wood fibre insulation products using 100% softwood (100SW) fibres and one with a blend of 80% softwood and 20% hardwood (80SW-20HW) fibres, against PIR insulation boards.

The research demonstrates the advantages of using hardwood insulation (80SW-20HW), with a 16% saving in material thickness against the 100SW boards to reach the same U-values, and with the lowest level of moisture accumulated on the wall when compared to both traditional wood fibre and PIR boards.

The benefits of using the 80SW-20HW are explicated when the GWP is taken into account, with a saving of 29% and 24% against 100SW, respectively for MiR and MaR. In comparison with PIR, the 80SW-20HW boards guarantee a saving of 15% for MiR, and 52% for MaR. However, wood fibreboards are mainly imported, and greater advantages on the GWP will be achieved if the products are manufactured locally. This study shows how the GWP could be further reduced, up to 60% against PIR boards, if the 80SW-20HW is made in the UK.

Keywords: wood fibre insulation; condensation risk; embodied energy; carbon footprint.

1. Introduction

Of total UK GHG emissions, 18% are associated with housing (LETI, 2021), mostly attributed to poorly delivered new homes and high energy demands of older existing housing. Improving the performance of these existing homes is a crucial action of the UK Government's strategy towards net zero performance of the built environment. The highest heat loss across a building envelope is attributed to the external envelope, 35% according to Yaman (2021), most of which could be reduced by adding insulation.

The benefits of natural fibre insulation products have been widely explored, with different studies demonstrating its adaptability and hygrothermal benefits as well as its lower global warming potential (GWP), also known as embodied carbon.

Densley Tingley, *et al*. (2015) have shown that, with or without taking into account the carbon sequestration of these materials, wood fibre boards present the lowest GWP when compared to PIR, Rockwool, expanded polystyrene and phenolic foam. Similar results were confirmed by Grazieschi, *et al.* (2021), analysing the embodied energy of products, identifying wood fibre boards as being the highest energy consumers during its production stages relying on up to 70% of renewable primary energy (PER).

Despite the GWP benefits of certain natural products, a preference for products with lower thermal conductivity values is adopted for optimal retrofit projects as shown by Walker and Pavía (2015). However, work by Volf, *et al.* (2015) confirms that thermal conductivity should not be the only consideration in the selection of insulation products, as indoor benefits such as humidity and temperature buffering improve better delivered by natural fibre materials can contribute significantly to homes indoor air quality and thermal comfort of occupants.

Previous studies focus on analysing specific characteristics of the insulation materials such as environmental impact, thermal conductivity, etc.). Meanwhile, Lee *et al.* (2019) suggested pursuing a holistic approach that takes into consideration a range of variables.

Considering the above, this study aims to explore the benefits of using wood fibre boards made with a blend of softwood and hardwood as suggested by Imken, Kraft and Mai (2021). This paper explores various objectives focused on not just reaching a similar thermal performance (U-value), but equally considering condensation risk analysis and the embodied carbon of such product from cradle to grave. To achieve this, results and analysis seek to demonstrate the distinctions between the manufacturing and delivery of such products, with the end-of-life showing disposal, recycling and re-use of such insulation materials.

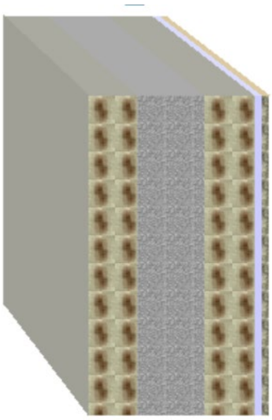
2. Methodology and materials selection

2.1. Methodology

To accomplish the evaluation of this study a pre-1919 tenement flat is used as a common, often poorly performing, archetype in Scotland; as described by the Scottish Government (Scottish Government, 2019b) and by Piddington *et al.* (2020). Often the external walls of these buildings used traditionally built masonry made of 600mm local sandstone and interior lath and plaster finishing, presenting a typical U-value of 1.0 ±0.2 W/m^2K (Baker, 2011; Jenkins and Curtis, 2021).

The existing wall was modelled using the BuildDesk-U software. Taking into consideration the inconsistency of the wall due to the stones' sizes and the presence of the mortar, a simplified stratification was used, with 30% sandstone, 40% mortar, and 30% sandstone, see Figure 1. In accordance to Baker (2011), and Jenkins and Curtis (2021) the final U-value of the wall is 1.13 W/m^2K.

Figure 1. Final configuration of the existing wall

Existing wall		
	*U= 1.13 W/m²K*	
	RT= 0.89 m²K/W	
	Wall Build Up	**Thickness [mm]**
	Sandstone	180
	Limestone mortar	240
	Sandstone	180
	Unventilated air layer	25
	Render, lime and sand	25
	Total thickness	650

The holistic approach of this study looked at the U-value of the upgraded wall as the independent variable.

Following the Scottish Government directives, section *6.2.11 "Alterations to the insulation envelope"* of *Scottish Technical Handbook – Domestic* (Scottish Government, 2022), a U-value of 0.22 W/m^{2}K may be achieved in case of envelope alteration. However, this value should be reached if "*reasonably practicable*" (Scottish Government, 2022). In light of the above a higher U-value, of 0.50 W/m^{2}K, was also selected, having two main scenarios, Minor Retrofit (MiR), with U=0.50 W/m^{2}K and Major Retrofit (MaR) with U=0.22 W/m^{2}K.

The insulation materials under investigation were selected based on the knowledge of the benefits of using wood fibre insulation products for retrofit projects (Jenkins and Curtis, 2021). The study conducted by Imken, Kraft and Mai (2021) suggests wood fibre boards made with 80% softwood and 20% hardwood (80SW-20HW) have a 16% lower thermal conductivity value than the traditional wood fibre boards (100SW), consequently, the two products have been compared. In addition, PIR boards were selected as a sample, due to their low value of thermal conductivity, U=0.02 W/mK, and taking into consideration their presence in the UK insulation market.

For the 100SW, variations in the density and thermal conductivity are recorded for different thicknesses. 100SW boards, with a thickness lower than 80mm, have a thermal conductivity of 7%, and a density of 38% higher than 100SW boards with a thickness above 100mm (Suprema, 2022). The same proportions were applied to the 80SW-20HW boards.

The U-values of the upgraded wall were undertaken using the software BuildDesk-U. The two wood fibre boards, 100SW and 80SW-20HW were modelled as directly applied to the existing wall with a breathable adhesive. Mechanical fixings, 6/m^2, were selected for the simulations, as suggested by the Wood Fibre Insulation Academy (2023). With PIR boards, the existing render was removed, and the boards were installed mechanically to timber battens.

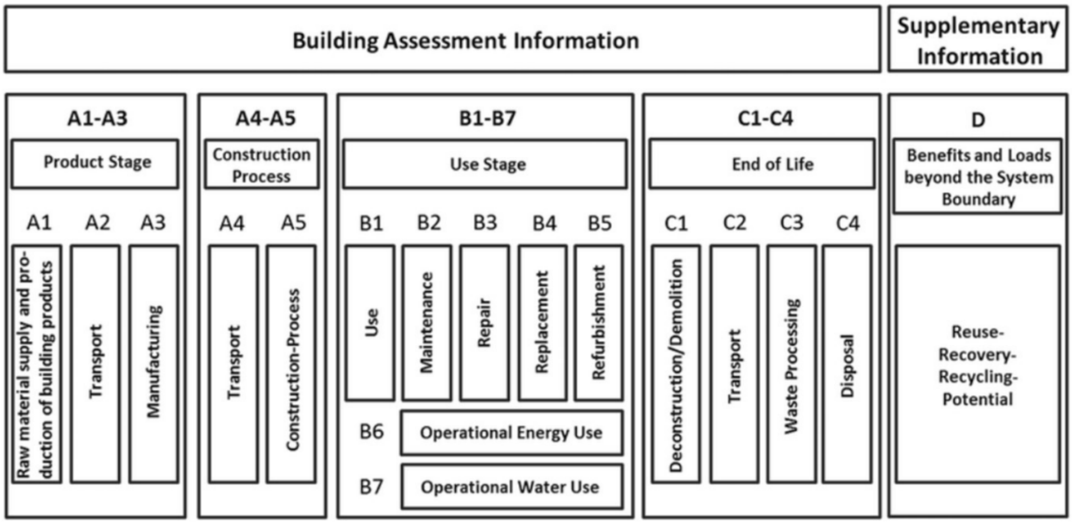
With the BuildDesk-U software, a hygrothermal evaluation of the upgraded wall was also undertaken, considering the presence and absence of an air and vapour control layer (AVCL). This evaluation allows us to understand the condensation risks that may occur when a wall is insulated internally.

The CRAs were assessed with the Glaser method, according to the BS5250 and BS EN ISO 13788 standards. Nevertheless, the static approach of the Glaser method has its constraints. Previous case studies indicate that the use of natural insulation materials creates a state of equilibrium within the wall (Little *et al*., 2015; Baker, 2016; AECB, 2016). The research by Little *et al*. (2015) shows how with the Glaser method none of the insulation products under investigation passed the risk assessment when the AVCL was not applied.

However, with the numerical simulation, it was possible to establish that the RH on the wall, upgraded with phenolic foam, was accumulating during the time. The case study conducted by AECB (2016) proves how the Glaser method overestimates the RH that may occur on the external wall when wood fibreboards are in place. Nonetheless, the in-situ measurements of the AECB (2016) case study, point out that moisture may occur between the cold side of the wood fibre insulation.

To evaluate the effects of the retrofit interventions in terms of embodied carbon (EC), the life cycle analysis (LCA) was conducted covering stages A1-A5, and C1-C4 and D of the BS EN 15978 standard (BSI Standards Publication, 2011). Supporting guidance by the Royal Institution of Chartered Surveyors (RICS) (2017), and the Institution of Structural Engineers (Gibbons and Orr, 2022) were also used.

Figure 2. System boundaries according to BS EN 15978



Finally, to understand the impact of Module A4, transportation, two extra scenarios were set, considering the wood fibre insulation products manufactured first in Europe, and then in the UK. Module A4 was calculated according to the following formula (RICS, 2017; Gibbons and Orr, 2022):

- A4= Material mass (a) x transport distance (b) x carbon conversion factor (c).
- Embodied carbon factor (ECF)= b x c

The default ECF values for Module A4 for the UK were selected according to Table 1.

Table 1. Default EFC values for Modula A4 for the UK (Gibbons and Orr, 2022)

A4 transport scenario	Km by road	Km by sea	ECF A4 ($kgCO_2e/kg$)
Locally manufactured e.g. concrete, aggregate, earth.	50	-	0.005
Nationally manufactured e.g. plasterboard, blockwork, insulation	300	-	0.032
European manufactured e.g. CLT, façade modules, carpet	1500	-	0.160
Globally manufactured e.g. specialist stone cladding	200	10,000	0.183

ECF selected for this study

For the LCA, data were extrapolated from the Environmental Product Declaration (EPD) of existing products on the market. Data of the 80SW-20HW were taken from the 100SW EPD, Pavafrance SAS (2020). The declared functional unit of the 100SW EPD is $1m^3$, with a conversion factor of 1kg equal to 0.005 (Pavafrance SAS, 2020). The above conversion factor was applied to the 80W-20HW boards, considering the different densities of the two products. In addition, an area of $50m^2$ was hypostatised to be covered by the insulation materials.

The initial operational energy, B-6 was calculated considering the Energy Performance Certificate (EPC) of an existing building in Scotland, as reported in Table 2.

Table 2. Building characteristics

Total floor area (FA)	Operational energy consumption	Annual energy consumption
84 m^2	295 $kWh/m^2/year$	24780 kWh/year

Following the (Scottish Government (2019a) guideline, the average household consumption by end-use has been calculated as shown in Table 3.

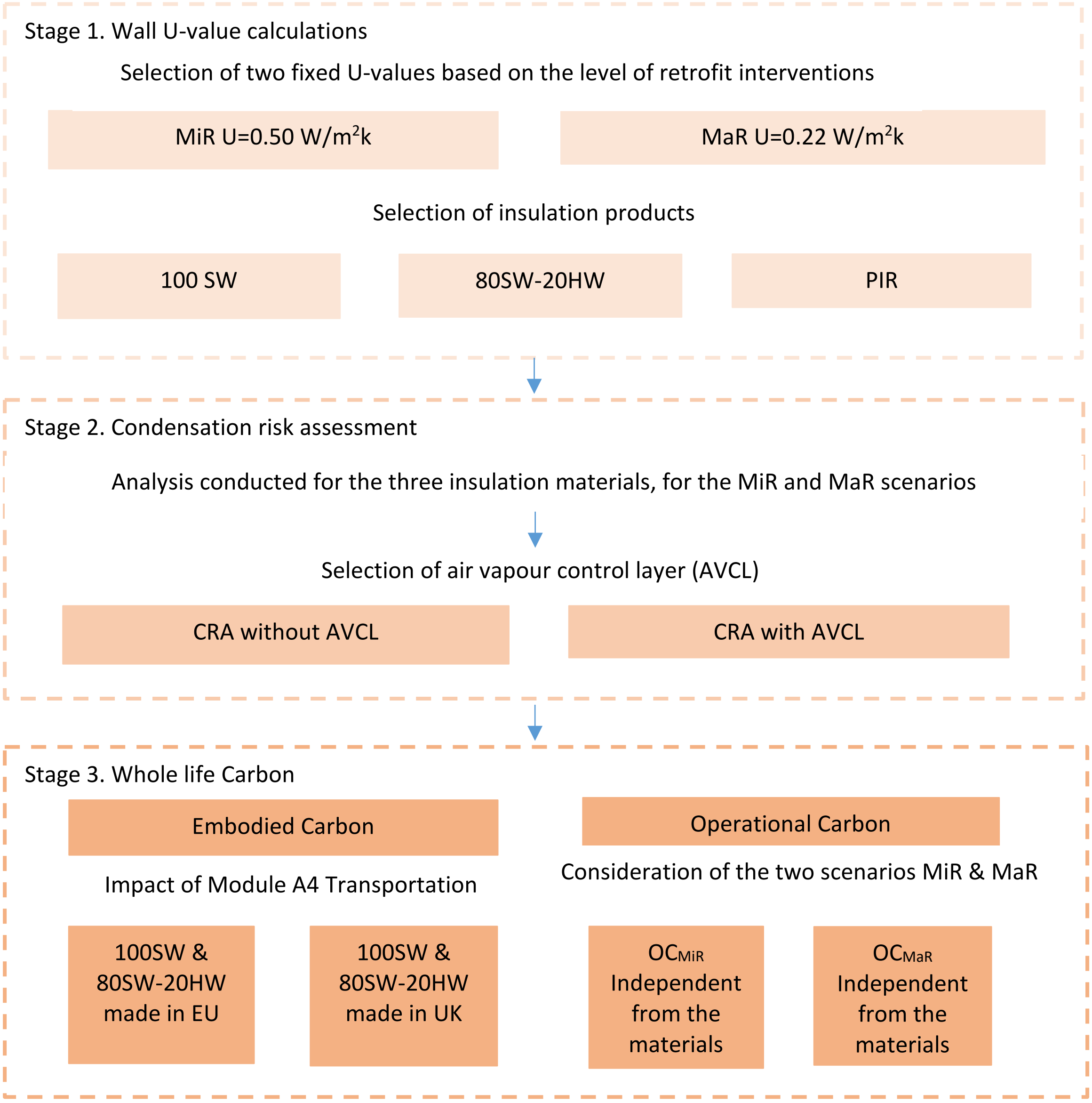
Table 3. Annual energy consumption breakdown

	Annual energy consumption [kWh/year]	Energy consumption	Carbon Intensity Factor [kgCO2e/kWh/year]	Operational Carbon [kgCO2e/year]
Space heating (74%)	18337.2	Natural gas	0.18486	OC_h=3390
Water heating (13%)	3221.4	Natural gas	0.18486	OC_w=596
Appliance (10.5%)	2601.9	Electricity	0.23314	OC_a=607
Cooking (2.5%)	619.5	Electricity	0.23314	OC_c=144

Having the fixed U-values for the two scenarios, OC_h will be reduced with circa the same significance, independently of the insulation material applied. For the above reason, the operational carbon (OC) of the upgraded building, has been considered constant for MiR, OC_{MiR}, and for MaR, OC_{MaR}.

A summary of the research methodology is reported in Figure 3.

Figure 3. Research Methodology summary



2.2. Material characteristics

The characteristics of the 100SW were selected after reviewing the existing products on the market. The 80SW-20HW board features were taken by the study conducted by Imken, Kraft and Mai (2021). PIR board values were selected using the BuildDesk-U catalogue. Table 4 shows the different features of each insulation product.

Table 4. Insulation products characteristics

Insulation products	Density [kg/m3]	Thermal Conductivity [W/(mK)]	Water vapour diffusion resistance value µ	Specific heat capacity [KJ/(kg K)]
100SW Thickness 30-80 mm	200	0.044	3	2.1
100SW Thickness 100-200	145	0.041	3	2.1
80SW-20HW Thickness 30-80 mm	177	0.037	5	2.1
80SW-20HW Thickness 100-200 mm	129	0.035	5	2.1
PIR	32	0.020	50	0.92

The values for AVCL were also designed by using existing products. The same AVCL was applied to the 100SW and 80SW-20HW products, see Table 5 for further details.

Table 5. AVCL characteristics

AVCL	Water vapour diffusion equivalent (Sd) [m]	Thickness [mm]	Water vapour diffusion resistance value µ
AVCL for 100SW & 80SW-20HW	6	0.40	15000
AVCL for PIR	1500	0.40	$3.75E10^6$

3. Results & analysis

3.1. U-values and thickness of the upgraded wall

Having settled the two scenarios, MiR and MaR, and selected the three insulation products, six simulations were undertaken in total for the U-values calculations. The results of the simulations are reported in Table 6.

Table 6. U-values and thicknesses of the wall were upgraded with the different insulation products.

Product ID	Insulation products	Targeted U-value [W/m²K]	Scenario ID	U-value [W/m²K]	Required thickness [mm]	Final wall thickness [mm]	Thickness increment [%]
1	100SW	MiR=0.55	1.1	0.47	60	725	12
		MaR=0.22	1.2	0.22	160	825	27
2	80SW_20HW	MiR=0.55	2.1	0.48	50	715	10
		MaR=0.22	2.2	0.21	140	805	24
3	PIR	MiR=0.55	3.1	0.43	30	667.5	3
		MaR=0.22	3.2	0.19	100	737.5	13

The 80SW-20HW boards offer a minimum saving on the final wall thickness when compared to the 100SW boards. However, up to 17% of insulation material can be saved when using the blended boards.

The advantages of the 80SW-20HW boards are explicated when looking at the comparison of the 80SW-20HW VS PIR boards, and 100SW VS PIR boards. In fact, despite the higher increment of thickness of the natural products, when compared to the PIR boards, up to 33% of insulation material can be saved for the 80SW-20HW boards against the 100SW. In addition, the 80SW-20HW boards offer an increment of the wall thickness equal to 7% for MiR and 9% for MaR when compared to PIR boards, against the 9% and 12% increment of the 100SW boards. The direct comparison, between the insulation products, is shown in Table 7.

Table 7. Direct comparison of the insulation products

Insulation products	Targeted U-value [W/m²K]	Thickness of the insulation comparison [%]	Thickness of the wall comparison [%]
80SW-20HW VS 100SW	MiR=0.55	-17	-1
	MaR=0.22	-13	-2
80 SW-20HW VS PIR	MiR=0.55	67	7
	MaR=0.22	40	9
100 SW VS PIR	MiR=0.55	100	9
	MaR=0.22	60	12

3.2. Condensation risk analyses of the upgraded wall

Firstly, the analysis of the existing wall without any improvements was undertaken to record the initial conditions. The stone wall, due to its nature, presents interstitial condensation during the winter months, but all the condensate is predicated to evaporate during the summer months, with a total of 8 months free of moisture, and with a maximum of accumulated moisture content per area equal to 23 g/m², see Table 8 for further details.

Table 8. Monthly moisture content per area gc [g/m²] and the accumulated moisture content per area Ma [g/m²] for the existing wall

		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Sandstone / Limestone Mortar	gc	7	10	5	-9	-14	-	-	-	-	-	-	-
	Ma	7	18	23	14	-	-	-	-	-	-	-	-

Afterwards, the condensation risk analysis was undertaken, for both scenarios MiR and MaR, and considering the absence and presence of the AVCL, with a total of twelve simulations.

For the 100SW, without AVCL, the upgraded wall did not pass the assessment for both MiR and MaR. The maximum accumulated moisture content per area (Ma) recorded for MiR, is equal to 2013 g/m^2.

When the AVCL is applied the wall maintains its initial conditions for MiR with a Ma of 15 g/m^2, and 8 months free of moisture. For MaR, despite the presence of the AVCL the wall has a Ma of 73 g/m^2, 387% higher than the original conditions, with just 4 months free of moisture.

Similar results were recorded for the 80SW-20HW boards with the accumulated moisture content per area during the months slightly lower than the 100SW boards. The major differences were recorded for MiR without AVCL, with the highest accumulated moisture content (Ma) 13% lower than the 100SW, and a final Ma on the wall 19% less than 100SW.

The data reported above, indicates how pushing the boundaries to reduce at the minimum the U-value of the walls could increase rapidly the risk of moisture, having an average of moisture free half time shorter than the walls had originally.

As for the previous insulation materials, the PIR boards did not pass the risk assessment when the AVCL was not applied. Nonetheless, the accumulated moisture content per area Ma, was 52% and 81% lower respectively for MiR and MaR when compared to the 80SW-20HW board. However, when the AVCL was applied the results showed no moisture content on the wall, with a total of 12 months free from moisture.

In reality, an AVCL is always applied in PIR boards, with the majority of PIR insulation products on the market having a vapour control layer integrated with the panels. The consequence of this result is that the existing wall loses its ability to let the vapour pass through, the moisture movement is not therefore allowed, with higher risks of decay in case of any infiltrations.

The results of the CRAs for the three insulation materials for scenarios MiR and MaR, with and without the AVCL are reported in Figures 4 to 7.

Figure 4. CRA results for MiR without AVCL

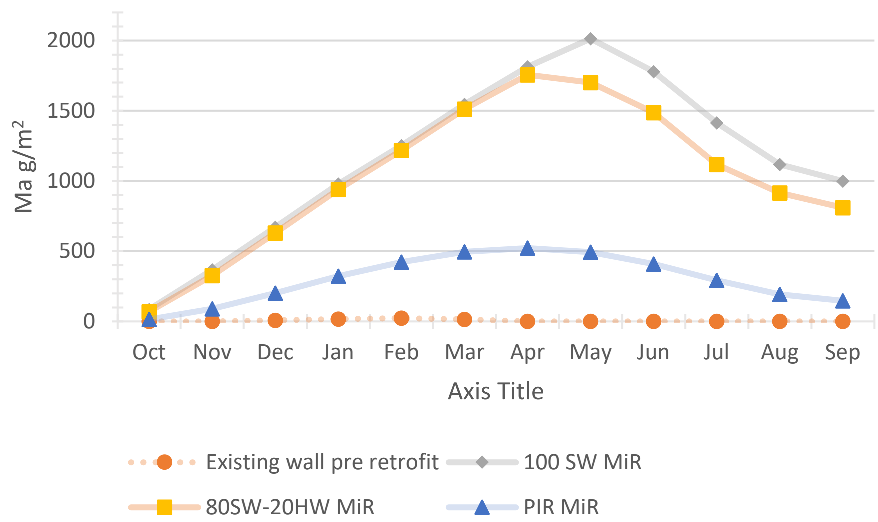


Figure 5. CRA results for MiR with AVCL

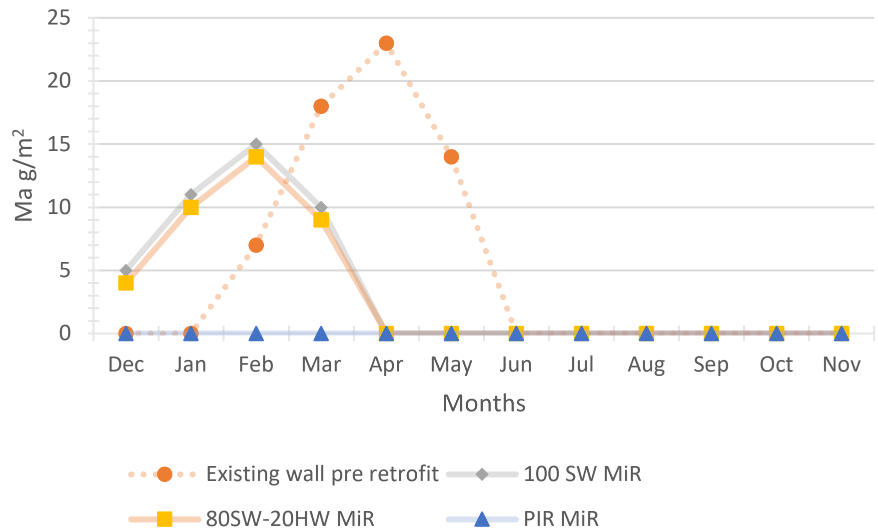


Figure 6. CRA results for MaR without AVCL

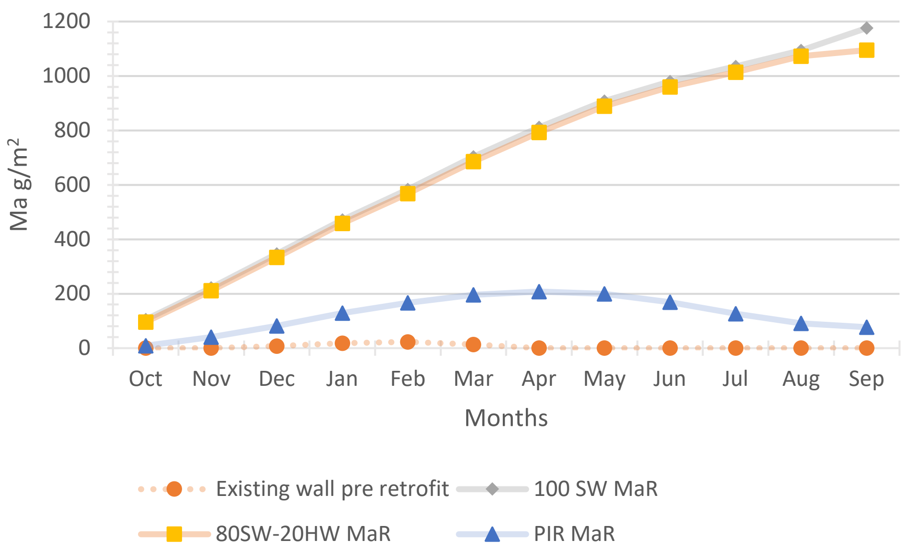
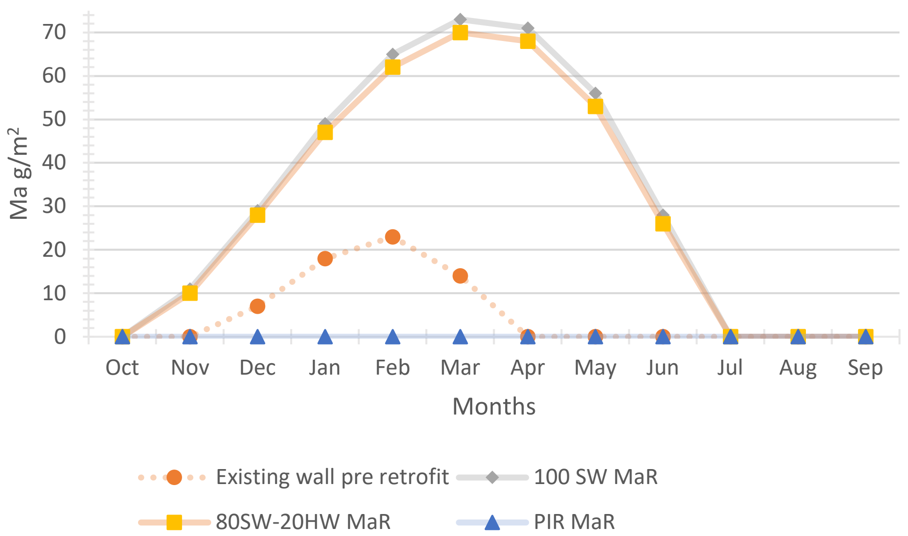


Figure 7. CRA results for MaR with AVCL

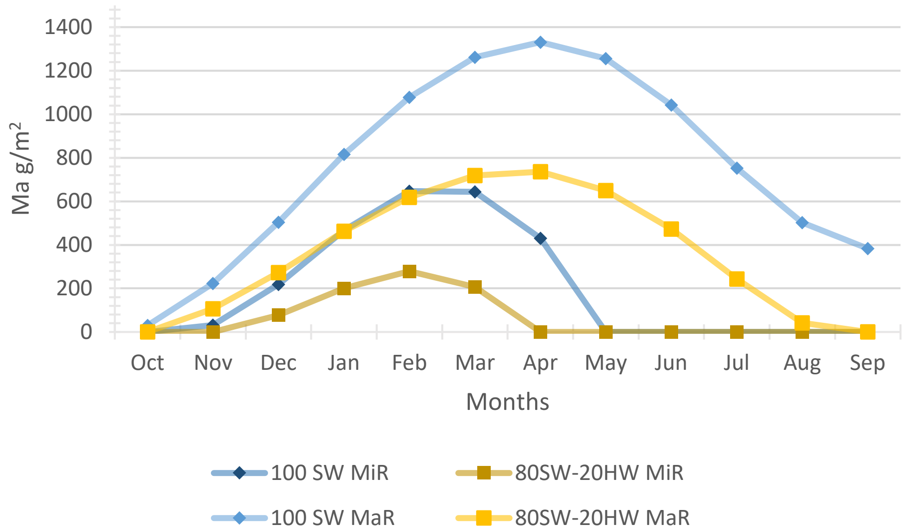


This study was limited to the use of the Glaser method which is based on the simplified static approach of condensation behaviour in building components, highlighting the most impermeable option. However, as mentioned in Section 2 Methodology, previous research studies have shown that with the dynamic simulation, which takes into account the permeability of the material, and the actual weather conditions, the relative humidity (RH) of the upgraded walls with wood fibre board is balanced during a period of time, and there is always an equilibrium of state (Little *et al*., 2015; Baker, 2016). On the contrary, when no hygroscopic insulation products are applied internally the RH accumulates during the time (Little *et al*., 2015; Baker, 2016). In addition, AECB (2016) showed that for wood fibre boards, the Glaser method overestimated the level of RH when compared to in situ measurements.

It should be also noted that the AVCL selected for the PIR boards, has a water vapour diffusion equivalent (Sd), 250 times higher than the AVCL selected for the natural insulation materials. Both the 100SW and the 80SW-20HW boards rely less on the AVCL. Moreover, this study was limited to the use of the Glaser method.

Both, 100SW and 80SW-20HW boards, recorded moisture on the cold side of the insulation materials when the AVCL was not applied. For MiR the 80SW-20SW boards have the maximum accumulated moisture content per area (Ma) 57% lower than the 100SW boards. For MaR the risk of moisture within the insulation materials increases exponentially with a maximum of two months free of moisture for the 80SW-20HW, and an equivalent moisture content of up to 16%, see Figure 8.

Figure 8. Comparison of the accumulated moisture content per area Ma (g/m^2) for 80SW-20HW and 100SW on the cold side of the insulations



The results are in line with the AECB (2016) case study where in situ measurements showed 15% moisture content on the cold side of insulation boards, when the wall was upgraded with 200mm wood fibre boards without AVCL, and with a final U-value of 0.156 W/m^{2}K.

The findings of this study alongside the AECB (2016) suggest that when using natural fibre insulation products, the masonry wall may need to be treated with a rain screen or a protecting layer, to reduce the effects of the rain loads. If treatments of the walls are not possible, the use of the AVCL may help in reducing the risk of rot of the insulation materials. Lowering the U-value should be also avoided.

3.3. Whole Life Carbon (WLC)

3.3.1 Embodied Carbon (EC)

The EC of the insulation products was conducted considering the two main scenarios MiR and MaR, plus an evaluation of the impact of having the wood fibre boards, 100SW and 80SW-20HW manufactured in the UK. A total of 10 scenarios were evaluated.

Table 9 shows the materials' quantities required to reach the wall U-value. To take into consideration the different densities of the natural insulation materials the functional unit used in this study is the mass.

Table 9. Quantity of insulation required for each scenario

Insulations & scenarios	Density [kg/m3]	Thermal Conductivity [W/(mK)]	Wall U-value [W/m²K]	Insulation thickness [m]	Area [m²]	Volume [m³]	Total Mass [kg]
100SW MiR	200	0.044	0.47	0.06	50	3	600
100SW MaR	145	0.041	0.22	0.16	50	8	1160
80SW_20HW MiR	177	0.037	0.48	0.05	50	2.5	442.5
80SW_20HW MaR	129	0.035	0.21	0.14	50	7	903
PIR MiR	32	0.020	0.43	0.03	50	1.5	48
PIR MaR	32	0.020	0.19	0.10	50	5	160

Data for the 100SW were extrapolated from the Environmental Declaration of Performance (EPD) of an existing product. The characteristics of the material, and the LCA declared by the company are reported in Table 10 and Table 11.

Table 10. 100SW specifications

Name	Value, Unit
Declared unit	1.00 m³
Declared Density	200.00 kg/m³
Conversion Factor to 1 Kg	0.005

Table 11. EPD 100SW boards (Pavafrance SAS, 2020)

Declared unit 1 m³	A1-A3	A4	A5	C1	C2	C3	C4	D
GWP [kgCO_2eq.]	-2.35E+2	-	1.04E+1	0.00E+0	5.19E-1	3.22E+2	0.00E+0	-2.62E+2

Data for the EC of the 80SW-20HW were taken from the 100SW EPD (Pavafrance SAS, 2020), and adapted according to the product density, using the conversion factor to 1kg of 0.005, as reported by the 100SW EPD.

Finally, also the data for the PIR EC were extrapolated by using the EPD of an existing product on the market, reported in Table 15.

Table 12. EPD PIR boards (Finnfoam oy, 2021)

Declared unit 1 kg	A1-A3	A4	A5	C1	C2	C3	C4	D
Global Warming Potential (GWP) (kgCO_2eq.)	2.66E+0	1.83E-02	-	0.00E+0	6.08E-3	0.00+E0	2.59E+0	0.00

Module A5 in this case was calculated according to the following formula (RICS, 2017; Gibbons and Orr, 2022):

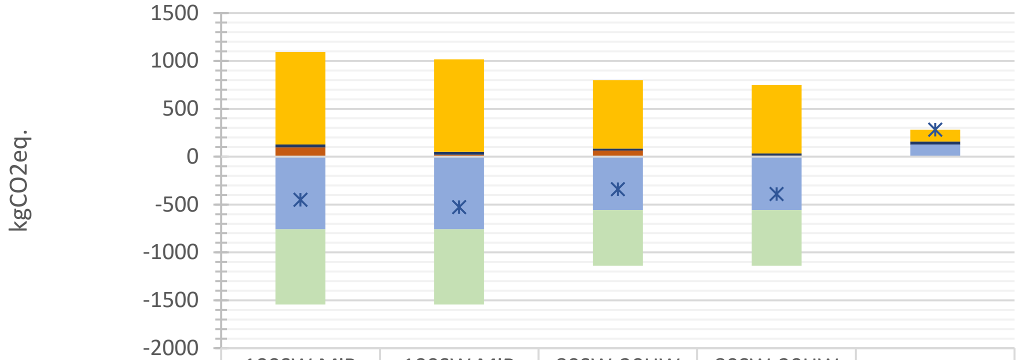
- $A5 = WF \times (GWP_{A1\text{-}A3} + GWP_{A4} + GWP_{C2} + GWP_{C3\text{-}C4})$
- WF= Waste factor

Considering a waste rate for PIR equal to 10%, the WF for this study has been assumed to be 0.111 (Gibbons and Orr, 2022).

3.3.2 EC comparison of the different insulation products

The LCAs for MiR and MaR of the different products are shown in Figures 9, and 10 with Modules A1-A3 and Module D offering the major saving in terms of CO_2 emissions for the wood fibre boards, due to their nature, and the opportunity to recycle the materials at the end of life.

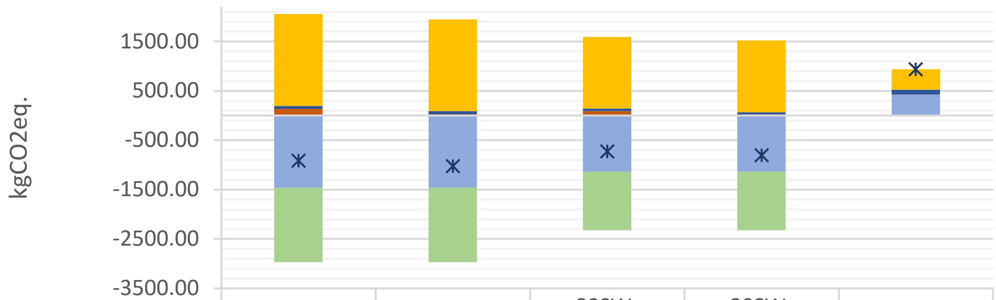
Figure 9. LCAs comparison for MiR



	100SW MiR EU	100SW MiR UK	80SW-20HW MiR EU	80SW-20HW MiR UK	PIR MiR
D	-786	-786	-579	-579	0
C1-C4	967.56	967.56	713.15	713.15	124.29
A5	31.5	31.5	23	23	28.3
A4	96.1	19.2	62.6	12	0.96
A1-A3	-759	-759	-559	-559	127
EC with module D	-449.84	-526.74	-339.25	-389.85	280.55

A1-A3 A4 A5 C1-C4 D EC with module D

Figure 10. LCA comparison for MaR

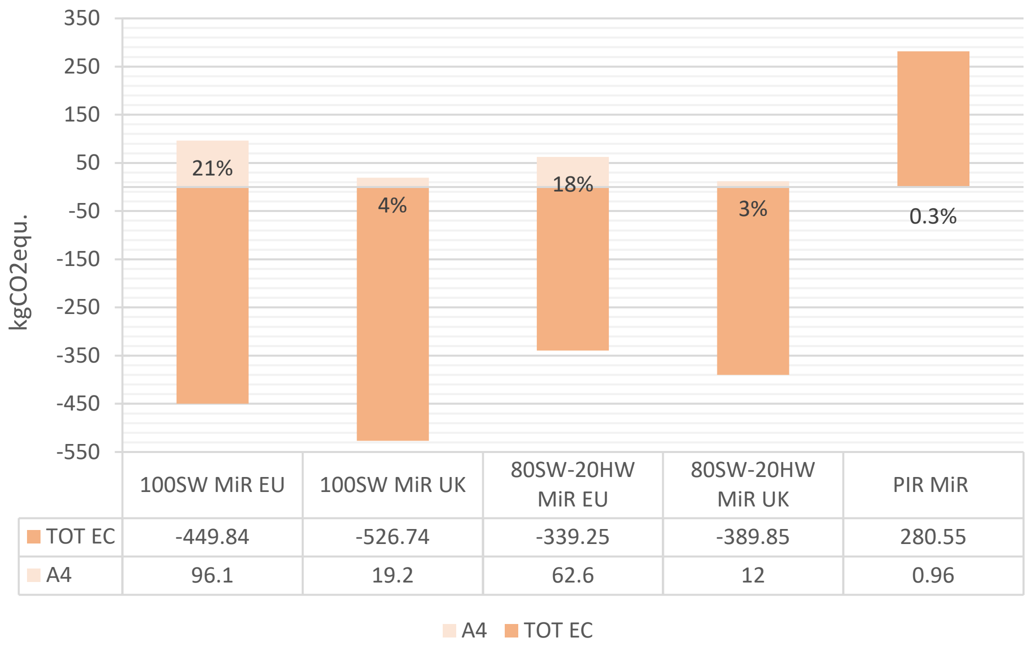


	100SW MaR EU	100SW MaR UK	80SW-20HW MaR EU	80SW-20HW MaR UK	PIR MaR
D	-1510.00	-1510.00	-1180.00	-1180.00	0.00
C1-C4	1863.01	1863.01	1452.34	1452.34	414.97
A5	60.60	60.60	46.90	46.90	94.90
A4	134.00	26.90	93.10	18.60	3.20
A1-A3	-1460.00	-1460.00	-1140.00	-1140.00	425.00
EC with module D	-912.39	-1019.49	-727.66	-802.16	938.07

A1-A3 A4 A5 C1-C4 D EC with module D

For both natural insulation products, 100SW and 80SW-20HW, Module A4 has an impact of 21% and 18% circa respectively on the total EC, against the 0.3% of PIR boards. With the wood fibre boards made in the UK, the impact of Module A4 could be potentially reduced by up to 4%, see Figure 11.

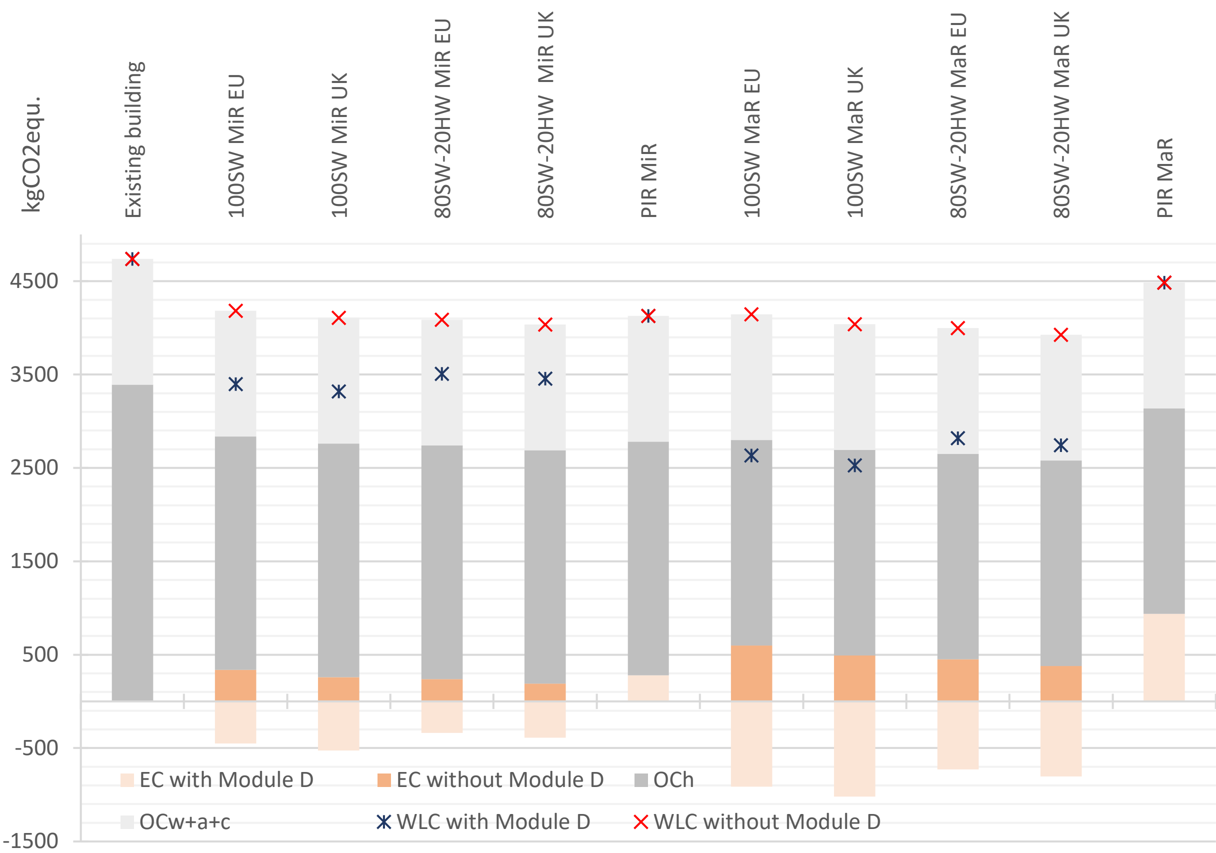
Figure 11. Module A4 impact on the total EC



3.3.5 WLC comparison

The whole life carbon of the different scenarios has been evaluated against each other and the existing building pre-retrofit, see Figure 12.

Figure 12. WLC of the different scenarios



If the 100SW and 80SW-20HW boards have benefits explicated in Module D, the 100SW insulation product guarantees the lowest level of WLC, being 45% for MiR, and 81% for MaR less than WLC of the PIR boards. When compared against the existing building a saving of 28% in carbon emissions for MiR, and 44% for MaR are recorded for the 100SW boards. On the contrary, for the PIR boards, 13% of MiR, and 5% of MaR of carbon emissions are saved in comparison to the existing building.

When Module D is not taken into account, for MiR, the 80SW-20HW boards guarantee the highest savings in terms of carbon emissions, -3% against the PIR boards, and -6% against the 100SW. Looking at the MaR, 100SW and 80SW-20HW have WLC values of 15% and 21% respectively lower than the one for PIR. An extra 5% could be saved if both wood fibre boards were made in the UK. In comparison with the existing building, for MiR all three insulation products offer a saving of carbon emissions that ranges between 12-15%, with the 80SW-20HW boards having the highest saving rate. On the other hand, for MaR, the scenarios change drastically with the PIR boards having a WLC value just 5% lower than the existing building, contrary to the 100SW and 80SW-20HW that are offering a saving of carbon emissions of respectively 13% and 16% against the original status quo. See Table 13, and Table 14 for further details.

Table 13. WLC comparison between insulation products

Scenarios	**Carbon emissions saving with Module D** **[%]**	**Carbon emissions saving without Module D** **[%]**
100SW MiR EU VS PIR MiR	-45	3
100SW MiR UK VS PIR MiR	-50	-1
100SW MiR EU VS 80SW-20HW MiR EU	-11	6
100SW MiR UK VS 80SW-20HW MiR UK	-14	5
80SW-20HW MiR EU VS PIR MiR	-38	-3
80SW-20HW MiR UK VS PIR MiR	-41	-6
100SW MaR EU VS PIR MiR	-81	-15
100SW MaR UK VS PIR MaR	-86	-20
100SW MaR EU VS 80SW-20HW MaR EU	-30	8
100SW MaR UK VS 80SW-20HW MaR UK	-40	7
80SW-20HW MaR EU VS PIR MaR	-73	-21
80SW-20HW MaR UK VS PIR MaR	-76	-25

Table 14. WLC comparison against the existing building (EB)

Scenarios	Carbon emissions saving with Module D [%]	Carbon emissions saving without Module D [%]
100SW MiR EU VS EB	-28	-12
100SW MiR UK VS EB	-30	-13
80SW-20HW MiR EU VS EB	-26	-14
80SW-20HW MiR UK VS EB	-27	-15
PIR MiR VS EB	-13	-13
100SW MaR EU VS EB	-44	-13
100SW MaR UK VS EB	-47	-15
80SW-20HW MaR EU VS EB	-40	-16
80SW-20HW MaR UKVS EB	-42	-17
PIR MaR VS EB	-5	-5

4. Conclusions

There is a need to upgrade the existing UK building stock, and any choices made will have an impact on the UK Government's strategy of reducing the carbon emissions associated with the construction industry. Insulating the building envelope is the key point for reducing the heating demand of existing structures, and the selection of those materials has an overall impact on the emissions generated by those interventions.

Considering the above, this research aims to understand the impact on the whole life carbon of upgrading a pre-1919 tenement flat, with three different insulation materials applied internally, 100SW, 80SW-20HW, and PIR boards. In doing so, a holistic approach was undertaken.

Firstly, considering two different scenarios, Minor Retrofit (MiR), with U=0.50 W/m²K and Major Retrofit (MaR) with U=0.22 W/m²K, the influence of the different levels of thermal conductivity on the final thickness of the upgraded wall was evaluated. The reduction of the thermal conductivity value, with a product made with a blend of softwood and hardwood, offers a saving in terms of final insulation thickness material equal to 17% and 13% against the traditional 100SW boards. However, when compared to PIR, both wood fibreboards offer an increment of the total wall thickness between 7-12% higher.

Nevertheless, the hygroscopic nature of the PIR boards may put the existing building at a higher risk of moisture. The condensation risk analyses, undertaken in this study, show that the application of PIR boards, limits the breathable nature of the existing wall, becoming not permeable after the insulation application. On the other side, the wood fibreboards, 100SW and 80SW-20HW have shown very high levels of moisture content when a layer of vapour control (AVCL) was not applied. However, this study was limited in using the Glaser method for the CRA, with previous research showing that the values obtained with this method are overestimated. The CRA for the wood fibreboards also showed that moisture might occur on the cold side of the insulation, with similar results obtained by AECB (2016) with in-situ measurements. The study suggests that the 80SW-20HW boards have a lower level of moisture content between the wall and the cold side of the insulation, up to 55%, when compared to 100SW boards. The application of the AVCL, even if is not generally necessary for natural insulation products, could prevent this risk.

Finally, an evaluation of the materials embodied carbon, and its impact on the whole life carbon was undertaken, considering the different set scenarios, MiR and MaR. In addition, being wood fibre insulation products mainly imported from Europe, this study analysed the impact of that added carbon for transportation to the UK.

The results show great advantages of using the two natural insulation products, up to 45% and 81% for MiR and MaR. Having those products manufactured in the UK could reduce up to 17% the impact of Module A4 on the total embodied carbon.

For this study, the information for the LCAs was taken by EPD of existing products. The wood fibre boards, in this case, have also benefits in Module D, considering that the material is transported to a biomass power plant, with an energy retrieval combustion.

If the above are not satisfied, and there are no gains for Module D, the scenarios change completely. The research suggests that in this case, the 100SW boards have an EC for MiR, higher than the PIR boards, 20% circa unless they are made in the UK, -8%. On the contrary, the 80SW-20HW boards have an embodied carbon 14% lower than PIR boards for MiR, and -32% with the product made in the UK.

Conversely, even without taking into consideration Module D, when looking at the whole life carbon against the existing status quo, the differences in savings between the three insulation products for MiR are almost negligible. For the MaR, the PIR boards offer the lowest carbon emissions saving, -5%, against the 13% and 16% offered by the 100SW, and the 80SW-20HW, with a 1-2% extra saving for products manufactured locally.

Overall, the research shows the importance of looking holistically at a retrofit strategy, and that different factors need to be taken into consideration. Despite natural insulation products offering advantages in terms of embodied energy and condensation risk, the boundary conditions of where those products are made and how they are used at the end of life have a great impact on the final whole-life carbon.

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