Sustainable Insulation products in the Scottish construction industry

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_Contents

_Declaration

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_Executive summary

This document has investigated the current natural fibre and recycled (NF+RI) products available in the UK with a particular focus on Scotland using local and regional supply chains. This information serves as a vital piece of knowledge for new product manufacturers and the Scottish construction industry when considering low embodied carbon materials for building projects. This document explored the parameters that determine existing relevant products as well as links the relevant literature available providing industry and academic overview of evidence such as the different types, performance values and considerations. A particular objective set out for this document, was to unpick the existing challenges and barriers faced by the NF+RI industry in Scotland and to seek some dialogue in the solutions and opportunities to overcome them. Many were aimed at a lack of policy actions and vision, others were around supply chains and the construction industry's lack of knowledge and fear of investment. A particular outcome when discussing the uptake of such insulation in the industry was the cost barrier between synthetics and NF+RI products, as well as the lack of availability and performance values that seldom match those of available synthetic products.

The following recommendations are based mainly on the review made of current NF+RI products, the current market uptake and the future industry shift to low embodied carbon materials as well as meeting some of the government targets on net-zero performance. To explore the shift into NF+RI products it is important to take four important steps:

1. **Have discussions with existing supply chains**,
2. **Forge agreements with existing manufacturing setups,**
3. **Introduce biowaste and embodied carbon legislation in construction,**
4. **Incentivise the construction industry to use NF+RI products,**
5. **Conduct thermal and UKAS accredited fire resistance testing and determine its fire combustibility.**

Future work in this field seeks to explore some of the recommendations mentioned above in three different ways. The first is to explore the different supply chains and manufacturing facilities for the partnerships and shared capacity this industry requires. Also planned is a long-term approach through a PhD studentship with specific laboratory testing and innovation in the use and products from homegrown wood fibre and other fibres. A shorter-term second phase of this project will explore the outreach to the industry on the up-skilling and support needed to make NF+RI competitive against available synthetic products.

1. Introduction

This project was funded by Zero Waste Scotland and Built Environment Smarter Transformation (BE-ST) formerly CS-IC and originated after an industry workshop held in March 2021[1] that discussed ways to support and upskill the construction industry over the different types of sustainable and natural insulation products available. This particular workshop concluded that the construction industry in Scotland needs to gain additional knowledge on natural fibre and recycled insulation materials ability to contribute towards a net-zero economy as well as highlighting their advantages, uses, challenges, barriers and opportunities.

Achieving net-zero carbon performance from the built environment as set out by the Scottish Government by 2045 requires a holistic approach by those involved in the delivery of buildings. This can only be achieved through specific supply chains, private investment and public policy-driven support. A vital piece in achieving net-zero goals is to consider the origin and waste streams of building materials, prioritising the low-embodied carbon options available. Solutions such as the use of locally sourced, natural fibre and recycled (NF+RI) materials are excellent examples of ways to reduce the carbon emitted during the whole life performance of buildings. Considerations such as this present a real opportunity to change how the industry considers natural fibre and recycled materials from being an expensive one-off niche product to being a more mainstream and readily available building material at a competitive cost with comparable performance to synthetic equivalents.

Some NF+RI products already have a place in the UK and Scottish insulation markets. However, only a few are fully produced in the UK and Scotland. Most products of biomaterial origin are produced and imported by companies in mainland Europe through small-scale UK distributors, mainly specialist natural product suppliers, and representatives of EU-established brands. NF+RI products offer solutions to two net-zero performance criteria. They contribute to lowering operational energy and carbon emissions by reducing heat loss through the building envelope, a quality that most insulation materials at varying levels will have. Additionally, they present a much lower environmental footprint by having a lower global warming potential, and if renewable and efficient energy sources are used can claim to be low embodied energy.

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1 Sustainable Insulation Workshop on the 31st of March 2021 by Mabbett and Construction Scotland Innovation Centre (CSIC) to support the Scottish Government's Construction Recovery Plan.

To understand how more natural fibre and recycled insulation (NF+RI) can be produced in Scotland there needs to be an open dialogue between supply chains and existing manufacturing set-ups. Therefore, this document aims to explore the wide variety of UK and Scottish natural and recycled insulation products whilst identifying those that are imported and how they can all be used in the construction industry.

The main objectives of this report are:

1. To provide an understanding of the different parameters and performance values of existing products;
2. Conduct a literature review of existing methods, materials and innovative products;
3. Understand the barriers and challenges faced by the existing UK and Scottish products as well as identify the opportunities;
4. Provide the Scottish construction industry with a guide on natural and recycled insulation products;
5. Support the knowledge and skills required to reach net-zero carbon performance in the Scottish built environment.

2. Literature and product review

2.1. Existing literature – industry and academic

Academic literature for this document provides a summary of research projects, new materials testing for performance and innovative sources, composites and uses of sustainable insulation products and materials.
The rising costs and geopolitical conflicts of the 2020s require us to be strategically more frugal with energy, particularly in the operation of buildings with the potential to lower energy bills and reduce the risk of fuel poverty. Insulation products in buildings, both synthetic and sustainable (recycled and natural) can limit heat loss leading to reducing carbon emissions into the atmosphere. Additionally, some products can emit fewer carbon emissions during their extraction, transportation and manufacturing which makes them an environmentally conscious alternative. This approach contributes to developing a circular economy strategy considering the building stage, occupancy and deconstruction and re-use. An emphasis on locally sourced raw materials and products through their contribution to lowering carbon emissions by transportation and origin will be discussed as well as the longevity and life cycle of insulation products.

_Use of insulation, operational & embodied CO_2 impacts

Figures in 2019 show that 87 MtCO2e direct greenhouse gas emissions came from buildings, which is approximately 17% of the UK total.[2] [1]. This can be split between homes (77%), commercial buildings (14%) and public buildings (9%). Most heating requirements in the UK are currently met by natural gas, phased out in new buildings by 2025. If indirect emissions are included, buildings contribute 23% of the UK total[3]. Existing Building Regulations in Scotland provide a good set of thermal performance criteria to follow, however, most are focused on the reduction of operational emissions (direct emissions) [2]. Despite this, there is a drive to achieve low-carbon sustainable buildings that consume less energy and therefore emit fewer carbon emissions during their operation and sourcing of materials [3].

The emissions from products and manufacturing stages of building materials and construction stages are significant, in some instances accounting to more than half of the carbon emissions over a building's life [4]. Examples of total whole-life carbon emissions of certain buildings show that in

[2] Direct emissions in buildings result primarily from the use of fossil fuels for heating.

[3] Indirect emissions include appliances and lighting in homes as well as cooling, catering and ICT equipment in non-domestic buildings.

domestic buildings, embodied carbon of materials contributes 51%, and operational, direct and indirect emissions a further 31% with further emissions in-use (maintenance & replacements) around 18%. An office building is similar with 35% embodied carbon emissions, 33% operational and 32% in-use [5]. This shows the importance of reducing the carbon emitted during the creation of building products, particularly as buildings become more efficient through low energy efficiency building regulations and standards (Passivhaus, etc) [6].

_Wood - natural fibre insulation (NFI)

Most natural fibres can be categorised according to their source predominantly from lignocellulosic materials known as cellulose-based materials, such as wood, and non-wood or plant-based fibres [7]. Natural fibre insulation, just like any other insulation (synthetic) can act as a thermal barrier that limits and resists the passage of heat through it. Most sources are those from seeds, bast, leaf, stalk and cane, grass and reed. Wood-derived natural fibre insulation includes different forms of tree bast, including wood itself (soft and hard wood species), hemp, jute and flax [8]. Such fibres are hair-like continuous filament materials that can be pressurised and thermally bonded at varying densities to form insulation materials. The use of fibre products in buildings as construction materials and reinforcement has been widely explored in different forms and uses. Most wood-based products are processed into low-density batts, or into rigid boards through a dry or wet process, however, they have enhanced properties through their strength, shrinkage control and formation of cracks. If placed accordingly, natural fibres can have good thermal insulation properties and can enhance the regulation of temperature and humidity [9]. Despite this, if not treated properly wood-derived fibres tend to degrade over time making them less durable than synthetic equivalents [10]. There have been efforts in making natural fibre products more durable by using chemical treatments such as certain coatings and substituting or blocking the hydroxyl group in the fibres by converting the organic compounds into alcohols, enhancing their solubility in water [11]. Hemp shives, for example, are normally used as an alternative aggregate in lime, clay or magnesia binders but can be used as an insulation product. Kosinski et al, [12] have explored their use in the construction industry and have obtained thermal conductivity values of between 0.049 – 0.052 W/mk. Wood fibre has many products on the market with its primary application in the retrofit of existing buildings [13].

_ Natural plant & animal fibre insulation

Mainly derived from other natural vegetable sources, including those that extract their fibres from plants seeds & fruits (cotton & coir), leaf (sisal & henequen), stalk (wheat, maize, rice) and the cane or grass and reed (bamboo and bagasse) [14 & 15] see Figures 1 & 2. The sourcing of such raw materials can be done by picking and purposely cultivating the plant or by agricultural wastes as explained by Gaspar et al. [16]. Animal-derived products are also purposely extracted or can be bi-products from their processing. For example, the shavings and use of low-grade sheep's wool in insulation products and the use of leather shavings which can be collected and used as insulation, mainly as strips stacked in a cavity. Most, create a product requiring bonding the fibres by using polyester and other natural or synthetic fibres. Another form of animal bi-product is bird plumages, often recycled from bed pillows mainly goose or duck feathers, however, chicken feathers are known for their excellent thermal insulation properties with a thermal conductivity value between 0.024 and 0.033 WmK. Their robust tough central quill makes it resilient to loading and shape retention. Their effective hygrothermal performance traps air which even when bonded together can have favourable performance in the form of a flexible batt of insulation [17 & 18].

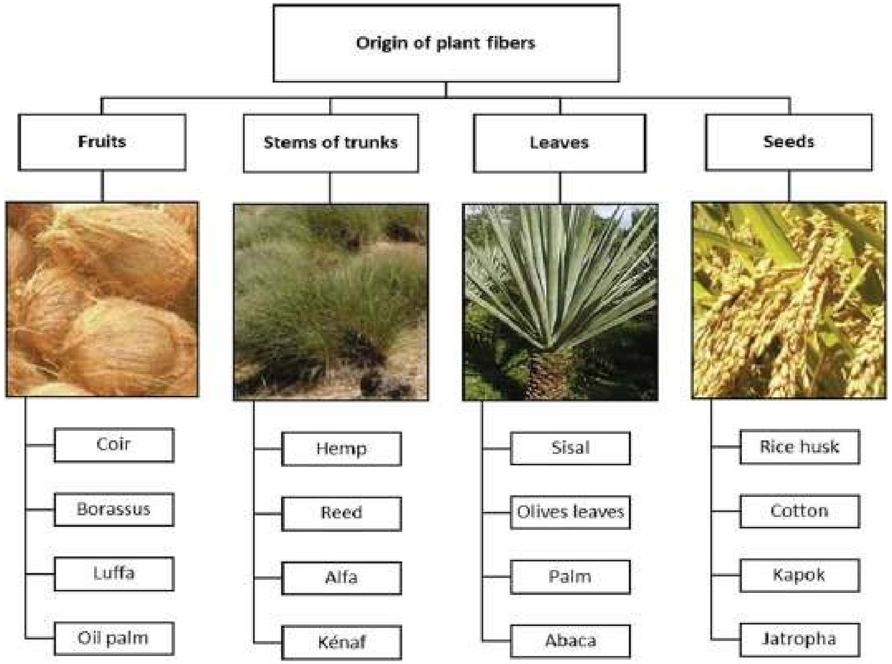

Figure 1 (left): Plant fibres derived from biomass by Benallel et al. [18]

Figure 2 (right): Examples of agricultural wastes raw materials for insulating materials: (A) rye straw, (B) flax boon, (C) Jerusalem artichoke, (D) rice husk, (E) jute fibres, (F) flax noils, (G) waste of cotton fibres, (H) coconut fibres, and (I) oil palm bark fibres.

_Recycled products

The insulation products that are derived from recycled products and materials are wide-ranging. There are two main types; those that re-purpose natural and synthetic bi-products and those that recover from waste streams originally used in other industries (news print, textiles, plastics) which include those that require a post-processing stage of synthetic materials used in insulation and re-used in a different format. One example of these is insulated panels or waste off-cuts from buildings sites, which are recovered and granulated into smaller parts which are then re-purposed as insulation. Figure 3 explains different products that fit into these categories.

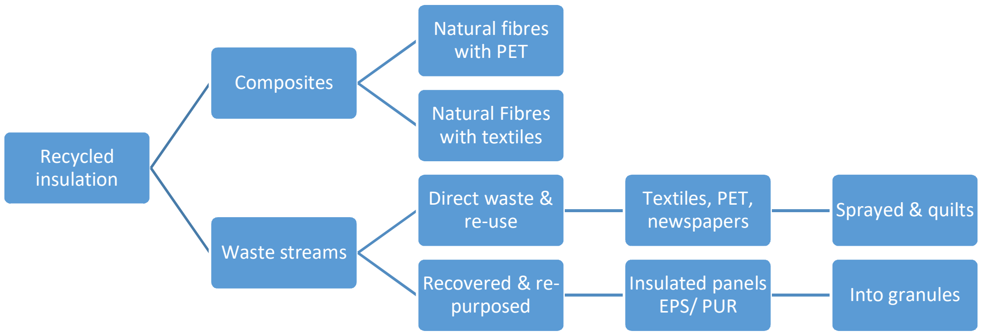

Figure 3: Different recycled uses and products from waste, recovery and re-purposing.

Figure 4: a) Newspaper cellulose insulation, b) PET recycled insulation, c) Polyester recycled insulation, d) Chicken feathers insulation

Perhaps the more common and available insulation product on the market is recycled polyethene (PET) plastics from juice and drink bottles. These are widely recovered in most cities and are post-processed into fire-resistant thermal-acoustic insulation with high thermal properties [19]. Another excellent product comes from the re-use of newspapers into cellulose insulation. It is often in the form of cellulose wadding as loose-fill, sprayed and as wadding panels of low density generally [20]. Such materials or insulation are composed of ground paper fibres treated with inorganic additives that act as fire retardants and mould growth inhibitors. Recycled newsprint or chemical pulp could also be incorporated [21].

_Product properties, performance & innovation

Insulation products and materials are often measured against their hygrothermal performance values, with thermal conductance (W/mK) being the determinant factor. Although thermal conductivity is a measure often compared against products, just as important is the way the material absorbs and released heat/ water vapour, values that depend on the materials decrement factor, time lag and vapour permeability and water vapour resistance factor (μ) [22]. Other thermal properties such as specific heat capacity (J/kg°K), density (kg/m^3) thermal inertia (J/K·m^3), thermal diffusivity and effusivity are vital as they determine their capacity to store heat and buffer humidity, qualities that often are ignored and deemed difficult to quantify any benefits.

Also important is the compressive and tensile strength and in those using fibres, its composition, and length. In terms of the environmental impact of such materials, the global warming potential (GWP – kg/CO_2e) and embodied energy (EE – MJ/kg)) are required to understand the carbon emissions intensity associated with all the life cycle stages of such products as well as the energy intensity required. Some materials will have low values for the extraction and origin of the raw material, but its processing and transportation for manufacture alters these benefits due to the high level of non-renewable energy use and high-intensity manufacturing requirements. Also important is the capacity for materials to release toxins and volatile compounds (VOCs) into the atmosphere and indoors once placed in a building. Work by Maskell et al. [21] highlights the benefits of natural insulation materials against synthetic ones based on the level of off-gassing and harmful toxins negatively impacting indoor conditions. Lopez-Hurtado et al. [22] present data on the embodied energy based on a kg of material required for insulation materials; synthetic materials range between 20 – 45 MJ/kg, recycled products range between 4-20 MJ/kg and most natural fibres around 4 MJ/kg, however, flax tends to be high (39.5 MJ/kg), mainly due to the complex manufacturing process, see Appendix A.

2.2. Review of materials & products

Synthetic materials on the market are readily available and can come at an affordable cost to the DIY and wider industry. This is not necessarily the case with NF+RI products, most of which are imported and currently available through specialist suppliers. However, it is important to highlight the wide range of existing products and understand their characteristics, best practice use and how they compare with synthetic market leaders. This section outlines the materials and products that are commonly available, as well as some innovative ones such as a product and building systems.

2.2.1. Classification – recycled, natural fibre, natural other, synthetic with recycled content

For this document, insulation materials have been split into three categories, depending on the process used to create them; synthetic (man-made), natural and recycled insulation. Furthermore, the different categories of insulation have been split into subcategories depending on the type of material they are made from as shown in Appendix B and Figure 5.

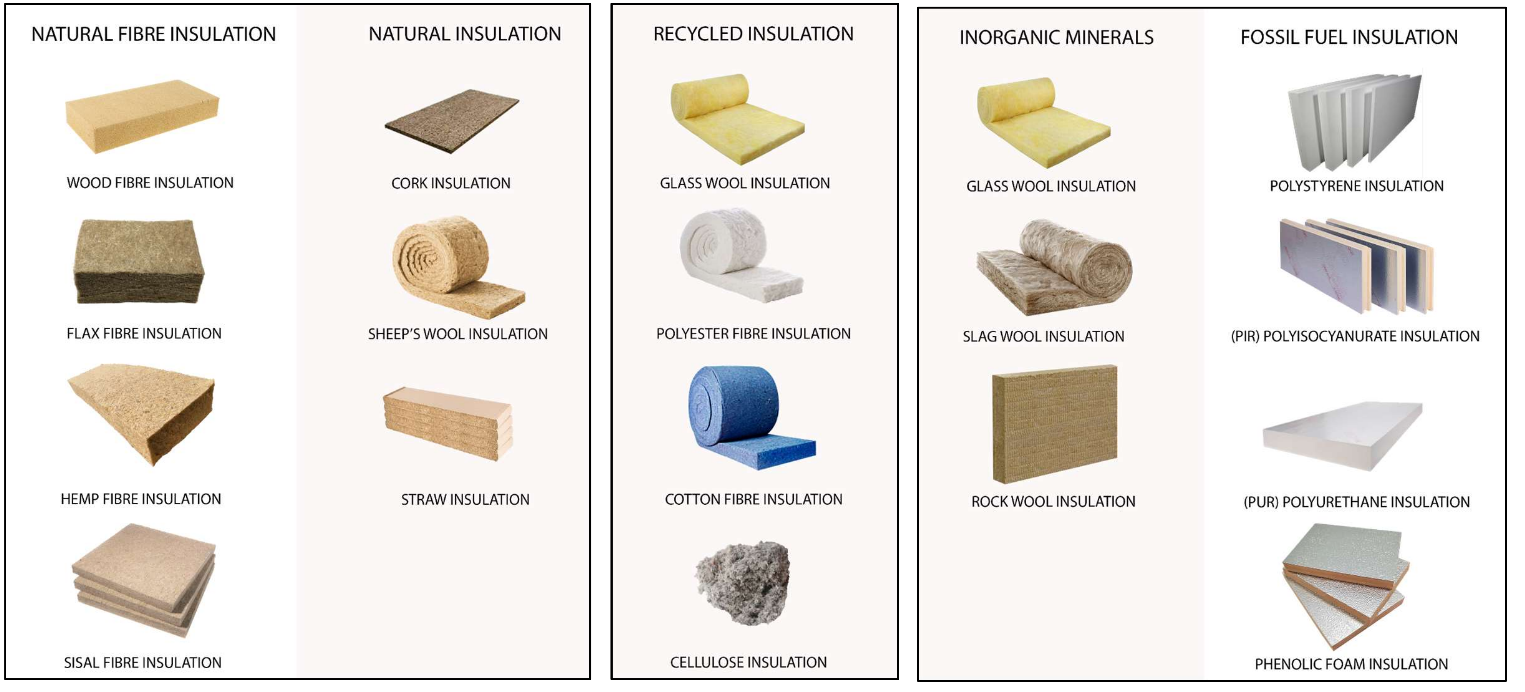

Figure 5: Building insulation example materials

_Natural fibre insulation

Natural fibre insulation consists of tree and plant-based wood that is debarked and made into chips and shavings which then undergo a loose dry or wet-formed process eventually reaching the mechanical press. Thermal bonding is done with an adhesive and binder to create low and high-density products. The most common sources are wood, flax, hemp and sisal fibre products. For example, wood fibreboard uses untreated spruce and fir wood chips harvested and grown using sustainable forestry management practices as per PEFC and FSC standards. The wood fibre industry uses shavings that are by-products produced by other timber manufacturing processes, however, the hemp and flax products use purposely grown and harvested crops that are economical and yielded efficiently.

Wood fibre insulation is currently manufactured outside the UK therefore most is imported from mainland Europe. Pavatex which has its manufacturing facilities in Switzerland and France along with Steico with two manufacturing plants in Poland and one in France are the leading suppliers of wood fibre insulation to the UK. Other manufacturers include Best Wood Schneider and Gutex from Germany and Beton Wood from Italy. These products are distributed by insulation merchants such as Suprema, Mike Wye, Back to Eath, Green Building Store and Ecomerchant.

Flax insulation is similar to wood fibre insulation also not manufactured in the UK. The Dutch company Isovlas which manufactures its insulation in Germany supplies this insulation type through Ecomerchant. Their product contains 80% flax along with 12% binder and 8% salt and uses a bi-composite polyester binder. Isolia is another flax insulation product, in a form of a roll which contains linen fibre, and recycled textile binder fibre with safe and environmentally friendly flame retardant. It is imported to the UK from Finland.

Hemp fibre insulation is manufactured in Scotland by IndiNature. Their two products, IndiTherm and IndiBreathe will be manufactured (October 2022) in the Scottish Borders and harvested from UK farms. Sisal fibre insulation has also been developed in Scotland by a Scottish-based company called SisalTech. Their product Sisalwool 100 is currently manufactured in Spain & Belgium and contains recycled wool, eco-binder and sisal fibre which is imported from Tanzania and helps small-scale farmers increase their incomes.

Also, an option is coconut fibres collected from the coconut husk, a resource that is widely available in its place of origin (Tropics). Only a fraction of the nuts is collected for industrial use, mainly from the food industry. Coconut fibre has a very high lignin content so it is very tough and despite this quality, it is also elastic and hardly deteriorates over time. The fibres are first spun and shaped into a fleece and then transformed into sheets then sprayed with natural latex (natural rubber) to provide structure and elasticity with other additives that are hypo-allergenic, anti-microbial and dust-mite-resistant. The Dutch company Enkev BV produce the Cocolok product with a Polish and UK (Cumbria) distributing office.

Figure 6: Natural Fibre (from left to right): Wood Fibre, Flax Fibre, Hemp Fibre, Sisal Fibre, Coconut Fibre.

_Other Natural insulation

Alternative natural insulation products include bi-products from other parts of plants, trees and animals such as cork, straw and sheep's wool. These require insect-repellent additives as well as binders to create a stable and manageable product. Within the recycled insulation products, some include re-purposed materials as well as inorganic minerals using bi-products from natural sources such as slag and rock wool.

Cork insulation from the cork oak tree (*Quercus suber*) is predominantly sourced and manufactured in Portugal with Corticeira Amorim as a leading manufacturer of cork products. Corklink is a distributor of cork products with a significant UK presence, it offers cork boards as well as a product of granulated cork used as an insulating filler. More information on this product can be found in Section 5.

Another material is straw, used as insulation material in a bale form and often used to form a dwelling or buildings outer envelope (wall) without any further processing. Straw insulation is protected on both sides with a moisture-open plaster and render, often lime or clay to enhance vapour transmission and avoid condensation build-up. It is a cost-effective solution, however, the thickness of the walls requires a larger footprint than other methods of construction. These vernacular construction methods have acquired some popularity in bespoke eco-dwellings, however, products are emerging that use straw insulation within a timber structure such as ECOCOCON, also described in Section 5.

Sheep's wool insulation is one of the only natural insulations manufactured in the UK. Thermafleece and Black Mountain with manufacturing plants in Yorkshire and Wales utilise British wool to make rolls and slabs of insulation. Insulation made by Thermafleece contains 75% wool in combination with recycled plastic fibres (20%) such as PET in combination with a bi-component binder to prevent slumping once installed. Based in Essex, UK, Black Mountain's product NatuWool contains 95% natural wool fibres and 5% combination recycled adhesive binder.

An innovative creation emerging is a tree bark-derived product found in vast quantities in many sustainable managed forests. This protective layer in a tree is used as a natural insulation material, however, it is important to place it accordingly opposite the direction of heat flow (loss) as suggested by Kain et al [23]. Currently, there is no product on the market, however, studies have been conducted to investigate its properties and even produce insulation panels. More research by Kain, Tudor & Barbu (2020) [24] experimented with urea-formaldehyde and a tannin-hexamine resin as a binder to create different panels. The bark chips were sourced from small sawmills in Salzburg and Upper Austria and the panels proved to be suitable for insulation material where thermal conductivity is not the primary focus.

Figure 7: Natural insulation (from left to right): sheep's wool, Cork, straw, & wood bark.

_Recycled insulation

Recycled products include; polyester fibre from unused bedding and winter clothing, PET recycled bottles chipped and processed into a loose quilt, cotton fibre from unused textiles made into thread and shreds bonded together to form a quilt/ batt product, and finally cellulose fibre from newspapers. Although recycled insulation is made of synthetic products, recycling them minimizes the number of products which end up in the landfill contributing to overall sustainability and promoting a circular economy. Insulation which is classified as recycled insulation has different recycled content and even some of the insulation which is made from natural raw materials contain some percentage of recycled material which can be seen in Table 1.

The Inno-Therm company based in France produces recycled cotton fibre insulation based on the recovery and re-processing of textiles such as jeans and velvet in factories located in France, Belgium and the Netherlands. The product uses 85% recycled cotton and 15% PES (Polymer binder) for their products. Old jeans tend to leach over time therefore they do not contain VOC emissions which can contribute to better indoor air quality. At the end of the insulation's life textile fibre can be recycled again which contributes to a circular economy within the construction industry.

Type of Insulation	Manufacturer	Recycled Content (%)
Hemp Fibre Insulation	Thermafleece - Natrahemp	37.5
Sheep's Wool Insulation	Thermafleece – Cosywool Roll/Slab	20
Sheep's Wool Insulation	Thermafleece - Ultrawool	20
Polyester Fibre Insulation	Thermafleece - Supasoft	>95
Glass Wool Insulation	Superglass Timber & Rafter Roll 32	82
Hemp & Jute Insulation	Thermo Hemp Combi Jute	29
Cotton Fibre Insulation	Inno-Therm - Métisse	85

Table 1: Recycled Content of certain products, source: Product technical sheets

Glass fibre insulation which is manufactured by Superglass is made from post-consumer waste. The insulation contains up to 84% recycled glass. Recycled glass is heated and when it melts it is spun into fibres that are then bonded together using thermosetting urea-extended Phenol. However, if the binder is exposed to high temperatures (above 230ºC) it can decompose and release carbon dioxide as well as some trace gases.

_Inorganic and fossil fuel-derived Insulation

Comparatively, fossil fuel and inorganic insulation are chemically formed products which are renowned for their energy intensiveness production and material origin, often petrochemically sourced. Both insulation types are often used because of their thermal performance particularly in their thickness-to-thermal conductivity ratio, i.e. reducing heat loss more effectively with a much thinner product. Inorganic mineral insulation is a popular product and is available from many wholesale distributors. Many products are produced in the UK and represent the bulk of the insulation market in the country. Most products achieve Euroclass A fire rating which indicates the level of non-combustible material in case of a fire where installed.

2.2.2. Applications & Composition

Sustainable insulation products can be categorised into three main typologies: loose fibre insulation, flexible batts, and rigid boards.

_Loose fibre insulation

Loose fibre insulation products contain fibrous materials injected at high pressure. A homogeneous filling is achieved in cavity walls, roofs, and floors. Its application is suitable for new buildings but offers greater advantages for retrofitting due to its compatibility with existing materials and less invasive installation. Loose fibre is installed through high-pressure injection apparatus providing a faster installation compared with manual board/ batt insulation that requires a frame or access to the component during construction or retrofit. Required before installation, a survey of the component is undertaken to identify the cavity depth and estimate the amount of volume covered. To inject the material, 50mm holes are bored on one side of the component, however, this might vary accordingly to the depth of the element, as the lower the depth the bigger the holes required. The density of loose fibre insulation is suggested by the manufacturer but is related to cavity depth, and the component type.

_Flexible batts

Flexible batts are ductile insulation panels suitable for compression and used between studs in walls, and rafters in roofs. The insulation application does not require high skill levels as the material can be cut with a saw, applied, and pushed between studs or rafters using a flat surface. Flexible batts are produced with the dry process, and synthetic fibres such as polyester, polyolefin, or synthetic thermoplastic polyester are used as binders to produce a product between 30-60kg/m^3 in density. Also required is a fire retardant which the industry commonly uses ammonium polyphosphate.

_Rigid boards

Rigid boards have multiple applications, mainly insulation for sheathing and sarking on roofs, externally rendered insulation for walls, and load-bearing/water-resistant insulation for below-floor screeds. Manufacturers shape the panels with tongue and groove, edges square, or shiplap edges for easy installation. A wide range of densities is offered on the market, mostly between 150 – 250 kg/m^3.

2.2.3. Characteristics, parameters & properties of performance

Most sustainable and natural insulation materials can outperform most synthetic materials by providing thermal resistance to heat loss and balancing moisture within them.

_Hygrothermal Properties

One of the disadvantages of natural insulation is that it has higher thermal conductivity than synthetic products on the market. This, therefore, places sustainable insulation products at a disadvantage if compared only with this parameter. To achieve the same thermal transmission performance (U-value) more natural insulation is needed which requires wall panels and envelopes to be adjusted and re-designed. This increases the total thickness and the cost of the project as more material is needed.

To demonstrate this, a timber panel wall has been designed with two different insulation products, where the synthetic wall panel uses PIR insulation as the baseline with a lambda (λ) value of 0.021 W/mK, achieving a U-value of 0.15 W/m^2K. To compare against, Hemp insulation by IndiNature is used instead with a λ value of 0.038 W/mK. Figure 8 shows the baseline PIR build-up wall with an overall thickness of 405 mm. In contrast, Figure 9 shows the Hemp build-up with an overall thickness of 475mm and a U-value of 0.14 W/m^2K. This shows an increase of 80 mm thickness respectively against the baseline wall to achieve a similar U-value performance[4]. Further configurations of insulation to match the same U-vale are seen in Table 7.

What is Thermal conductivity: Also known as the lambda value (W/mK), it represents the ability of a material to conduct heat through its mass; the lower its value the slower heat passes through it, hence more insulating by limiting heat loss.

What is Specific heat capacity (J/KgK): It is defined as the amount of heat necessary to raise the temperature of one unit (kg) of material by 1 unit of temperature (1K). This characteristic is also important for absorbing heat and limiting the rapid release of heat.

What is Thermal diffusivity (mm^2/s): It combines thermal conductivity, density and specific heat capacity and is a good indicator of overall thermal performance. It refers to the ability of the material to transfer and store heat but also limit heat passing through it rapidly. The lower its value the better the insulation product performs.

[4] The evaluation used product available thicknesses that resulted in a better U-value when using Hemp fibre IndiNature products.

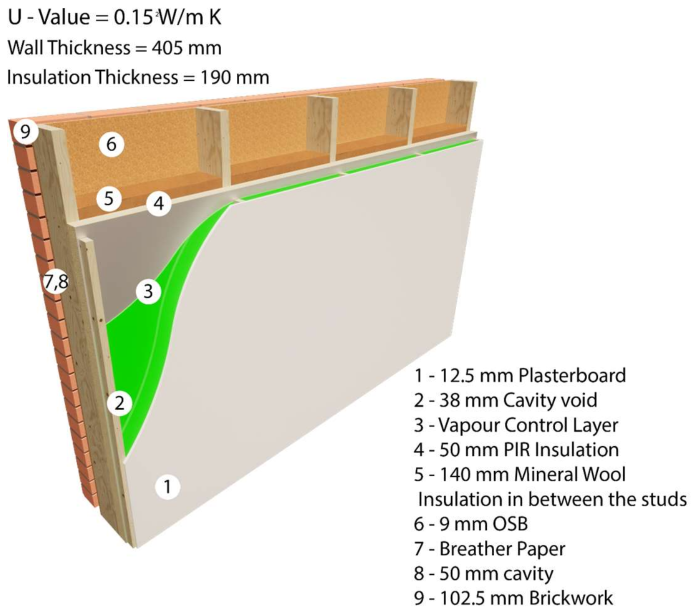

Figure 8: Mineral wool & PIR baseline wall

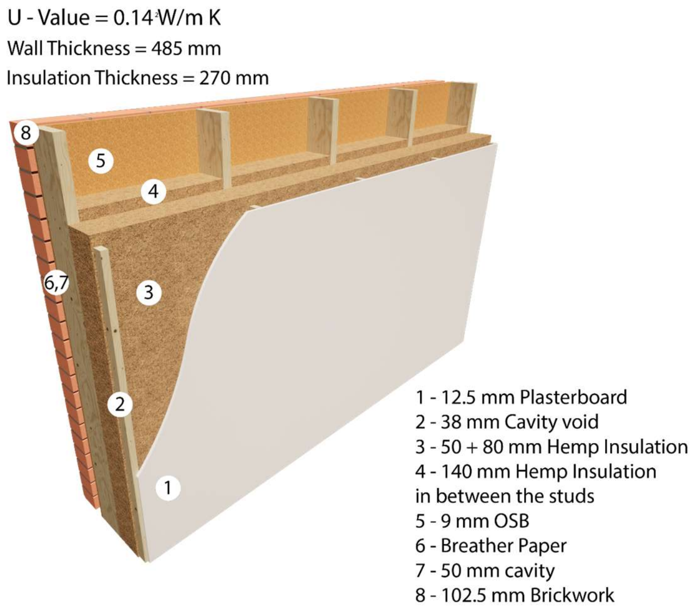

Figure 9: Hemp insulation wall example

Thermal conductance and transmittance (U-value) should not be the only measure of performance. Specific heat capacity and thermal diffusivity should also be important factors of comparison. Natural materials can manage liquid and vapour moisture (hygroscopicity), therefore all three characteristics should be analysed in parallel. Nevertheless, as the density varies between product types, the amount of heat storage and its thermal conductivity will vary, as shown in the thermal diffusivity. Also vital to consider is the vapour diffusion denser products tend to have a higher coefficient between 3.5 and 5 making them less vapour permeable. This applies for example to wet-processed natural fibre products (Wood fibres). The dry processed boards can have a diffusion resistance coefficient of 3 or lower and are more vapour permeable due to their open structure and lower density, however, require more additives and binders to hold them together. Flexible batts are less dense and have a lower diffusion resistance coefficient of approximately 1. However, a far more important characteristic is the varying liquid transport capability, i.e. how much liquid can be quickly absorbed and transported through its pores, dissipate and evaporate out (if allowed) avoiding moisture accumulation in the component (wall, roof or floor).

Wood fibreboard manufactured using the wet-processed with a similar high density as originally grown as a tree is capable of moving moisture, therefore, is considered to have a high liquid transport. The dry processed boards with polyurethane resin coats, whilst being very vapour-permeable, are not able to transport moisture very quickly, as individual fibres are bonded together which prevents the transfer of moisture between them. The flexible bats have moderate liquid transport as they are less dense and poor at transporting moisture.

_Fire resistance

All the products analysed have an E fire rating classified for combustibility according to the BS EN 13501-3 Euroclass, see Table 2. This category means that most sustainable insulation is considered a combustible material due to its flammability, thus igniting easily at ambient temperatures. However, due to the high thermal and heat capacity, the penetration takes longer though it and fire in close contact take longer to spread, for example, wood-based products tend to char rather than ignite and disintegrate quickly.

Insulation type	Fire Classification
Rock Wool Insulation	**Euroclass A1**
Glass Wool Insulation	**Euroclass A1**
Cork Insulation	**Euroclass B2**
Sisal Fiber with recycled Harris Tweed	Euroclass E
Sheep’s Wool Insulation	Euroclass E
Cotton Fiber Insulation	Euroclass E
Wood Fiber Insulation	Euroclass E
Hemp Fiber Insulation	Euroclass E
Polyester Fiber Insulation	Euroclass E
Cellulose Fiber Insulation	Euroclass E
PIR Insulation	Euroclass E

Table 2: Fire classification of analysed products

Additionally, a further review of products such as natural fibres shows that they can achieve a fire-resistance rating of REI30 to REI90, i.e., between 30 and 90-minute fire protection until it penetrates and spreads further. However, the UK Government states that in the past five years, the most common cause of death during a building fire has been gas or smoke inhalation, causing 25% to 30% more deaths than fatal burns (8). Despite this, in the event of a fire, wood fibre insulation emits less toxic gases producing up to ten times less smoke than synthetic insulants (9).

_Waste – material circularity

Sustainable products were analysed to comply with current European Waste Codes (EWC) 030105 by indicating their level of non-hazardous waste products and materials such as sawdust, shaving oils, cutting residues, wood and particle board. Additionally, most plan-based fibres and no-fibres achieve the EWC 170201 code classified as wood or similar. Most of the information obtained was available in the technical sheets or available Environmental Product Declarations (EPDs). In addition, natural insulation products are biodegradable and used as biofuel as it provides a calorific value of approximately between 15-19.3 MJ per kg, with the potential to generate heat and electrical energy. The waste disposal and re-use of a product and its capacity to be recycled and disposed of appropriately at its end of life are becoming increasingly important. There are three main aspects that the analysed companies prioritise:

- use of waste material (off-cuts, shavings and sawdust) as an energy source during the manufacturing process;
- products at their end-of-life can be recycled or compostable;
- removal of any formaldehyde (or similar) emissions from products.

Natural fibre and non-fibre insulation can positively contribute to a building's circular economy as it’s a product that can be re-used and recycled and once at their end of life, it’s naturally disposed of without ending in a landfill like other products. However, other insulation products such as stone wool insulations claim to be recyclable and dedicated recycling facilities are available in the UK. A study comparing the types of insulation products that were recycled and disposed of appropriately found that the UK recycles 33% more EPS/XPS insulation than many EU countries. A study conducted by the University of Sheffield has shown that wood fibre insulation boards are 50% more resistant to compression compared with EPS boards and phenolic foam, thus resulting in less damage during its extraction at the deconstruction stages, benefiting the collection and recycling process [24].

_Toxicity & Health Benefits

During this analysis, it was found that natural products in these materials were high and in some such as wood fibre, its content ranged between 80% and 98.5%. In most products, it is common to use synthetic materials as additives such as binders and flame retardants. Binders constitute between 3.5%- 6.5% of the mass for rigid natural fibre boards produced, and up to 10% in flexible batts. The less common materials and those through recent analysis, have incorporated natural binders, such is the case of cork which one manufacturer claimed used natural rubber resins. Flame retardants applied to flexible batts constitute between 1.3% and 8% of the product's total mass. Rigid high-density boards typically contain hydrophobic agents such as paraffin which constitute less than 1.5% of the product's total mass.

Furthermore, established companies such as many of the wood fibre producers (Steico & Pavatex) conform to the NaturePlus certification. It’s an international eco-label for sustainable building products, founded in Germany by specialist building materials suppliers and trade co-operatives, Who only certify products that are comprised of a minimum of 85% of renewable raw material, or are from mineral-based materials. Other requirements for the certification are as follows [25].

- only mineral additives are allowed as flame retardants;
- waterproofing agents should not exceed 2% of the dry weight of the product;
- synthetic binding agents should be limited to ≤4% of the dry weight of the product.

Also worth considering are the benefits to occupants wider health where the use of natural materials can improve people’s perception of space and provide more calm environments to work and live in. Although insulation products are often hidden within the building fabric, the hygrothermal benefits of moisture and heat balancing have an overarching effect and positive impact on occupants thermal comfort and indoor air quality.

_Well-being potential – Indoor air quality

Petrochemical-derived materials tend to produce pollutants during their manufacture and when used in closed environments have a tendency to off-gas volatile organic compounds (VOC) which when occupants are exposed for long periods can produce detrimental health problems.
For instance, there is substantial evidence to show negative effects to occupants in buildings that have been exposed to sprayed polyurethane foam (SPF) insulation with unreacted methylene diphenyl diisocyanate (MDI) [26]. Side effects include negative and increased occurrences of

asthma, itching and burning eyes, headaches, dizziness, and difficulty concentrating. Naldzhiev et al. [25] in a recent academic paper of 2019 conducted a study on the effects of isocyanate board insulation (PUR/PIR) and spray polyurethane foam (SPF) insulation products and their impact on indoor quality. Despite the risks of exposure to VOCs and SVOCs during the installation of SPF even after one month of its application, the long-term effects of such products on the building's indoor air quality (IAQ) have shown that occupants' concentration and productivity diminish resulting in staff absences and long term illness.

In contrast, fewer health risks are associated with the use of natural fibre insulation, mainly due to the product's moisture balance inside the building coupled with good building detailing to reduce thermal bridging and gaps in insulation. Evidence shows that if poorly designed or applied, regardless of what insulation product is used, this can lead to mould growth and other health problems.

_Acoustic performance

It is essential to consider an acoustic layer to absorb sound and provide acoustic performance in buildings. Sound insulation is achieved in three ways: reduction of airborne sound or noises that move through the air (e.g. talking, music, traffic noise), impact sound caused by something striking something else (e.g. footstep, moving furniture, rain noise) through walls, floors, ceilings and roofs and flanking noises those that travel through, under or over a sound barrier. This is the case of the building's structure using steel, concrete and timber. A useful characteristic is the product's density, mass and position within the construction component and layer. Less so, is the thickness of the materials in absorbing sound, hence the importance of the product's density. In the case of wood fibre insulation, products often produced using the wet system, reaching densities above 100 kg/m3, can support effective noise protection. Wood fibre and others such as hemp and other natural fibre insulation products uniquely combine high bulk density with low thermal conductivity and thus equally support energy efficiency and noise protection [26].

_Global Warming Potential (GWP) & Embodied energy

Global Warming Potential (GWP) has been developed as a metric to compare (relative to another gas) the ability of each greenhouse gas to trap heat in the atmosphere. Carbon dioxide (CO_2) was chosen as the reference gas to be consistent with the guidelines of the Intergovernmental Panel on Climate Change (IPCC). GWP is often referred to as the embodied carbon of a product or materials where carbon emission equivalent accounts for the total impact on the environment, with the units $kgCO_2e$. It measures the carbon emissions released during the life cycle stages of the product or material. The higher the GWP of a material, the bigger the impact it has on global warming.

For this research life cycle boundaries A, A2 & A3 have been included, also referred to as cradle to gate. These 3 stages include the energy and carbon released and stored during the extraction of raw material, transportation to the manufacturing plant and processing it into a product. The majority of natural insulation available in the UK is shipped from its origin, however, sheep's wool is fully manufactured and sourced in the UK. As manufacturing takes place within the UK, less transportation is required therefore GWP is lower at stage A2. Table 3 shows the GWP of some products compared with synthetic equivalents.

Material	GWP ($kgCO_2eq$): FU: m2	GWP ($kgCO_2eq$) : FU: m3
Mineral Wool (roll 30.7 kg/m³)	3.6	36
PIR (board 32 kg/m³)	16.9	169
Glass wool (low density)	5.12	51.2
Hemp Fibre (roll 35 kg/m³)	-2.22	-22.2
Sheep's wool (roll 18 kg/m³)	0.05	0.5
Sheep's wool (slab 31kg/m³)	0.0461	0.46
Recycled PET (slab 15kg/m3)	1.27	12.7
Wood Fibre - high density (210kg/m³)	-25.59	-255.9
Wood Fibre - med density (140kg/m³)	-16.51	-165.1
Recycled paper Cellulose (loose)	-7.8	-78
Cork (board 130 kg/m³)	-19.8	-198
Straw	-11.587	-115.87

Table 3: GWP Comparison table (Functional Unit (FU): 1m² & 1m³)

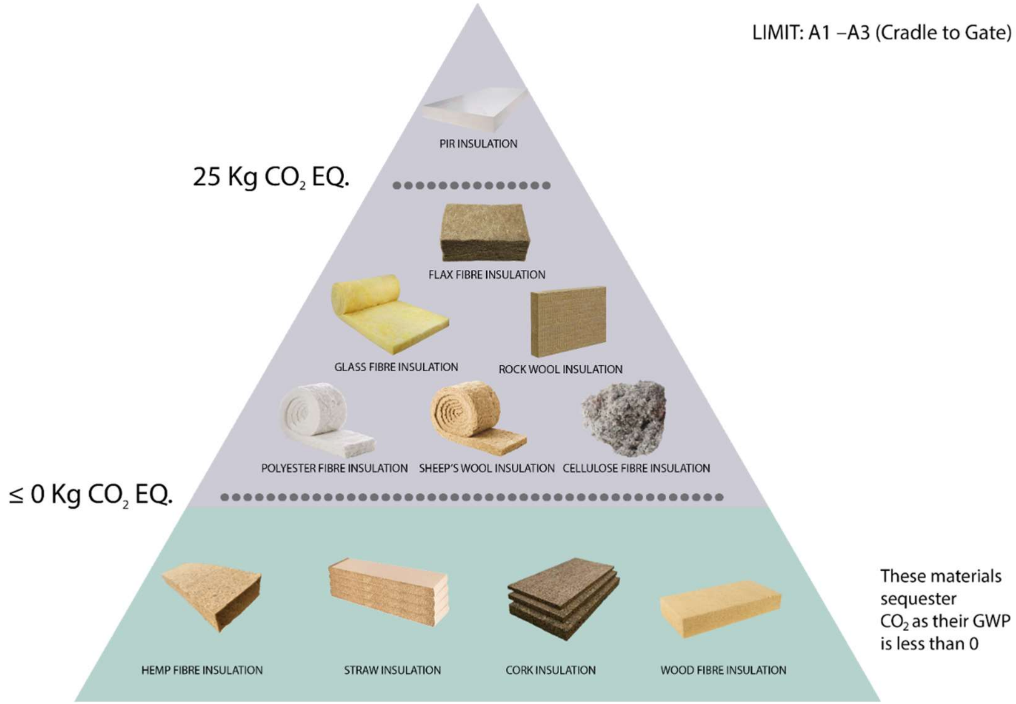

Figure 10: GWP pyramid of insulation products in the UK – FU: 1m²

The term embodied energy is also used in EPD certificates as a measure of the amount of energy required to produce a product or material. In most evaluations, there is a balance between the energy from fossil fuel and renewable energy consumed in each lifecycle stage of a product or activity including that used in extracting raw materials, the processing and manufacture of products, maintenance and repair and end-of-life disposal. The unit of assessment is mega joules per metre cubed of material (MJ/m^3) and is often converted into kWh/m^3 of material and compared over the lifespan of a building, typically 60 years.

Even though natural materials tend to have higher thermal conductivity values (more conductive), and they do not achieve the highest fire rating, the entire life cycle and its environmental impact outstrip most synthetic equivalents, making them more environmentally friendly. As can be seen in the GWP pyramid for UK-sourced insulation materials, those with a GWP ≤0 (zero) has a minimal environmental impact, some absorb carbon, and many sustainable products absorb or sequester CO_2 which means it locks in carbon rather than emit any throughout its life time also referred to as a carbon sink. Examples of insulation materials good for storing carbon during their growth later maintained after processing are hemp, cork and wood.

2.3. Benefits

The associated benefits of using sustainable insulation over synthetic products are generally applicable in both new and retrofit interventions in existing buildings. The industry is particularly focused on thermal conductance and overall contribution to the reduction of U-values, however, as discussed, this is not the only determining factor and users need to look at the broad spectrum of benefits in the short and long period. There are six main benefits aligned with the use of sustainable insulation.

- Recyclable: capacity for the material to be re-used with minor changes to its composition or be re-purposed.
- Durability: the length of time the material is in use once installed and in use.
- Indoor air quality: the benefits it provides to occupants in an indoor environment.
- Low carbon emissions: its capability to lower emissions by decreasing heat loss.
- Breathability: low vapour permeability, allowing any moisture to dissipate rather than remain on the surface or in the material.
- Global warming potential: the capacity to emit less carbon during its processing and the raw material sequestrated carbon.

More information on these is as follows.

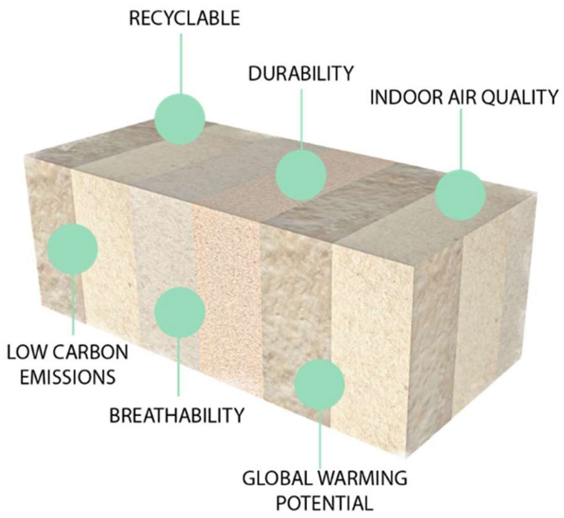

Figure 11: Benefits of using natural and sustainable insulation products

_Recyclability

An estimated 120 million tons of construction, demolition, and excavation (CD&E) waste were produced in 2016, while in 2018, 137.8 million tons of waste were produced [24]. One of the main benefits of natural insulation is that at the end of its life it can be recycled, re-processed or it can even used as compost in gardens. Eliminating materials ending in a landfill helps to tackle the issue of waste during construction.

_Durability

The durability of materials is important to plan and optimise maintenance plans for certain materials installed in a building. Equally, even with project estimates of 60 years of life expectancy, many outperform their performance, however, it is important to evaluate and track performance. Some materials, mainly those exposed to the elements, have a shorter life expectancy, which requires the detailing and design of components to withstand fluctuations and weather changes, particularly if planning for climate change resilience is in mind. Work by Landlfi & Nicolella [27] applying accelerated ageing of insulation materials concluded that product life-cycle assessment must take into account service life and durability for each material and that after such studies, natural materials showed little changes with minimal reduction in thermal conductance.

_Breathability and Indoor Air Quality

Natural insulation is breathable due to its hygroscopic properties. It stabilizes indoor air's humidity levels by absorbing and releasing moisture and reducing condensation risk within the wall, floor, and roof build-up. Consequently, it reduces the risk of damp issues and increases indoor air quality allowing for temperature balancing and reduced heat loss. Sustainable materials tend to have less toxic adhesives, despite the bonding agents used. If compared with synthetics, the level of off-gassing is minimal and during manufacture, there is a reduced amount as may constitute less than 10% of the materials.

Considering the specific heat capacity and thermal inertia of materials is becoming more important as structures are often built with lightweight rather than heavyweight structures, hence relying on other materials to provide that mass to the envelope. The main benefit of adding mass to construction is that it provides thermal mass within the building and the capacity to absorb, store and release heat resulting in a more stabilised indoor environment and can reduce temperature fluctuations. However, the main disadvantage is the materials which can be used as a thermal mass tend to have high embodied carbon which has an impact on global warming and a balance is often the best approach.

Sustainable & most natural insulation outperforms synthetic insulation as it has higher specific heat capacity which means it takes longer for the material to heat up and transfer the heat which avoids indoor overheating and a decrease in thermal comfort. High specific heat capacity is a feature of materials providing thermal mass. For more specific heat capacity values please refer to the table in Appendix A.

_Low Carbon Emissions and GWP

In analysing carbon emissions of building materials, the whole life span of the materials needs to be considered, even at its disposal and possible re-use. Natural insulation has low embodied carbon and often can be considered negative given its capacity to lock in carbon absorbed during its life, i.e., the carbon absorbed by a tree over its 20-30 years as an active carbon sink. That carbon is kept in the product until released (burned into the atmosphere). The process of making insulation out of natural materials is less energy-intensive which only adds to the sustainability of the natural products. Even though natural insulation increases the thickness of the wall/roof/floor due to the higher thermal conductivity, the additional embodied carbon does not exceed the energy savings [28]. As natural insulation sequesters CO_2, the process of manufacturing it is less energy-intensive and at the end of its life span it can be recycled or it can even degrade global warming potential is a lot slower than the GWP of synthetic insulation.

3. Challenges & Barriers

This section introduces the key challenges and barriers that need to be addressed and in turn, brings opportunities to the industry for the adoption of natural and sustainable insulation products in Scotland and the UK. These can be summarised in Figure 12 and explained further in the points below.

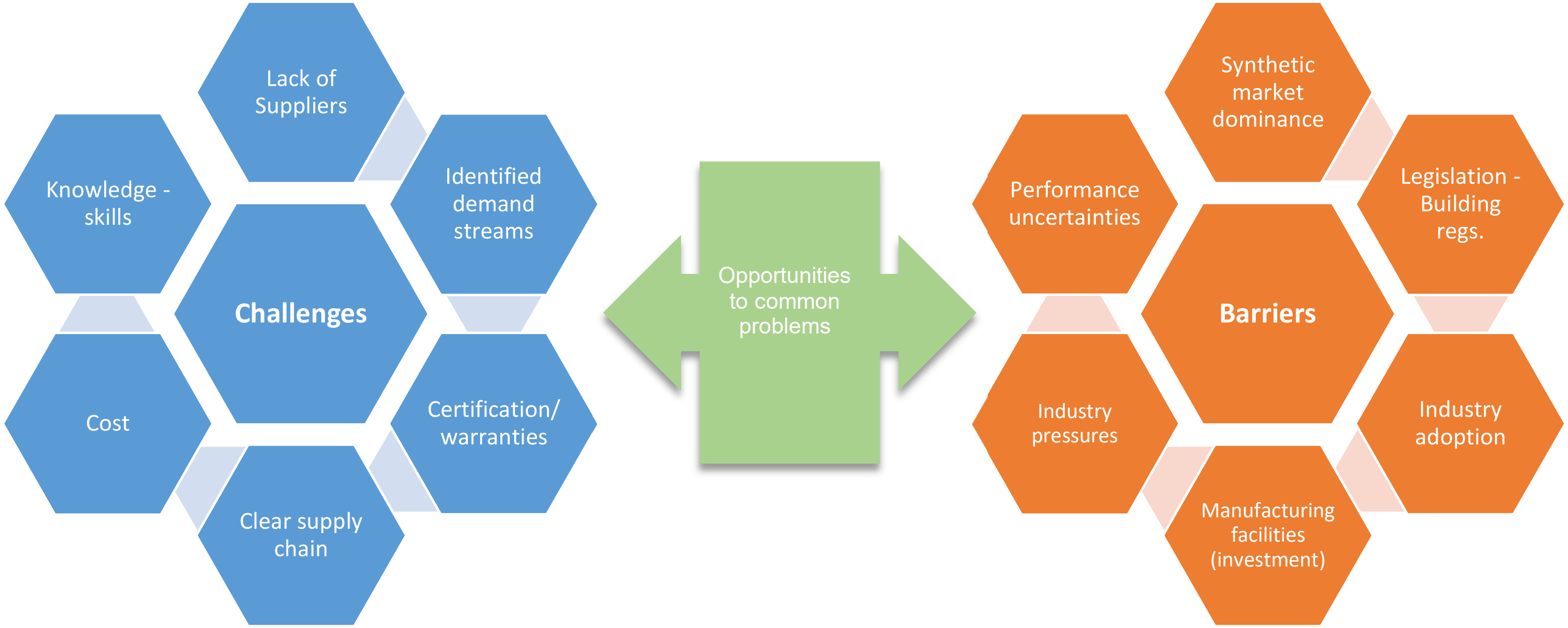

Figure 12: Challengers and barriers diagram

3.1. Challenges

Challenges	Opportunity	Discussion
Lack of suppliers: Although there are identified suppliers, who specialise in such materials (representatives and retailers) most are located in England/ Wales. UK mainstream retailers need to provide such products more freely to their customers. Large UK retailers have a handful of recycled insulation products, however, natural insulation is rare and most advertise such products on a demand basis.	Although the demand is low at the moment, suppliers have an opportunity to influence that demand by advertising and playing a leading role in the availability of such products. This can make consumers consider such products if easily available and on display. As demand grows, suppliers can increase stock.	Without an identified demand and supply for such products, this first step by suppliers may create uncertainty and risk.
Identified demand streams: It is unclear where the demand is heading and how policy influences this to create clear markets. The retrofit market is a clear demand area, however, it is not backed fully by incentives and government support. The net-zero agenda will also enable change, however, the industry is slowly picking up on the role that natural insulation plays and how to adapt designs and methods of construction. The benefits are clear, but the driver is not clearly defined by the policy.	There needs to be a clear identification of the market enablers and demand streams. Creating policy-driven standards that set a staged approach to net-zero carbon performance highlighting natural insulation as a clear solution, will create quantifiable market uptake to inform production and give the confidence to supply chains.	Three clear demand streams emerge that need to be strengthened and assured with the dedicated market size. These are: - New builds: domestic and non-domestic - Retrofit: domestic and non-domestic - Innovation in composites and new products There is a great demand for isolated retrofit building projects as well as for small new buildings. If this small-scale supply is established, larger developments and projects will take notice and demand will grow.
Certification & warranties: The off-site timber panel industry and house builders in Scotland and the rest of UK are sceptical of switching to natural insulation as they have already invested in certifying their systems. Making the change would require more tests and validation, despite existing products already holding these assurances.	Existing products from the EU and in the case of sheep's wool in the UK have individual product certifications, however, some industry stakeholders don't have assurances about its use inside closed timber panels, such as for fire, humidity, etc. This creates opportunities to provide knowledge exchange between academics and industry as well as partnerships to provide that testing. Nees government backing to support such testing if required.	Warranties and the uptake of materials used to come from the industry professionals (architects & engineers) when specifying and implementing new products through their liability, however, now its shifted to independent warranty groups (NHBC, etc) and building control taking away that professional judgement. Local Authority certification isn't taken up that much in new product use. Some manufacturers of off-site products don't want to take the risk and invest in new tests.
Clear supply chain: As demand grows, relying on imports will no longer be fully viable which will require support and manufacturing capacity in the UK. The raw	There is an opportunity to engage with relevant industries (sawmills, raw material suppliers, recycling ventures and manufacturing options) to outline partnerships and	Shared facilities such as manufacturing plants would facilitate the production stages, however, there needs to be an alliance with sustainable timber yards/ suppliers

materials and most supply chains are in place, however, the connectivity between these and investment into machinery and factory setups is slow and recently stalled by COVID and the 2022 cost-of-living crisis	ventures that can define the supply chain. Innovation in certain components is essential that can avoid highly toxic or petrochemical-derived adhesives/ binders.	and with recovered timber from pallets, furniture and deconstruction. Also timber from hardwoods and softwoods between England/ Wales and Scotland to assure supply at the manufacturing point aligned to demand.
Cost: natural insulation remains a niche product which is not readily available and requires large orders to lower cost. Off-the-shelf products are rarely available and usually at a high cost per unit.	As demand increases, costs should lower, however, the current premium price is a concern as it easily deters any knowledgeable client of such products. There are opportunities to inform clients better of the added benefits against alternatives.	Current costs are driven by availability in the region but are generally lowered if large amounts are needed. Partnerships between existing brands and retailers are required in Scotland, to make such products more affordable in existing retailers (B&Q, Wickes and others)
Knowledge & skills: Specifiers, contractors and small-scale trades are unaware of these products and their capabilities or benefits. This creates a gap in industry knowledge which ends up in neglect and unjustified criticism. Industry-wide promotion, marketing and awareness are required with recognised theoretical and practical training.	The creation of CPD and technical training programmes is essential to de-mistify and increase knowledge leading to larger uptake and recognition of such materials. Knowledge transfer and new skill training can be provided at different scales and levels that can enhance awareness, and provide new knowledge through technical and practical training. Funding from Scottish Futures Trust (SFC) and Skills Development Scotland (SDS) can provide this to support the industry with the long-term approach to increase the market and uptake.	A clear area of growth is the existing buildings retrofit market therefore it is essential to strengthen the knowledge of the best application of materials in separate interventions. For example, low-density batts in roofs and rigid boards under the floor and existing stone walls. There are uncertainties about vapour permeability and the need for VCL membranes and overall the effectiveness of materials, impacting cost and best practice installation.

Table 4: Challenges faced by the NFI industry

3.2. Barriers

Barriers	Opportunity	Discussion
Synthetic market dominance: Most of the available products on the market are synthetic with some post-processing of recycled content. This makes it harder for specifiers to change original build-ups and invest in certification using alternative measures. Influencing change is difficult as it requires matching alternatives that provide like-for-like performance.	With adequate knowledge and increased demand, the industry can push for change and make NFI more competitive at varying scales. Most house builders/ contractors are not tied to a product unless it's for a particular project. This creates opportunities for trials and partnerships to introduce NFI alternatives.	Currently, only PET recycled insulation is available in most wholesale shops such as B&Q, Wickes and Jewsons. Also available through specialist suppliers are cellulose, sheep's wool, Hemp fibre and wood fibre, however, these need to be purchased with anticipation and as a bulk purchase in most cases. Other more innovative materials can be experimental and at a high cost and not commercially available in large quantities.

Legislation - Building regulation: Influencing policy remains a barrier as unlike Germany and France which have built-in NFI guidance into building regulations compliance, it remains a barrier between the net-zero targets and the practical implementation of low-carbon materials. Clear net-zero carbon regulations are needed to embed circular construction practices.	The Scottish Government has recently had a consultation on the introduction of a Circular Economy Bill with a Route Map to 2025. This creates an opportunity for dialogue on the supply chains and the role NFI has in the use of recycled supply chains, natural resources and embodied carbon benefits. It will promote and support responsible production and consumption as well as limit the landfill of construction products.	Despite the named consultation, there still remains a barrier on specifically advising the use of NFI and other natural products which can drive certain designers and specifiers towards the use and installation in projects.
Industry adoption: This remains a difficult barrier to overcome as the industry seems adamant about only specifying and designing with synthetic products. The industry's slow uptake of innovation and new methods is directed by policy and the "business as usual" attitude is driven by old practices and reluctance to change.	The U-value-driven approach of the industry, influenced by building regulations, has narrowed the adoption of new materials that may give higher U-values but can provide other benefits and improved performance (moisture balance, CO2 and thermal mass). By highlighting alternative benefits and influencing change and policy change this can be shifted slowly.	Skills development at all levels and analysis of building envelope build-ups with NFI should provide assurances and open up dialogue into benefits beyond U-values.
Manufacturing facilities: Currently there is little investment into the UK production of NFI or other sustainable insulation products. Some funding has been provided to emerging products for new manufacturing sets up's but it does not expand across other products and supply chains.	There is an opportunity to create partnerships between manufacturing that have received funding and those that have a similar process to some NFI's. One example is OSB and MDF composite boards that share similar supply chains but undergo different density levels. There is also a lack of investment from established products in the EU into the UK, driven by the lack of policy and stable growth in the market.	Partnerships between existing and new products seem the way forward, however, the use and enhancement of the performance need to be explored further to match or improve synthetic products. Supply chain issues and agreements need to be in place to push forward investment into manufacturing setups. Also important is a defined demand to make it worthwhile.
Industry pressures: This is a well-developed industry that is embedded into our society. Any policy-driven change will need to overcome the weight of different sectors, (raw material extraction, plastics and chemicals). Political commitments and long-term agreements are difficult to set aside.	Synthetic products have their place in the market and will always be stronger than NFI's and recycled products. The government needs to identify the markets where NFI's can exist and incentivise their uptake.	Although there is clear dominance from certain products, there will eventually be a stronger push for NFI's to develop and innovate. This is the case in the EU where certain countries give tax levies and other incentives for the uptake of NFI.
Performance uncertainties: One main barrier is the industry-driven U-value performance of buildings which disregards other qualities such as humidity and heat control, the global warming potential and acoustic	There is an opportunity to conduct research & development in the enhancement of thermal conductance values of NFI's while maintaining its current benefits. This also allows for the measurement of U-values in different	All insulation products have a declared thermal conductivity value, however once installed the holistic benefits do not compare with NFI's.

qualities that NFI's and some recycled products provide. In many cases, thermal conductance and higher thermal resistance values drive a design and its specification.	settings such as new buildings and in the retrofit of existing buildings.	

Table 5: barriers faced by the NFI industry

4. Market analysis & cost review

From 2013 to 2015 the UK market for building insulation products experienced a downturn, driven by a significant fall in government subsidies, such as following the end of the Carbon Emissions Reductions Target (CERT) and the Community Energy Savings Programme (CESP), which incentivised the retrofitting of insulation and the scrapping of the Green Deal due to financial constraints and poor uptake. In 2018, according to the Alliance for Sustainable Building Products (ASBP), the market share alone for natural insulation products in the UK was worth less than 0.1% of all insulation sales compared with 6% in Germany, partly due to government policy on such product use, incentives and funding. Various forums and sales reports by UK distributors of natural insulation products estimate that between 2022 and 2023 the UK market will grow and may be worth between £2 million to £3.5 million or less than 0.20% of the total insulation UK market [5]. Such uptake of materials is minimal compared to the synthetic and inorganic products widely available for contractors in large developments and the D-I-Y market. This is the case of PIR/PUR products which now hold the largest market share, due to a combination of thin profiles balanced by high thermal performance and ease of handling on site.

4.1. Challenges

A recent sales report for Steico, a major wood fibre insulation producer, indicated that in the UK comparing the first quarter of 2021 with that of 2020, there was a decline of 2% in revenue from €7.5 to €7.4 million. However, this included all their products and not only wood fibre insulation. Overall the revenue of wood fibre insulation alone experienced an increase of 30% from 2020 to 2021 which indicated the uptake from the rest of the EU on the use of such products. This represents an increase of €15 million in sales from €47 million to €62 million.

[5] Due to the post-COVID recovery and the rise in energy costs.

By contrast, as stated by the ASBP natural insulation materials in the EU represent between 5-10% market penetration. In France, for example, all public buildings require the use of at least 50% of total materials from natural sources by 2022 which creates an important driver for the uptake of natural insulation products. Past statistical analysis has shown that the UK represents a fifth of the total EU insulation sales. It is estimated that EU sales of natural insulation range between €250 and €300 million meaning the UK market can be worth approximately €55 million or just over £45 million, indicating room for growth in the uptake of natural insulation products.

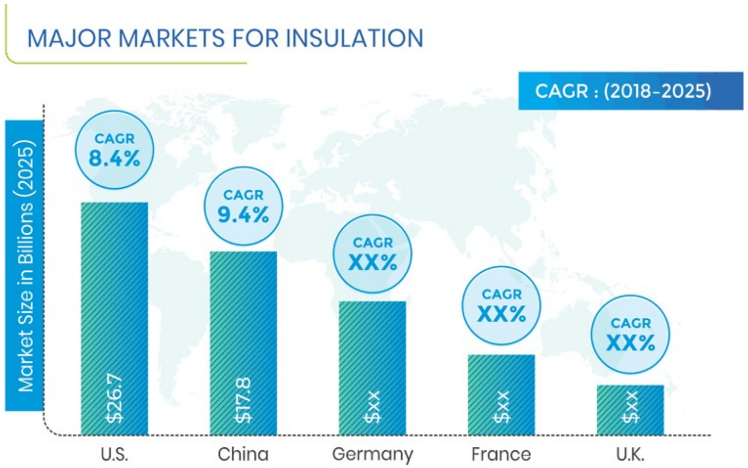

Figure 13: Compound annual growth rate (CAGR) of insulation by country, source: P%S intelligence, www.psmarketresearch.com

Internationally, the insulation annual growth in sales is defined by the compound annual growth rate (CAGR) which indicates the market size as shown in Figure 13. EU currently has the largest CAGR % due to the focus on sustainable approaches, energy efficiency and incentives. However, the UK remains at the lower scale of the insulation CAGR and to match that of Germany, its CAGR% would need to grow by 20 to 30% in the next decade[6]. The natural insulation market of Germany remained at 10% for 15 years to reach the levels it has at the moment, possible through incentives, commercial partnerships, improved skill set of the construction industry at all levels and production capacity that grew with demand. The UK requires similar distinct financial support if it's to fulfil its potential and increase demand.

[6] From Mark Lynn, Managing Director – Eden Renewable Innovations Ltd (Thermafleece), Vice-Chair – The Alliance for Sustainable Building Products. Environmental Audit Committee: Inquiry into Energy Efficiency of Existing Homes.

Natural insulation imports from continental Europe have not yet been directly impacted by the trade changes introduced by Brexit. Discussions with UK distributors have highlighted that a slight delay in getting products has been due to increased paperwork when arriving on UK soil causing more bureaucracy in the approval and customs arrival. Changes in UK legislation, certification, product criteria and performance are currently undergoing some restructuring from those set up by the EU, however, large changes aren't expected. More of a concern is the delivery delays and shipping of such imported products into the UK, due to shortages in delivery drivers and border checks.

In the UK, the building insulation end-user market shares have also changed over recent years. The dramatic fall in household energy efficiency incentives and grants means that the domestic retrofit market no longer represents the largest end-use sector, now accounting for less than a third of insulation installed by area. This has resulted in the non-domestic market having the largest share by end users, mainly flat roofs and site-built metal cladding and roofing systems.

4.2. Market opportunities

The market for insulation products is related directly to the two dominant sectors; new-build and retrofit homes and non-domestic properties. To obtain a relationship between the potential for insulation products and their use in buildings it is important to extract the latest new-build and retrofit completions in Scotland. To provide an overview of new homes built in Scotland, the latest Housing Statistics Quarterly Update of June 2022 indicates a rise in all sector new housebuilding completions by 26% since September 2021. In 2019, completions reached 22,000, similar to a previous high of 25,000 in 2007. However, the COVID lockdown measures reduced housebuilding by 33% to just over 15,000 completions not experienced since 2013. These figures include private, housing associations, local authorities, rehabilitation[7] and conversions[8] homes. There were 2,364 housing association new build completions in 2020-21, a decrease of 1,840 homes or 44% from the previous year. Local authority new build completions totalled 1,411 homes, a decrease of 57 homes (4%) compared with 2019-20. A total of 11,023 homes were built by the private sector in 2020-21, a decrease of 5,344 homes (33%) from the 16,367 homes built in 2019-20. Analysing these sectors better, the 3,750 completions from a housing association and local authorities, are the least inclined sectors to change from existing supply chains of

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[7] Rehabilitations include houses acquired by housing associations and refurbished either for rent or low cost home ownership. Refurbishment of private dwellings funded wholly or partly through the Affordable Housing Supply Programme (AHSP)
[8] Conversions include net new dwellings created by conversion from non-domestic to housing use or by alterations to existing dwellings in all tenures.

synthetic insulation methods, despite this being a future growth area through changes in legislation. The private house-building sector can be split into two: self-built single dwellings and large developments by private house builders. It is estimated that in Scotland approximately 1,600 homes in 2019 [9] were self-built representing an estimated 10% of the private market. For the 2020-21 period this would equate to 1,100 self-built homes and just under 10,000 larger ones. Through better marketing and client/ architect education, the self-build new housing market is estimated to grow, making this an important sector to follow for wall, roof and floor insulation being supplied with natural fibre insulation. Larger developments can also be a growth market, however convincing private developers to change to a more expensive product will require education, set building component design changes and specific NFI policy-driven uptake incentives similar to Germany and France.

The existing building sector is a more attractive market for NFI. From the above housing statistics, 560 homes in the 2020-21 period included rehabilitation and conversions, which offers a glimpse of registered retrofit projects in Scotland. Peak rehabilitations and conversions were reached in 2017-18 with 1,700 completions followed by a steady decline due to a decrease in incentives and a lack of government help. These do not include the D-I-Y market of house retrofits nor the privately owned and rented homes that require and undergo retrofits at various scales. To do so, Scotland will encourage home owners to achieve EPC band C or above by 2030. This leaves the potential to improve these properties which in Scotland currently represent 96% of existing homes (2,400,000 homes). Solid wall insulation remains the untapped market as most homes in Scotland including the UK have experienced a decline in installations of loft and cavity wall insulation, see Figure 14, and a remaining potential of solid wall insulation installs of 92% compared with 33% loft insulation and 26% of cavity wall insulation, as seen in Figure 15. In Scotland, 22% of privately owned homes have uninsulated solid and NFI and some recycled products are an ideal solution due to their humidity buffering and compatibility with existing materials. The non-domestic sector does not hold such statistics, but it is known that there are approximately 230,000 privately owned buildings with those over 1000 m2 undergoing energy improvements since 2016. It is unknown how many of these are solid wall construction, however, many of Scotland's towns and cities have pre-1919 buildings with low levels of energy performance with C or lower EPC band performance.

[9] According to statistics by the National custom & self build association (NaCSBA) - https://nacsba.org.uk/news/single-dwelling-data-shows-self-build-numbers-growing/

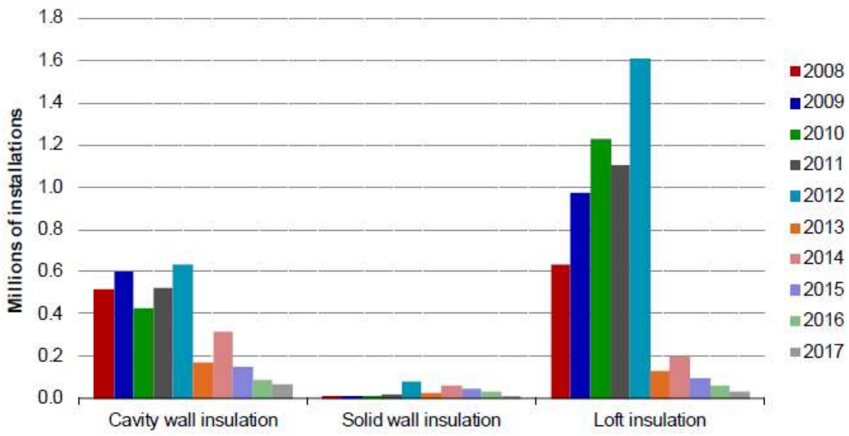

Figure 14: Insulation in UK homes[10].

Figure 15: Potential of insulation methods in UK homes.

Key trends over the next few years include; a decline in output for key non-domestic construction sectors, slower growth in new housebuilding compared to 2016-17, limitations in Government funding and new schemes to support installation, and reduced levels of consumer and business confidence due to uncertainty regarding the EU exit situation. Despite increased fuel prices in the UK in 2022, the UK government is more inclined to support the energy production sector, rather than the reduction of energy demand, which may produce more uncertainties for the creation of insulation products.

4.3. Scottish companies & construction industry perspective

This section of the report outlines the perspectives of two Scottish and one English manufacturer with emerging insulation products available through their website and some UK retailers. A more Scottish-based perspective is offered by the outcomes of interviews with representatives from one private housing developer, a Local Authority, two house builders/ contractors and two registered social landlords (RSL's) or housing associations.

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[10] Annual insulation installation rates under Government programmes (2008–2017), Source: Committee on Climate Change, UK Housing: Fit for the future? (Feb 2019), p.29

_UK-based NF+RI manufacturers

Three company case studies are analysed as part of a fact-finding and industry perspective analysis where two were interviewed and one was analysed via an existing EU-funded project, see Appendix C. Three case studies are made to explain the products and the current stage of product development as well as the perspectives on two relevant topics from a semi-structured set of questions:

1. **Market and investment insights**
   - **1.1.** How do you see the market for NFI in Scotland & UK?
   - **1.2.** Can NFI be competitive against synthetic insulation? Does it need to be? Or does it remain a niche product?
   - **1.3.** Have you had any success in making your product widely available to users?
   - **1.4.** Do you envisage any UK supply chain partnerships for your products? Or is your plan to stay local and independent?

2. **Manufacturing facilities**
   - **2.1.** Can you give us a summary of your current manufacturing plans?
   - **2.2.** How has the recent funding been put to use?
   - **2.3.** Are you open to partnerships with other NFI supply streams i.e. wood fibre?
   - **2.4.** What is your take on the Scottish government's appetite to invest and help these industries? Is it on their radar?

Two emerging companies in Scotland; Indinature and Sisal Tech, as well as a UK-based company (ThermaFleece), provided some key insights and perspectives to the questions which are summarised in Table 6.

Topic	IndiNature	SisalTech	ThermaFleece
1.1 Scottish & UK market	Some uptake & growth especially after the pandemic restrictions. Still difficult to get users motivated to take on NFI products.	The market is still very small and tends to either be people who are very concerned about sustainability, or people who have traditional/historic buildings and want to maintain breathability / avoid dampness.	Steady growth, largely by eco-conscious self-builders and owner-occupied retrofits. Some eco-specialists have a large interest but the private rental sector and housebuilders are generally not interested in the uptake of NFI's.
1.2 Competitiveness against synthetic	It remains a niche product but can outperform synthetic in many aspects so can gain	Currently, it is not due to economies of scale. However, the price differential is narrowing as	There are many barriers mainly the industry's lack of change and uptake of new methods/

	popularity in the retrofit market. Education is the key to gaining popularity while promoting the product. Conductivity result-driven market, should focus on airtightness of building.	carbon intensive products are currently increasing in price due to the increased cost of fossil fuels. The most significant change will come when building regulations start to take embodied carbon into account. It needs to be competitive if we want to move away from everything being plastic based and want to stop filling landfill with foam offcuts.	products due to lack of education. There are also fire concerns and cost seems to make competitiveness less likely and more one-sided towards synthetics.
1.3 Availability to others	The product range fits many uses. Available to order via the website. Little uptake from big retailers. Trade shows bring in some clients.	Sales is our current focus. The biggest challenge in getting into large builders or council use is the lack of BBA certification.	Making it available in all eco retailers as well as some larger regional suppliers.
1.4 UK supply chain partnerships	Recognise the link with wood fibre production, but it has an added complexity. Sawmill's variability of fibres is not uniform and is untraceable. Mixed timber fibres with treated wood fibres. Some R&D is in the pipeline.	Yes we are already in a couple of smaller stockists such as https://zuben.co.uk/shop/sisalwool_100_pro/ and https://igolo.org/products/sisalwool-100-coverage-27-5m2?_pos=1&_sid=e374279c5&_ss=r and we plan to grow this.	The supply chain has not yet expanded to increase supply. Seek Government support/ funding linked to Social Housing Decarbonisation Fund. Sheep's wool is used and would otherwise go to waste.
2.1 Summary of existing manufacturing plans	Grant money and investment into setting up of Hemp fibre manufacturing plant, Jedburgh, Scottish Borders. Waiting for completion and UK hemp supply.	We are outsourcing our production to a factory in Spain and a factory in Denmark (and we ship back by sea from both). However, we are planning on opening our own production line here in Midlothian.	Already set up delivering sheep's wool with recycled fibres, hemp and recycled PET products. Based in Yorkshire
2.2 Recent funding	ZWS: £800K South Scotland enterprise: £250K NFI bank: £3M Other investors: £500K Funding is used for manufacturing equipment, CAPEX & certification (BBA).	Yes, we have been supported by Scottish Enterprise and Zero Waste Scotland, and this has been used for product development and prototyping.	None – responds to investors
2.3 Partnership with others	Yes, but requires R&D and investment. Supply chain needs to be analysed and verified.	Yes	n/a
2.4 Scottish Gov investment in the future	Existing investors require time to evaluate returns and the success of the set up. Demand-driven, but the markets will hopefully increase popularity of the product. Certification costs need support - expensive needs time.	The Scottish Government currently has a big push on insulating building in order to reach net zero, which is great, but it has not yet addressed embodied carbon and it is not doing anything re sustainability of materials.	n/a

Table 6: Key insights by leading UK NFI manufacturers

_Scottish construction industry perspective

As part of a recent set of semi-structured interviews with a representative group of Scottish construction industry professionals, perspectives and insights provided a clear picture of where the industry could be heading with the adoption of NFI's[11]. The group included:

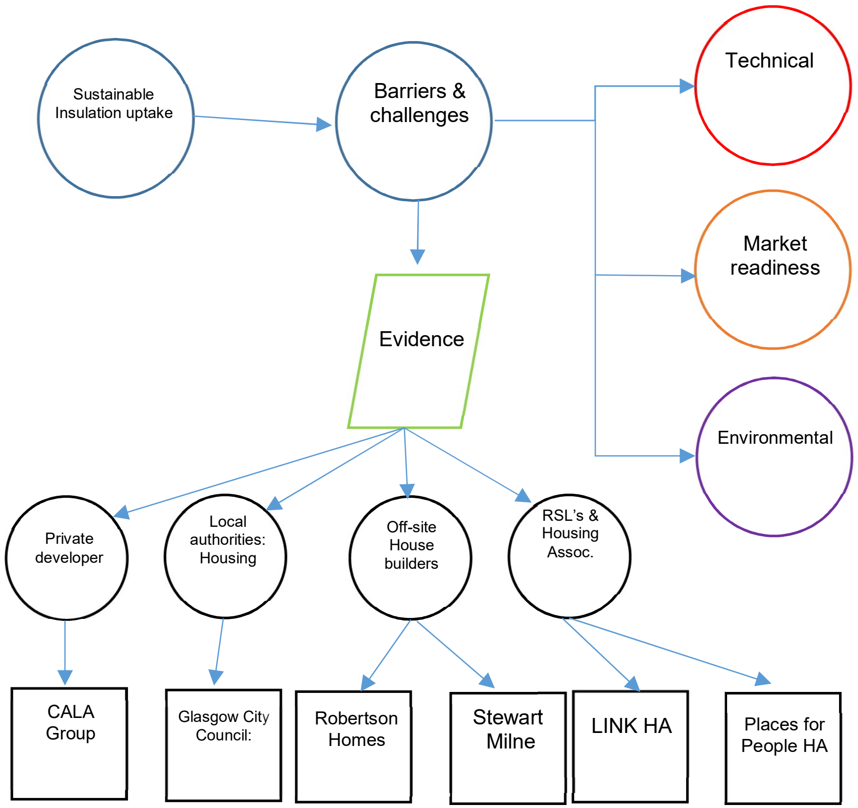


Figure 16: Industry members used to discuss barriers & challenges of NFI adoption.

[11] More information can be obtained in: Bros-Williamson, J., Seminara, P., Livingstone, A., & Reid, A. (2022) [29]. Innovation and commercialisation of Scottish homegrown wood fibre insulation. Scottish Forestry.

Sector representative	Main activity in the sector	General response	Opportunities and uptake
Developer & house builder	Provider of private homes	The company have considered alternative materials and those that are naturally sourced. Natural fibre insulation (NFI) has been researched as a good alternative but is largely driven by the low embodied carbon attributes. There are reservations about adequate sourcing and cost, but what stops the change is the level of assurances, warranties and certification of a home, particularly the fire regulations and requirements. For this reason, adoption would be in the next 5 to 10 years a wholesale change with all sites. They do accept that their builders and main contractors struggle with the concept, but this is due to a lack of technical knowledge, skills in installation, training and legislation awareness. However, this learning curve would be overcome quickly internally and at the procurement stage.	There is a desire to move into the use of NFI's, particularly as legislation pushes for defined net-zero performance. The company is open to trial and observing the implications to change into a more ecological approach. As volume grows their adoption would present lower costs, so they are keen to observe the market. Changing a method of construction can have resistance at first but after trialling and understanding a few installations should make the use of these products easier learning and adoption, thus a trial and desktop analysis should be made.
Local Authority	Social new housing provider and retrofit of existing homes.	To meet targets on carbon emissions, it's only now that net-zero legislation has been introduced that Council officials are adding more emphasis on carbon emissions. The shift from just analysing operational carbon to also considering embodied has not happened yet. There is a skills gap in knowing where these materials can be used and the benefits and implications. The real potential is in the retrofit sector with older existing buildings. Niddrie road (Glasgow) trial that retrofits a pre-1919 whole block of flats in a tenement has used NFI and tests are being done to understand the benefits. Adoption will be in line with Scottish policy changes and the push for embodied carbon.	Contractors purchase materials, and what can be done is procure and specify such materials. Larger developments in new buildings will be assessed and designed with the embodied carbon approach, but that may take longer than the retrofits. The cost aspect is a big barrier, however, if policy pushes for the adoption of these, it needs government incentives and area-based energy schemes (HEEPS) which should accommodate for this. Housing associations also have a play in new buildings, but little help is coming from the government to level up the costs – there needs to be a CAPEX and carbon reduction levy. The 2030 net-zero driver needs to address all factors of carbon emissions, so there is potential.

Off-site manufacturers, house builders	Main contractors for delivery of homes.	As main contractor and house builder, they are fully aware of the advantages of adopting natural materials to their supply chain. Robertson Homes have a very conscious approach to building, from using modern methods of construction (MMC) to innovative sustainability practices. Low embodied carbon practices are high on their agenda and plan to trial and adopt NFI's to their systems in the next 5-10 years. Projects have a direct focus on meeting current and future net-zero practices.	The only barriers identified are the security of supply and obtaining a competitive price for these materials. There are opportunities to conduct a trial and test of the insulation materials to further assure the performance and installation options.
Off-site manufacturers, house builders	Main contractors for delivery of homes.	Stewart Milne Homes are reluctant to make the change to NFI's such as wood fibre any time soon and would need the market to mature further until switching their wall systems to using it. Although the use of low embodied carbon materials has been considered, they recognise that their current wall system and design are well established with mineral/ glass wool insulation. They have an assured supply of such materials and seek to achieve carbon savings elsewhere.	Full adoption of NFI's is beyond the 10-year timeline, however, if legislation changes there would be a step to trialling and testing their designs.
RSL's Housing association	Social new housing provider and retrofit of existing homes.	Link Housing Association are fully engaged with the adoption of NFI's in the short term. The particular area of growth in uptake will be the retrofit of traditional existing housing stock. The compatibility with older materials helps overcome moisture migration and improve indoor air conditions. The embodied carbon aspect is very relevant as they move forward in meeting their net-zero targets. They hope that in the next 2-5 years there are procurement methods with their housing contractors to adopt such materials. Although it's a challenge, future policy-driven legislation should act as a driver to change designs in new home developments.	Opportunities will be embraced in the retrofit of their housing stock. This has been a priority in the HA's practice and trials and testing will be put into practice to demonstrate the new designs and changes. Upskilling is also something they require to understand fully the installation process and the benefits clearly outlined for future changes and adoption.

RSL's Housing association	Social new housing provider and retrofit of existing homes.	Places for People provide social housing and receive funding from the Scottish Government for the delivery of homes. Natural insulation has been piloted in many of their existing homes as retrofit interventions, particularly the use of Hemp fibre insulation. However, a full adoption into their new and existing homes will be at a long-term plan, beyond 10 years. The main barriers are the cost and availability of such products but hold concerns over the lack of knowledge on the performance and installation of such products. There is a concern over the contractors used in their homes as it has its unintended consequences, one concern is the warranty of such products and whether the homes will be covered through its assurance over performance. Cost is a concern, although would need to assure the cost and carbon benefits.	An opportunity emerges around solving the doubts over warranties of homes once installed with such NFI's. This leads toward certifications such as BBA or similar and whether they are enough to provide existing requirements and consumer assurances provided by National House-Building Council (NHBC), Local Authority Building Control Warranty (LABC) and Premier Guarantee. Other warranty providers operate include Build-Zone, for example, which adheres to the Code of Conduct for Home Builders and the Federation of Master Builders (FMB)'s unrated warranty is under the Consumer Code for New Homes (CCNH).

In summary, industry representatives highlighted the benefits of wood fibre insulation beyond the thermal conductance and reduced U-values, however, there was a need for the industry to recognise other qualities such as moisture control and heat storage. They all recognised that in the UK there aren't any current manufacturing facilities for homegrown wood fibre and that having this in place would increase the security of supply, lower embodied energy of the products and market increase with better representation in the UK.

Scottish industry leaders, in the housebuilding sector, are aware of the potential of wood fibre insulation, particularly in retrofit interventions. Most are worried about having the material readily available for larger projects and specifications. All recognised the embodied energy benefits to reach Net-Zero performance and targets in Scotland. There was a mixed response to switching to all-natural fibre insulation, where some would do it in the next 5 to 10 years but some are reluctant until the product is mature enough in the UK. The topic of certification, warranties and consumer satisfaction is a clear opportunity to explore as well as the testing and trials that could satisfy the technical representatives of the industry.

One clear source of inspiration and learning is the legislative changes and opportunities provided by other countries in mainland Europe, significantly those from France and Germany. Although most companies from mainland Europe are owned by conglomerates, farmers and small-scale producers, the market is large given the demand which is strengthened by existing policy-driven changes and incentives on building retrofit and adoption of natural materials, insulation included. Case studies 1.1 and 1.2 provide an outlook of the support available in such countries.

Case study 1.1: Bio-waste and use of natural insulation - France

In 2017, France became one of the few European countries to have adopted legislation on bio economy. A new law emerged (Waste & circular economy bill N.660) that minimises the waste of products into landfill and avoids the use of plastics and other bi-products from other industries. The law also aims to continue with the polluter-pays principle, forcing industries to be responsible for any waste streams that are polluting or going straight to landfill, with heavy penalties if found out. This law creates a national strategy to develop a bio economy which seeks to create a “bio-based product” label, already introduced in France, however, it now requires that materials includes certain amounts of bio-products, for example in insulation products with a certain amount of bio-based material.

This emerging industry has the potential to contribute €2,100 billion in turnover to the European Union, with France’s share to be in the region of €316 billion, making it the second-largest contributor behind Germany. It creates opportunities for existing products to flourish and open the market to new products that meet the guidelines. One example is the natural insulation sector, which has been slowly developing in France with Hemp insulation products exported as far as China or straw and cellulose fiber insulation also in the market. It also creates new waste streams into insulation such as the creation of biowaste insulation using malt, rye and wheat husks the waste generated by the cultivation of rice, spelt or buckwheat.

In terms of government incentives, the French “Ma Prime Renov” gave householders some support in the renovation of their homes by providing a tax credit for energy efficient renovations. It started in 2021 as a post- COVID-19 recovery package provided by the ANAH (National Housing Agency) and it has recently been extended to 2022 with a €2 billion financial aid, however, it is deemed as not enough by many in the industry. Ma Prime Renov is also a grant for owners and co-owners who wish to improve the comfort of their homes. It offers financial support for homeowners and landlords undertaking various types of energy renovation works. Eligible works include insulation, ventilation systems, updating of heating systems and work to improve the efficiency of temperature controls.

Incentives for creating new products and to upgrade (retrofit) buildings creates markets that sustain the natural fibre insulation industry, providing room for innovation and growing markets.

Case study 1.2: Financial help for energy efficiency, including retrofit and use of natural materials - Germany

Germany has introduced many energy efficiency, waste and market introduction programmes such as the BMEL, that systematically promoted the use of natural-fibre insulation. Between 2002 and 2008, a total of 17,000 home owners profited from the funding. Germany's state-owned development bank Kreditanstalt für Wiederaufbau (KfW) has been running a program for 10 years, supporting many different retrofit aspects including energy efficiency and heating. KfW also provides private sector finance— it received €10.6 billion from the German government in mid-September 2021 with additional funding of €83 billion from the private sector in 2020. In addition to support and enhance the skills in the retrofit of buildings, KfW has created an estimated 900,000 jobs through the enrgy efficiency sector.

In January 2020 the German Federal Government published an updated National Bioeconomy Strategy (NBS) which provides guidelines and objectives on bioeconomy policy and lists measures for their implementation. The strategy builds on the National Research Strategy 'BioEconomy 2030' to create a coherent framework. Two objectives and actions are set in the NBS, guidelines on biological knowledge and advanced technology and the re-use of raw materials used by industry into sustainable and circular economy practices based on the use of biogenic resources. This has opened opportunities in NFI products and direct applications into new and retrofit of buildings.

In May 2022, the German government introduced measures that included financial incentives, targeted support and regulatory adjustments in order to boost energy conservation. The plan includes funding and incentives to promote more energy efficient standards in heating and building and abolishing subsidies for gas heating and construction projects that do not meet a new building energy guideline, the Efficiency House 40 standard. This funding includes the support of households in older buildings that are the poorest performing, by supporting insulation installation and capital costs, which places natural insulation at the forefront thus creating worthwhile opportunities for new products and innovation.

_Cost comparison and value

A simple comparison of products shows the barrier of cost between synthetic and natural fibre products. Costs were obtained from online retailers and distributors to identify and compare medium-density batts and boards with an equal 100mm thickness but varying thermal conductivity values. Cost comparison parameters such as £/mm and £/m^3 were used to understand the variability in cost against well-known synthetic products on the market (mineral wool, glass wool, PIR and polystyrene) as shown in Appendix D and Figures 17 and 18[12]. The parameters used were then applied to a thermal transmission comparison between off-site insulated timber panels with varying insulation types.

[12] Costs include VAT but not delivery. Evaluation considers 100mm products, however, economies of scale and the thickness per board will vary the cost of products.

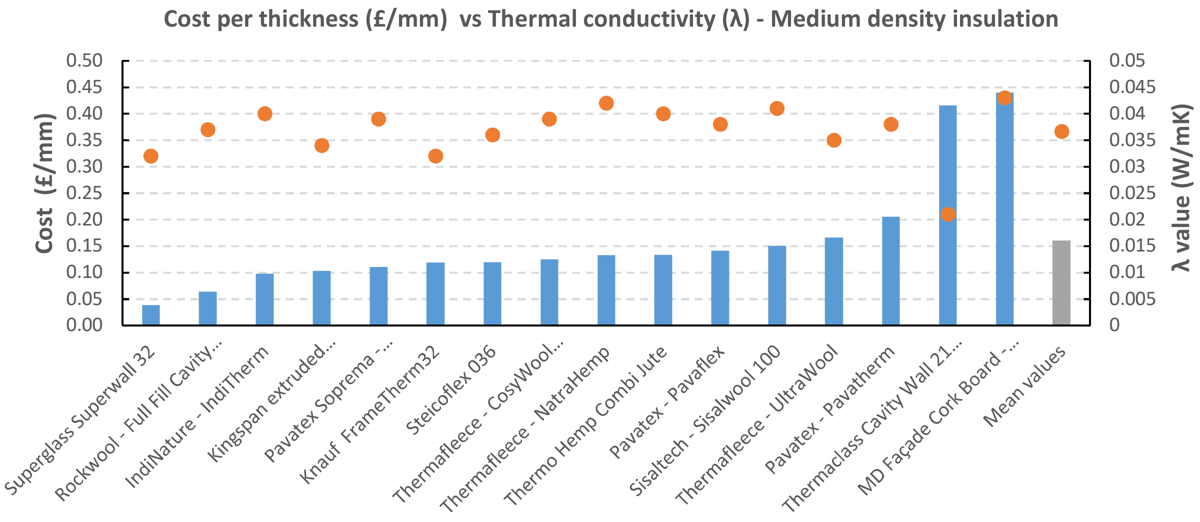


Figure 17: Evaluation of Cost per thickness (£/mm) vs Thermal conductivity (λ) of medium-density insulation products

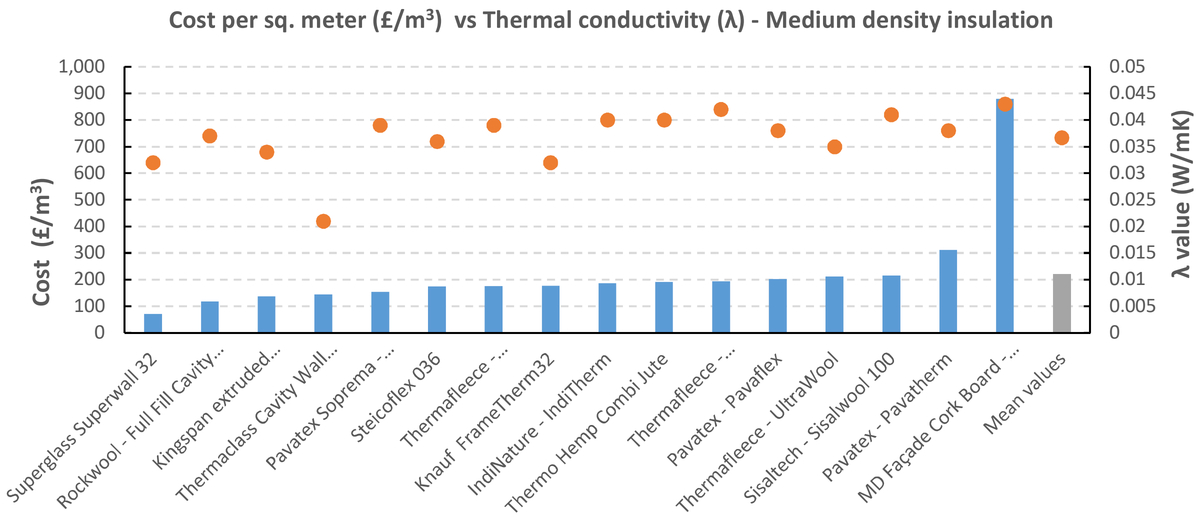


Figure 18: Evaluation of Cost per sq. meter (£/m³ vs Thermal conductivity (λ) of medium-density insulation products

Figure 17 provides a cost per mm of insulation product comparison between natural insulation and synthetic equivalents. The majority of the natural products fall in the range from 0.10 to 0.20 £/mm except for Amorim Cork insulation. Compared with the cheaper synthetic equivalents the cost per mm ranges between 0.04 and 0.10 £/mm. Two outliers emerge from this analysis; the Cork insulation which has a high cost per board of £44.00 and the PIR board which is £42.00 per board. The distinction between these products appears when considering the thermal conductivity values, with most natural products ranging from 0.036 – 0.042 W/mK and a mean value of 0.037 W/mK. PIR insulation presents the lowest conductivity value (λ) at 0.21 W/mK, while the mean value for all synthetic products remains lower than natural equivalents at 0.034 W/mK[13]. The comparison presented in Figure 18 focuses on the cost per cubic meter of insulation product (£/m^3) considering the 100mm thickness of boards. The mean result contemplating all products evaluated is £220/m^3, including the cork Amorim product which has the highest cost per cubic meter (£177.9/m^3 excluding it). A clear frontrunner is the PIR insulation, with a low thermal conductivity value of 0.21 W/mK and a cost of £144.5/m^3. Appendix D shows all the costs and parameters considered.

Considering the thermal implications of substituting synthetic products with natural and recycled products the increased volume of insulation material is affected. A baseline is used, as described in Figure 8 with mineral wool insulation between a 140mm timber closed panel and an additional PIR thermal bridge layer of 50mm with foil low emissivity membranes facing the cavity behind external cladding/ brickwork, achieving a U-value of 0.15 W/m^{2}K. Alternatives to this are proposed in Table 7 with varying insulation thickness to achieve a similar U-value performance. On average the thickness of the product increases approximately by 40% against Baseline A, which in the context of a timber panel requires on average 75mm extra of product. This is due to the higher thermal conductivity of the natural products which need more volume to reach the overall thermal transmittance value (U-Value). This is shown further in Table 7 where an analysis of the extra volume of insulation is required to meet a similar U-value. Adopting the example of a semi-detached home, as shown in Figure 19 and Table 7, using the Baseline A insulation thickness, provides approximately 110 m^2 of an exposed wall, which equates to approximately 21m^3 of insulation. Other insulation products including natural fibre, require more volume of insulation which results in a larger capital cost investment to reach the same energy efficiency.

[13] This excludes the PIR thermal condutivity value.

	U-Value (W/m²K)	Thermal conductance λ (WmK)	Insulation thickness (mm)	Increased insulation thickness (m)	Σ Insulation thickness (m)	Wall insulation (m^3) - typical semi-detached home (110m2)		Total volume (m3)	Volume increase (%)
Mineral wool + PIR	**0.14**	**0.034/0.021**	**140 + 50**	**Baseline A**	**0.19**	**15.40**	**5.50**	**20.90**	**-**
Glass wool + Mineral wool	0.15	0.035/0.038	140+60+60	70	0.26	15.40	13.20	28.60	37%
Hemp Fibre	0.14	0.038	140+50+80	80	0.27	29.70		29.70	42%
Sheep's wool	0.15	0.037	140+60+60	70	0.26	28.60		28.60	37%
Sheep's wool+ Wood Fibre	0.14	0.040/0.038	140+60+80	90	0.28	15.40	15.40	30.80	47%
Jute Fibre	0.15	0.04	140+60+60	70	0.26	28.60		28.60	37%
Wood Fibre (Medium + high density)	0.15	0.038	140+60+60	70	0.26	15.40	13.20	28.60	37%

Table 7: Typical insulated wall panel design (baseline) with natural insulation substitutions

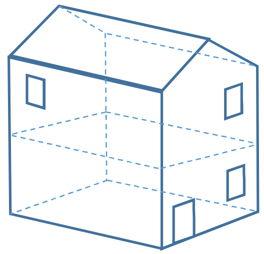


Figure 19: Typical semi-detached home with 110m² exposed wall

5. Manufacturing process

The manufacturing process of sustainable and natural insulation materials is dependent on the type of materials being processed, their origin, and the technique used to bond materials together. Within this analysis, there are manufacturing processes for materials that use recycled materials and those that have been extracted from a natural or industrial location. This section will explore the set-up required for certain streams of sustainable insulation, as well as its supply chains and waste streams. Essential are the environmental impacts of such materials, where manufacturing can contribute a large part, through material processing efficiencies, energy use and transport to other stages, see Figure 20.

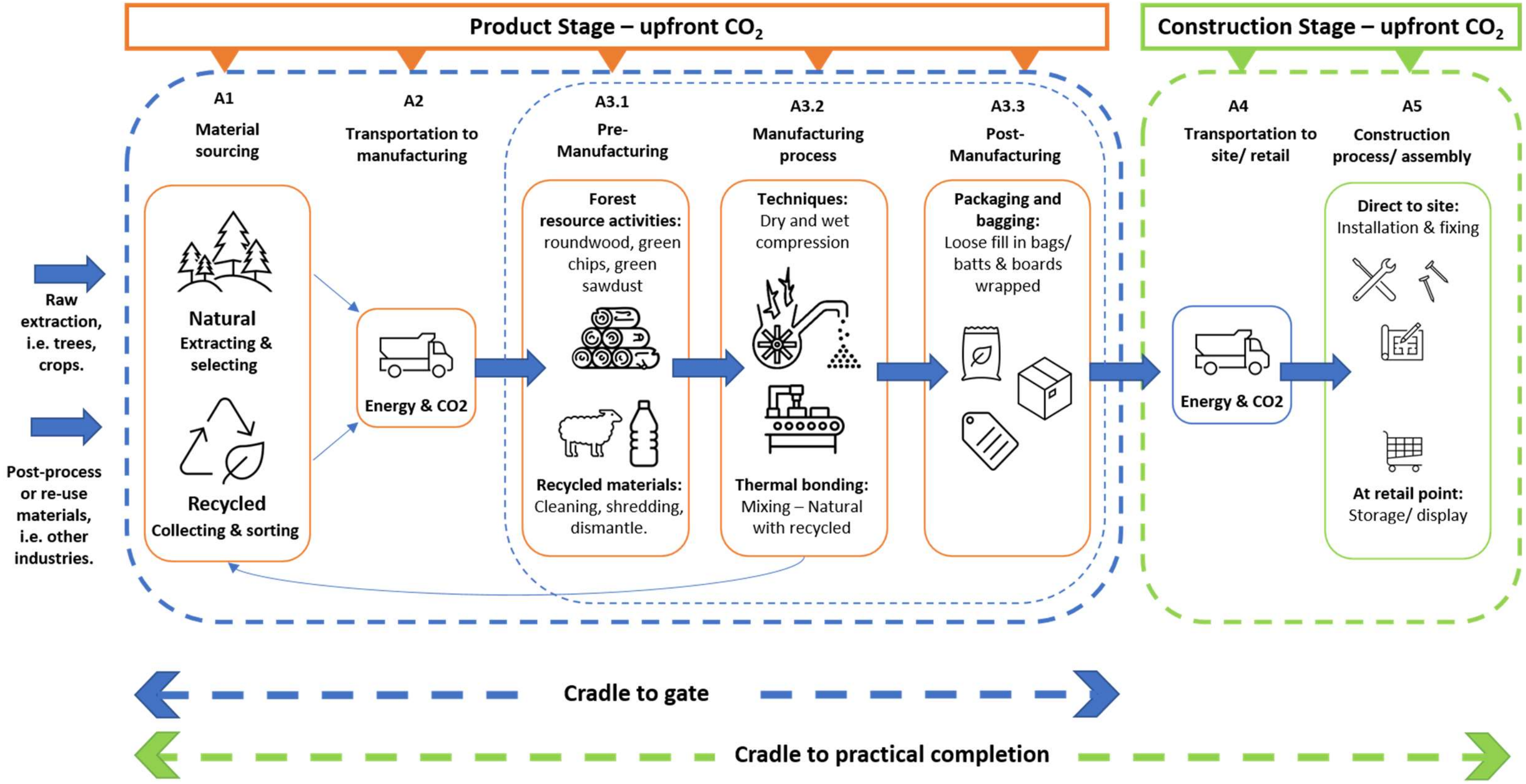


Figure 20: Product and construction stage carbon analysis for the manufacture of natural and recycled insulation

5.1. UK Manufacturing examples

Using Figure 20 and the different types of sustainable insulation available in the UK and Scotland for insulation, Table 8 explains further the process and requirements.

Insulation Group	Material Type	Supply chain:	A1 process	A2 process	A3 process	Limitations & opportunities
Natural plant Fibre	**Wood Fibre - Trees**	Currently from EU forests (France, Scandinavia, Germany), most are from virgin wood. Some from recycled sources, & sawmills.	Trees are cut down, branches detached, and cut for transportation at sawmills or on-site. Logs are debarked and turned into chips and shavings. Main yield is sold as timber planks for construction. Sapwood & sideboards are used for fibre.	Most have the supply chain close to the manufacturing plant. Energy/ CO_2 in fossil fuel for transport.	A3.1: Two main process types, dry and wet process. **Dry process:** 1] fibre dryer, 2] separated in cyclone, 3] Hopper with resins are added, 4] spreader, 5] Water vapour pressing, 6] sawing and milling into boards. **Wet process:** 1] Refiner, 2] Mixture in water made into a pulp, 3] Additives added, 4] Mechanical press, 5] drying process, 6] Sawing & milling. Thermal bonding is used for low-density rolls	Cradle to gate process can be low, but for the UK, A4 Transport to site/ retail is where CO_2 emissions are accumulated. Mainly by Lorry/ truck. **Wet process (multi ply):** 91% wood fibre, 2% white glue, 2% Paraffin, 5% Latex binders. **Dry process (single ply)**: 94.5% Wood fibre, 1.5% paraffin, 4% Polyurethane resin.
Natural plant Fibre	**Hemp Fibre stem- Hemp crops (*Cannabis sativa* L.)**	Hemp fibres are found in the stalks of industrial hemp. The crop is harvested 90-120 days after planting and after the flowering period.	Hemp fibres are broken down and left rotting. The bast and hurd are separated (decortation) by retting the stalk. Retting can be by field or wetting. Hurd fibres (shives) (interior of stalks) resemble wood fibres/ chips.	From the harvest, and storing, the hurds is transported to the manufacturing plant. Bast fibres are sent to another manufacturing process for textiles.	The hemp hurds are conditioned to 23'C and 65% RH. 1] Cutting mill pulverises it to reduce chip size. 2] Fibres of 6mm are collected after sieve processing, 3] Adhesives are applied. 4] Blended chips are pressed. 5] Cutting.	Hemp crops grown across EU and the UK. Both IndiNature and ThermaFleece have manufacturing plants from UK farmers. Hemp is a fast-growing crop that outperforms tree planting.
Natural plant fibre	**Sisal (*Agave sisalana*) fibre**	Sisal fibre is extracted from the leaves of the sisal plant. Leaves are cut off the plant and pre-processing happens on-site or nearby. Sisal can be	The post-harvesting process to extract fibres can be done by: 1] water retting, 2] Boiling, & 3] mechanical method. Methods 1 & 2 are not hygienic and require	Most post-processing is done by farmers or transported nearby to extract the fibres. For insulation, SisalTech transports the sisal to two manufacturing	1] Sisal fibres are created by carding (disentangling, cleaning and intermixing). 2] Before carding, untangled fibres are mechanically mixed and transported to carding cylinders. A fine fibrous web	At the moment sisal insulation is manufactured in the EU mainly using virgin sisal fibres from Tanzania. SisalTech are procuring the recycling of sisal sacks into the

		from virgin products after harvesting or recycled from sisal fibre sacks used for grain transportation.	larger-scale facilities. Method 3 is energy efficient but requires a large processing plant. Sisal sacks can be collected and fibres disassembled to be re-utilized into insulation batts.	plants from Tanzania to Spain & Denmark.	collected is open width and placed on a continuous conveyor and transported directly to the bonding step. 3] Carding sisal is blended with sheep's wool to create a semi-rigid batt using thermal bonding process. 4] Bonding adhesives and additives.	production of insulation. Manufacturing is being procured to be set up in Scotland shortly.
Natural animal fibre – Waste material.	**Sheep's wool fibre**	Wool is shorn from sheep and separated. White wool is used for textiles, and brown/ black wool of low grade is traditionally wasted and unused for textiles, thus a waste material.	Wool is collected after sorting into pressed bales.	Bales are packed in 400kg bales to minimise cost and energy to transport. Processing is rarely done at the sheep-shorn location, thus being transported to the insulation product manufacturing stage.	Bales are delivered and opened then blended to produce a certain specification. 1] The blend undergoes a scouring process in various baths by washing in warm water, 2] wool is then fully protected using Ionic protect, 3] The wool is dried and carded (combed) to achieve its desired thickness, 4] Layers are bonded and wound to make strong roll of insulation.	UK manufacturers of sheep's wool insulation blend with polyester fibre from recycled plastic bottles (PET) to make the final rolls of insulation. Thermafleece (Eden Renewable Innovations Ltd) manufactures sheep's wool in Mirfield West Yorkshire.
Natural plant fibre – recycled	**Recycled fibre from newspapers – cellulose loose-fill insulation**	Cellulose insulation is made from up to 75%-85% recycled paper and cardboard. Other elements include chemicals like boric acid, used as an insecticide and flame retardant. The paper is supplied pre-sorted, is broken into fibres,	Recycled newspaper, cardboard, packaging and office print is collected and piled for transportation.	Recycled paper is delivered in bulk.	The delivered paper undergoes, 1] Paper into the primary mixers which separate the bulk paper, 2] Staples and paperclips are removed by magnets, 3] paper goes into a shredder into 5cm long pieces, 4] Shredded paper is mixed with boric acid, 5] Shreds go into a fiberiser to create smaller pieces of 4mm long, 6]	The shipping distance from the factory to the consumer impacts the environment. Currently, there isn't any UK manufacturing company for cellulose insulation, this all is imported. The closest manufacturer is Ecocel in Republic of Ireland.

		mixed with mineral salts & ground in mill.			Open flammability tests are done.	
Recycled	**Recycled poly(ethylene terephthalate) (PET)**	Recycled PET from plastic bottles. Recovered PET from UK use and other industries (Construction, 23%).	Collected, sorted and packaged into bales.	Bales are transported to a processing plant. Some manufacturers then transport it to polyurethane plants at different locations.	1] Collected bales are opened and placed onto a mechanical recycling line, 2] Optical sorting to remove non PET objects, 3] PET is crushed, washed and shredded (flakes), 4] Densimeter stage to remove residual contaminants, 5] First reactor for chemical recycling, second for additives, 6] A polyol liquid is created & stored in tanks, 7] Foam or fibre insulation made at polyurethane plants.	Although recycled, it still requires post-processing using large amounts of energy. Some manufacturers have single recycled PET products, while others blend it with sheep's wool.
Recycled	**Recycled textile & denim waste, quilts and batts**	The main supply chains are recycled cotton textiles from clothes, bedding (pillows, duvet and mattresses) waste from textile companies (denim fibres), and recycling plants collected.	Collection and reclaiming textiles (denim and clothes cotton) is baled and delivered to the manufacturing plant. There is a process of pre-sorting by hand.	Transported from the collection points to the manufacturing plant.	85% of the fibres from recycled cotton and 15% PES (Polymer binder). 1] The textile is placed ona conveyor belt, 2] These are shredded into threads and thin strips. 3] all metal objects are separated from the textile, 4] shreds are further separated and threaded further, 5] Fire protection additives are added. 6] Threads are compiled and passed through a thermal bonding process at a given thickness blended with bico, an adhesive that keeps threads together at a low density.	3 pairs of jeans per square metre of insulation at 100 mm thickness. Recycling and sorting of textiles can be done in the UK. However, the thermal bonding process is not yet done in the UK.

Table 8: Product and materials manufacturing review.

_Discussion

The product and materials manufacturing review in Table 8, although not extensive, outlines some of the sustainable and natural fibre examples available in Scotland and the UK. The supply chain and process of manufacturing determine the feasibility and success of the products, as well as the investment and partners involved. The availability of a secure supply of the raw and main materials for such products is vital as it defines the involved stakeholders and subsequent stages. For example, wood fibre insulation depends on the early processing of wood after trees are harvested and felled, debranched and delivered to a sawmill as logs. Having control over sawmill processing and distribution of wood ensures appropriate wood fibre quantities from sideboards, bark and branches at the top log. The main yield can be sold to timber retailers for use in industry, however, without this control, the low-yield wood would be sold for chipping for fuel, landscaping or pallets. Sawmill control assures and destines wood towards a fibre supply chain directly destined to create insulation products. A similar agreement and assured supply can bring confidence in investors for subsequent capital investment for machinery, personnel and certification. This has been the case of Indinature in the agreements with hemp growers in the UK which helps develop production and the marketing of the products. A similar approach can be taken with recycled main materials from other processes as a waste bi-product or a purposely collected waste product with a second life turned into new products (plastic bottles, denim clothing and newspaper print). If early agreements and an assured supply chain are not obtained, the processing cycle is broken. Investment in facilitating this process is essential, as well as agreements from stakeholders and post-processing stages. Companies in France, Poland and Germany have been successful in keeping hold of these stages, such as sawmill agreements and clear resourcefulness of raw materials as many of the sawmills are owned by the manufacturers themselves with a clear distribution.

5.2. Embodied energy and global warming potential (GWP) of products – comparison

Existing synthetic and natural fibre products were analysed considering boundary conditions (cradle-to-gate), providing a good comparison between them. Omitted from the evaluation are A4 – Transport and A5 Construction as well as evaluations leading to cradle-to-grave analysis which would require more accurate data on UK manufacture and specific uses. The following analysis is based on the timber wall panel comparison already made on the cost of replacing a synthetic insulation material with natural insulation equivalents shown in Table 7 and Figure 19. GWP values from Table 3 were used based on the total insulation difference between panels based on a volume (m^3) functional unit.

	U-Value (W/m²K)	Thermal conductance - λ (WmK)	Total volume (m³)	GWP ($kgCO_2eq$) FU:m³	% difference against baseline
Mineral wool + PIR	**0.14**	**0.034/0.021**	**20.9**	**1,483.9**	-
Glass wool + Mineral wool	0.15	0.035/0.038	28.6	1,263.7	-15%
Hemp Fibre	0.14	0.038	29.7	-6,59.3	-144%
Sheep's wool	0.15	0.037	28.6	14.3	-99%
Sheep's wool + Wood Fibre	0.14	0.040/0.038	30.8	-2,535.4	-271%
Jute Fibre	0.15	0.04	28.6	13.7	-99%
Wood Fibre (Medium + high density)	0.15	0.038	28.6	-5,920.4	-499%

Table 9 (above): Global warming potential of different insulation materials keeping a similar U-value

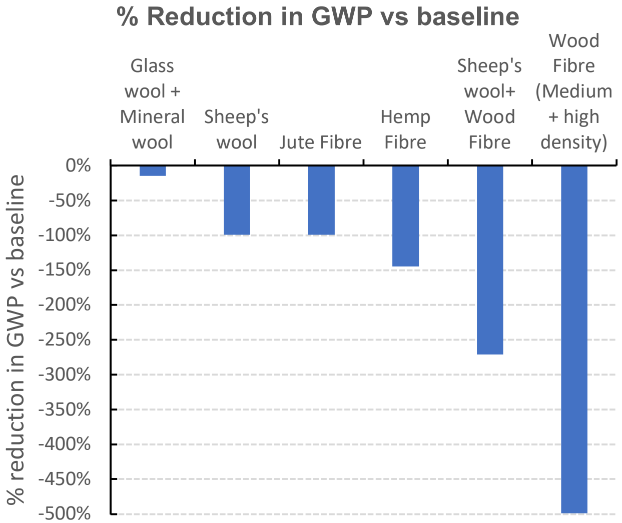


Figure 21(right): % Reduction in GWP between the baseline wall & natural fibre insulation replacements

Table 9 shows the results of the evaluation maintaining the U-value thermal performance of the wall at 0.15 W/m2K with the associated volume increase explained in Table 7. Despite requiring more volume of insulation, the embodied carbon savings can be considerably better under the cradle-to-gate considerations. These results show that a U-value can be kept similar to the baseline wall panel using low environmental impact materials.

6. Innovation and emerging products

6.1. New applications and materials

New materials, applications and construction systems continue to emerge at various technology readiness (TR) stages[14]. With the current focus on products that can reduce carbon emissions, more innovation and an assured performance evaluation are required of products and systems. Creating these requires sustained supply chain delivery, manufacturing & skills investment, storage facilities and a healthy stream of sales in an already tight market share of environmental products in the construction industry. Within some of the innovative uses and products outlined, there are hybrid systems using insulation in wall panels, innovative products and different ways of using some natural materials in the market. The following outlines some researched examples.

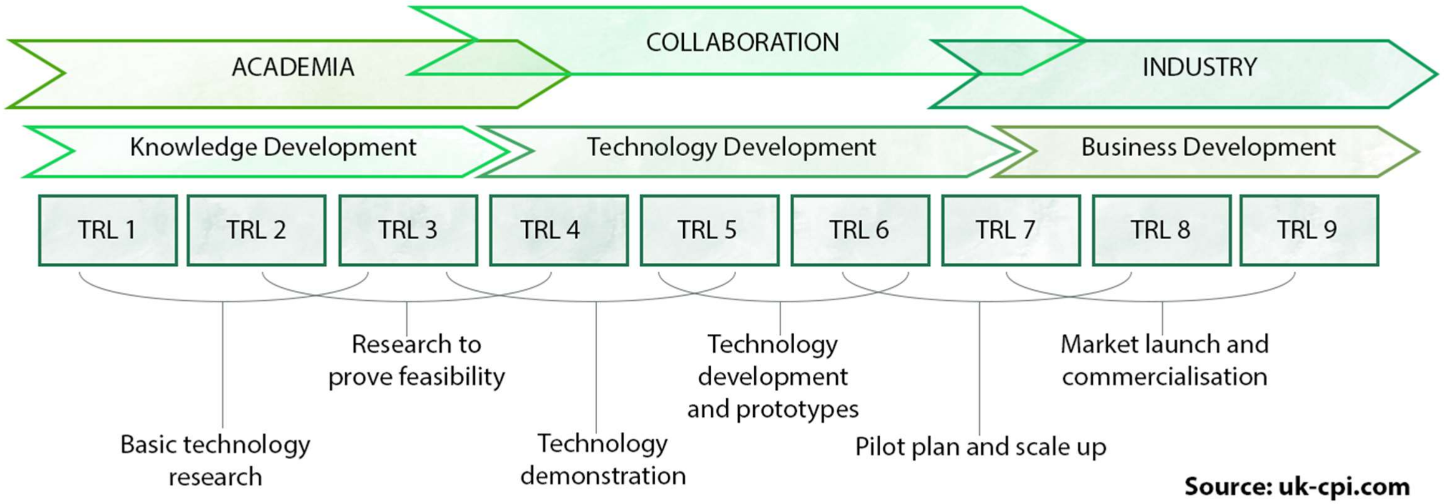


Figure 22: Typical technology readiness level stages linked to stakeholder involvement. Source: UK-CPI

[14] Technology Readiness Levels (TRLs) are a technology management tool that provides a measurement to assess the maturity of evolving technology and some products.

EcoCocon – compressed straw

Description - Product/ methods:	It is a system using straw in a prefabricated 400mm timber panel forming a wall with 89% of highly dense insulation. It provides an airtight envelope, yet vapour-permeable wall system that reduces moisture locking. (https://ecococon.eu/gb/)
TRL development stage:	TRL8 & 9
Raw materials & supply chain:	Straw (98%), binders and additives (2%). Straw is sourced locally close to the manufacturing plant which is located in Kybartai, Lithuania.
Manufacturing process:	The panels are prefabricated in a manufacturing plant with a controlled environment. The straw is installed in the panel with multidirectional press technology. Typically, high U-values (0.11 W/m^{2}K) are achieved by adding an external 100mm wood fibre layer to reduce thermal bridging through the timber stud work.
Market readiness:	This system is available in the UK as an off-site delivered panel. It is a commercially viable system achieving high levels of energy performance (Passivhaus) However, lacks awareness and policy-driven up-take. Example: https://ecococon.eu/gb/projects
Scaling up required:	In Scandinavia and EU this system is gaining popularity for small bespoke one-off dwellings. It requires full adoption into larger developments and buildings. Straw as a product also has a proven track record of performance and as a product, it has many possibilities. In Scotland, the supply of straw can be assured with agreements with farmers. Basic stud work and assembly would need to be set up on a factory line. Small timber assembly manufacturers would need to be involved.

Mycelium (BIOHM)

Mycelium insulation board

Description - Product/ methods:	It is a mycelium insulation panel based on the vegetative filament root structure of mushrooms. Biohm's mycelium insulation has achieved thermal conductivity as low as 0.03W/m.K. https://www.biohm.co.uk/
TRL development stage:	TRL 7, 8 & 9 – new products may start at TRL3 & 4.
Raw materials & supply chain:	Small-scale growth of mycelium using commercial and agricultural by-products that would otherwise go to landfill.
Manufacturing process:	Network of threads, called hyphae, from which mushrooms form mycelium by mycoremediation (or fungal degradation) processes. Also by orb binding (organic refuse bio-compound) to produce rigid insulation as 1200 x 2400mm rigid panel sizing. Panels can be grown to custom dimensions to fit in a complex space or an internal cavity of a structural panel system (SIP). This process can be used from any waste product, however, most experiments are done with food production or agricultural sectors and processing it into a homogenous filler which is bound together to form an organic binder which can replace wood-based sheet materials.
Market readiness:	The product is not yet available on the market. Bespoke products can range from a lamp shade to an insulation product or panel board. For insulation purposes, these are at a bespoke and early adoption stage.
Scaling up required:	Both the mycoremediation and Orb binding produce difficult-to-reuse or recycle by-products; that would otherwise go to landfill. At an early stage of the adoption scale. Very innovative and early mass production stage.

Cork insulation Amorim Cork Composites & multilayer panel materials

AMORIM

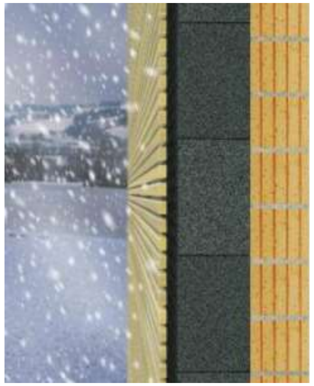
Cork granule insulation board

Composite ply & cork boards

Cork & coconut fibre board

Description - Product/ methods:	Sustainable oak cork insulation boards maintain their shape and integrity over time, have unlimited durability and are renewable, reusable and recyclable.
TRL development stage:	TRL9, new innovative composites at TRL3,4 & 5
Raw materials & supply chain:	Oak tree cork (95%), natural resins (suberin) (5%). Cork is mainly available on a large scale in Mediterranean countries. Products are transported from its manufacturing plant (Portugal) to UK suppliers.
Manufacturing process:	Cork is harvested by hand and removed from oak tree, then ground to create granuales that are stabilised and agglomerated with natural resins (suberin). Cork boards are formed, cut and packaged for shipping. Cork composites can be blended with other factory-based products such as plywood, aluminium, steel, plasterboard and others, using common bonding systems.
Market readiness:	Solid position in the European market, especially in the sustainable construction sector. Composite products, window frame infills, doors, wall partitions and expansion joints. Fully developed and available on the market. Products such as Corkoco which blends cork and coconut fibre provide a fully natural insulation board for wall, roof and floor applications. Other products iclude coconut fibre quilts and expanded granules used in screeds, cavity walls & flooring.
Scaling up required:	Available in the UK, however, its high cost makes it difficult to adopt at a large scale. There is a low uptake of these materials mainly from bespoke projects.

FOAMGLAS



Description - Product/ methods:	This cellular glass material is 100% waterproof and can achieve a thermal conductivity value of 0.036 W/(m·K). https://uk.foamglas.com/
TRL development stage:	TRL9
Raw materials & supply chain:	Insulation is manufactured from specially graded recycled glass (60%) and natural raw materials which are available in abundant supply (40% - sand, dolomite, lime). It is inorganic and contains no ozone depleting propellants, flame-resistant additives or binders. Without VOC or other volatile substances.
Manufacturing process:	Uses an electric melting process to break-down the collected glass. Currently a high energy process, but efforts are being made to reduce the carbon intensity of the energy used. Manufacturing takes place in Tessenderlo – Belgium.
Market readiness:	Foamglass has been developed with unique recycled content and natural sand/stone sourcing. Mining such sand/ stone will have an environmental impact unless using additional recycling options. It is a mature product which is available easily in the UK.
Scaling up required:	This recycled material insulation product has a place in the market. Carbon emissions in transportation between countries can be reduced if manufacturing is done in the UK which can provide a sustained glass recycling collection.

BIO-CIRC – Insulation from recycled bedding products

Description - Product/ methods:	Bio and Circular Insulation for Resourceful Construction (BIO-CIRC). The INTERREG VA France (Channel) England project is a Cross Border European Territorial Cooperation (ETC) Programme which aims at supporting the development of the France (Channel) England area.
TRL development stage:	UK-France research project – Advancing from TRL3 to 6 – promote further to TRL 7-9.
Raw materials & supply chain:	Innovation project investigating the waste bedding sector and the potential reuse of polyester duvets, which currently suffer from poor recycling rates and sanitary issues. Only 5% of non-clothing textiles are currently collected in the UK for reuse and recycling, with 20% of those being reused and 80% being downcycled into a low-value end market of wipes and stuffing
Manufacturing process:	After the collection of duvets and pillows, these are pre-sorted and non-recycled waste taken out. A second sorting stage would dismantle mattresses separating polyester and feathers later sold separately. Polyester fibres would be used for insulation manufacturing after a fibrerisation process.
Market readiness:	This project highlights the potential, barriers, changes and opportunities of the two countries working alongside each other to collect and process such waste products. The polyester fibres will be used to create prototypes combining them with help and sheep's wool.
Scaling up required:	The project stakeholders will network and engage with ASBP's Natural Fibre Insulation Group and Plastics in Construction Group, to gather intelligence and help create a business case for the development of natural and recycled fibre insulation (NRFI) materials.

6.2. Case studies and best practice

Case study 1: Old Holloway - EcoCocon

The building is in Little Birch, Herefordshire, UK and it was completed in 2017. The single storey detached house was built utilising the EcoCocon system. This building represents the first UK application of this system which allows accurate construction due to prefabrication as well as rapid erection of the structure. The external walls were erected in only three days and the house was watertight within four weeks.

The building also incorporates materials such as exposed self-finished (sealed) concrete slab, self-finished clay plaster walls, charred timber cladding from local cedar and corrugated metal roofing which was sourced locally. The home includes a large south roof overhang, openable windows throughout the building and an exposed concrete slab which helps to stabilize the indoor temperature.

Case Study 2: Jill Strawbale House

The building is located in Strontian near Fort William and it functions as a luxury getaway. Utilizing more than 500 bales of straw as the main form of insulation and harvesting power from 2 hydro generators while the ground source heat pump provides underfloor heating and hot water. The building, therefore, exports five times more power than it imports.

In order to protect the bale from moisture the walls are covered in lime inside and outside. On the internal side, 2 layers of lime putty are applied as a finish and hydrated lime acts as an external finish. That way moisture can be absorbed on the internal face of the wall, passing through the straw and leavening the build-up through the external surface.



Case Study 3: Cork House

Cork house is situated in Eton, Berkshire, UK and is built almost entirely from cork the house was carbon-negative when completed. Cork acts as a structure, insulation, and external and internal finish, and it can be easily reused. The cork utilized was a by-product as well as waste from cork forestry and the stopper industry. Walls are built from prefabricated expanded cork blocks and corbelled roofs which are supported by engineered timber the components are designed for disassembly and can even be constructed by hand. It is a self-build construction kit which can be constructed with no use of mortar or glue. Internally the cork is exposed, and the sky windows help introduce more light into the space.

Case Study 4: Carrochan Loch Lomond & the Trossachs National Park offices

Carrochan building is the headquarters of Loch Lomond & the Trossachs National Park located in Balloch. Within the wall build-ups Thermafleece sheep's wool insulation is used which is manufactured in Yorkshire. Natural materials are used throughout the building – the main structure is constructed of two storey Douglas fir columns and beams with prefabricated floor and roof panels; the external finishes include natural slate roof, natural stone walling and Scottish larch cladding. Most of the timber was sustainably sourced from Scottish borders.

Case Study 5: Holyrood Park Lodge

The lodge sits between the Scottish Parliament and Holyrood Palace in Edinburgh. It was built in 1857, originally meant to be used by park keepers, however, it was used as a cottage instead and now acts as a Holyrood Park Visitor Centre. Refurbishment of the B-listed building has placed a special emphasis on improving thermal performance with materials which preserve and maintain the character of the internal and external finishes.

The ground floor of the building is has timber joists which were repaired, and 100mm wood-fibre semi-rigid batt insulation placed between them. Due to the building's visual character and to keep external façade untouched, walls were thermally improved from the internal side where cellulose fibre insulation was blown into the 38mm air gap behind the existing lath and plaster wall linings. Extensive plaster patching was needed for this, as well as redecoration. Wood fibre insulation was fastened between the rafters in warm roof construction and on the east facing gable roof insulation was laid between the ceiling joists creating a cold roof construction.

7. Conclusions

7.1. Overview of work

The analysis that informs this document provides a good evaluation of the existing products in Scotland and the UK, some manufactured locally and others as far as mainland Europe and Africa. Appendix A, provides a guide on the performance values and characteristics of each product based on their origin and typology. This matrix, together with the evaluation of some products in 2.2.3 and 5.2 provide a hygrothermal performance explanation and environmental assessment which will be very useful to the government and the wider industry. This information and table can increase and be updated as other products and research emerge. Additionally, this information also acts as a support to the knowledge and skills sector for existing and new programmes of study related to the net-zero performance of buildings.

The academic research and existing products analysis have strongly shown that NF+RI products should not be evaluated or compared solely by their thermal conductance performance values, there are other values where it can outperform others such as their liquid and vapour moisture buffering (hygroscopicity), capacity to store heat (inertia/ thermal mass) and density which provides good acoustic and fire performance values. Evidence from many industry members shows that the thermal performance values are still considered over any other as they influence the amount of material used and the integration into existing component designs, particularly those using timber panels. However, the embodied carbon argument is a new one which most stakeholders in the industry recognise, but say requires legislation and a mandate from the government for them to officially act upon and make modifications to their supply chains, manufacturing and designs. The evaluation made on two wall panels in Figures 8 and 9 ad the consideration of thickness increase and cost based on the increased volume of material all show that this change can be done, but it needs to be planned and in line with UK available products.

Our market analysis compares investments and steps made by other EU countries as well as the US and China by comparing the Compound annual growth rate (CAGR) of insulation. For the UK to be competitive and make a mark, its CAGR would need to grow substantially, annually by 20-30% to meet that of Germany. It also depends on incentives, commercial partnerships, and improved skill sets of the construction industry at all levels and production capacity, all of which require a government catalyst into the NF + RI investment. The evident market opportunities are similar to other countries. New buildings can be fully energy efficient with the use of more natural fibre products, designs need to adapt and the cost is considered as an additional asset through the product advantages and benefits against other synthetics. The NF-R products are the panacea for the retrofit market of the UK with one of the largest amounts (60-70% of the stock) of historic and in need of repair properties in the whole of Europe. The clear area of growth is in the solid wall insulation market where all the product benefits can be put into action.

The document also explores the different manufacturing processes required in various NF+RI materials and products exploring the cradle-to-practical completion stage in Figure 20 and more particularly in Table 8 with specific product examples of wood fibre, hemp fibre, sheep's wool and recycled PET insulation products using a cradle to gate boundary assessment. This leads to the evaluation of embodied carbon by using the baseline of the Figure 8 wall system which primarily used mineral wool and PIR insulation to reach a U-value performance. The results show that when substituting the baseline with different products, wood fibre with varying densities and sheep's wood with wood fibre provide the biggest reduction in global warming potential (GWP), 500% and 260% respectively. This shows the full potential of the products and how GWP can outperform most synthetic equivalents.

As an exploration of innovation of NF+RI products, Section 5 assesses products and systems against the UK Research Council technology readiness levels (TRL) as a way to understand any emerging examples and their pathway to being a fully usable product. Most products identified are already available to purchase, some more established than others, however, they are still in ongoing research and development stages within their respective TRL's. Finally, Section 5.2 explores some case studies of best practices and application of NF+RI products in UK buildings from newly purpose-built to retrofit examples in walls, roofs and floors.

7.2. Recommendations

The following recommendations are based mainly on the review made of current NF+RI products, the current market uptake and the future industry shift to low embodied carbon materials as well as meeting some of the government targets on net-zero performance. To b explore the shift into NF+RI products it is important to take four important steps:

1. **Have discussions with existing supply chains**: crop and forest owners, recycling groups and waste streams that can assure supply to emerging companies that are innovating into the processing and creation of new insulation options. Essential to this is the control over certain sawmills that can assure some level of timber offcuts, sawdust and side boards for the exclusive use of wood fibre insulation. Currently, all sawmills have specific timber use in pallets and furniture.

2. **Forge agreements with existing manufacturing factories** of natural fibre insulation by discussing the possibility of sharing machinery and production facilities. One example may be to support further the existing Scottish products and their manufacturing facilities, other options could be to diversify the raw material in these to have various products available.

3. **Introduce biowaste and embodied carbon in construction legislation:** This forces the construction and manufacturing industries to minimise waste, and any unavoidable waste can be collected for reuse into other products, some for insulation as recycled products. Zero Waste Scotland is working on their 2025 roadmap for waste in construction, however, we need clear waste streams such as recovered timber that can be processed and turned into products. Examples include the OSB/ MDF recovery streams, wood from pallets turned into wood fibre, plastics into recycled insulation and others which could be used for new and innovative uses.

4. **Incentivise the construction industry to use NF+RI products:** In parallel with strong supply chains, developers and owners need the incentive to use these products to reach low levels of energy demand but do so with natural materials low in embodied carbon. Net-zero targets and roadmaps require embodied carbon considerations at the procurement and design stage, just as operational energy demand is considered early on. Building regulations need to implement a set target maximum of embodied carbon in buildings just as LETI[15] and the RIBA[16] have done.

Other recommendations are as follows:

- Allow for the certification and warranty and insurance policies NHBC, LABC, and Premier Guarantee to recognise the benefits and installation procedures for using such products. This would allow for further certification and uptake by Architects and developers,

- Conduct UKAS accredited fire resistance testing (under BS 476-20 to 24: 1987 § 5 and BS EN 1364-1: 2015) using natural fibre insulation specimens as a single burning product and in typical timber framed wall configurations to measure the failure point and resistance in time. Also required are tests of the capacity of smoke to accumulate in a room/ building comparing a NF sample with other well-known insulation products and determination of its combustibility (combustible or non-combustible material).

- Develop academic studies that can test and compare the variable configurations of natural fibres, their bonding and adhesive techniques to improve their embodied carbon, maintain their hygrothermal capabilities and improve thermal conductivity. As an example using wood fibre the study could:

[15] Low Energy Transformation Initiative: https://www.leti.uk/ecp
[16] Royal Institute of British Architects: 2030 Climate Challenge: https://www.architecture.com/-/media/files/Climate-action/RIBA-2030-Climate-Challenge.pdf

- replicate the composition of existing wood fibre products imported from the EU (softwoods);
- all fibres from available and suitable hardwood species;
- a mixture of softwood and hardwood fibres with varying compositions and species;
- explore varying low VOC, natural and non-petrochemical binders adhesives and fire retardants;
- differences in fibre quality directly from virgin timber and recycling sources.

- Creation of a Scottish natural fibre alliance (SNFA): with representatives from the supply chain members, existing manufacturers, government representatives (Scottish Forestry), natural fibre promoters (Confor, ASBP, Timber Trade Federation), home building federations, associations (SEDA, CarbonLite, STBA) academics and wider industry (architects (RIBA/ RIAS), builders, Passivhaus Trust.

- Organise awareness sessions and up-skilling to make the use of wood fibre insulation a feasible option in the Scottish construction industry. Create group sessions composed of:

  - Government: Local and central government learning from other EU countries on incentives, legislation and up-take (Germany, France);
  - Contractor groups: Identify contractors who are keen to drive the net-zero agenda to up-skill their workers and other sub-contractors;
  - House builders: deliver training to private house builders and registered social landlords on the benefits and requirements;
  - Architects: Approach architectural practices to discuss the benefits of wood fibre, best practice use and integration to designs to change perceptions by clients and means to meet net-zero performance.

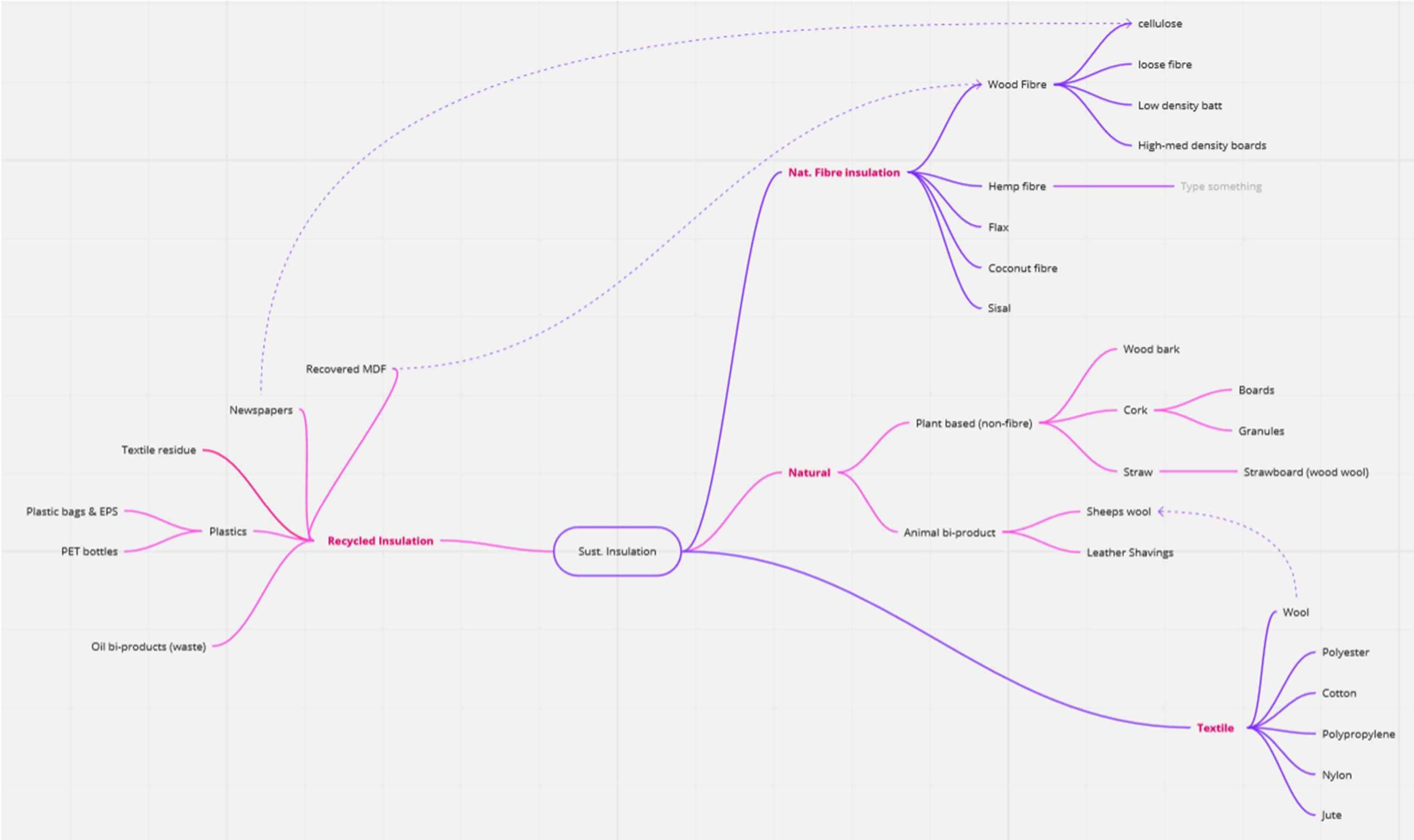
7.3. Future Work

Future work in this field seeks to explore some of the recommendations mentioned above in three different ways. The first is to explore the different supply chains and manufacturing facilities for the partnerships and shared capacity this industry requires. Also planned is a long-term approach through a PhD studentship with specific laboratory testing and innovation in the use and products from homegrown wood fibre and other fibres. A shorter-term second phase of this project will explore the outreach with the industry on the up-skilling and support needed to make NF+RI competitive against available synthetic products.

_Appendices

Appendix A: Matrix of products parameters and characteristics – Available as an MS Excel file: Click here
Appendix B: Sustainable insulation materials tree
Appendix C: UK/ Scottish products
Appendix D: Cost table

Appendix B: Sustainable insulation materials tree



Appendix C: UK/ Scottish produced insulation products

IndiNature Bio-based construction systems	**Type of insulation:** Flexible batt's and semi-rigid boards. **Materials:** UK hemp fibre (*Cannabis sativa ssp. Sativa*) & recycled wool **Product names:** IndiTherm, IndiBoard, IndiBreathe. **Technical specifications:** https://www.indinature.co/specifications **Uses:** Walls, roof and floors; between timber framing and over timber roof rafters. New and retrofit. **Origin & manufacturing:** Crops grown by various farmers near processing plant in Scottish Borders. **Stockist/ retail:** Own website www.indinature.co and

Sisaltech Natural Fibre Insulation	**Type of insulation:** Flexible batts **Materials:** Sisal fibre (*Agave sisalana*), starch based binders **Product names:** Sisalwool 100 **Technical specifications:** https://sisaltech.com/wp-content/uploads/2020/02/Sisaltech-100-data-sheet.pdf **Uses**: Walls, roof and floors; between timber framing. **Origin & manufacturing:** Sisal crop grown in Tanzania (East Africa), recycled wool from Harris Tweed industry (Scotland). Compostable starch-based binder. **Stockist/ retail:** Own website www.sisaltech.com/shop and Zuben www.zuben.co.uk

therma fleece® Nature's finest insulation	**Type of insulation:** Flexible batts (roll), flexible slab, **Materials:** 75% Natural British sheep's wool and 25% recycled polyester, recycled polyester fibres (PET bottles) & Hemp fibre 60%. **Product names:** CosyWool, UltraWool, NatraHemp, SupaSoft **Technical specifications:** https://www.thermafleece.com/our-products **Uses:** Walls, roof and floors; between timber framing. **Origin & manufacturing:** Natural British sheep's wool from Cumbria, England. Hemp grown from UK crops. PET repurposed in UK. **Stockist/ retail:** Ecomerchant, Keyline, Travis Perkins, Mike Wyne, Celtic renewables, Ty-Mawr, & others.

Appendix D: Insulation cost table

Example products	Material (Medium/high-density boards)	Thickness (m)	Coverage (m^2/board)	Coverage (m^3/board)	£/board or batt	£/m^2	£/m^3	Lambda value λ (W/mK)
Superglass Superwall 32	Fibre Glasswool	0.1	0.55	0.055	3.875	7.10	70.97	0.032
Rockwool - Full Fill Cavity Batts	Mineral wool	0.1	0.55	0.055	6.42	11.75	117.52	0.037
Kingspan extruded polystyrene	XPS	0.1	0.75	0.075	10.36	13.82	138.17	0.034
Thermaclass Cavity Wall 21 - Celotex	Polyisocyanurate (PIR)	0.1	2.88	0.288	41.64	14.46	144.58	0.021
Pavatex Soprema - Pavatextil P	Recycled textile	0.1	0.72	0.072	11.05	12.78	153.47	0.039
Steicoflex 036	Wood fibre	0.1	0.68	0.068	12.02	17.56	175.60	0.036
Thermafleece - CosyWool Slab	Sheeps wool & recycled polyester	0.1	0.71	0.071	12.50	17.65	176.50	0.039
Knauf FrameTherm32	Mineral wool	0.1	0.67	0.067	11.92	17.79	177.91	0.032
IndiNature - IndiTherm	Hemp & Sheeps wool	0.1	0.53	0.053	9.83	18.62	186.20	0.040
Thermo Hemp Combi Jute	Hemp & Jute	0.1	0.70	0.070	13.35	19.19	191.88	0.04
Thermafleece - NatraHemp	Hemp & recycled polyester	0.1	0.68	0.068	13.26	19.38	193.80	0.042
Pavatex - Pavaflex	Wood fibre	0.1	0.70	0.070	14.17	20.24	202.43	0.038
Thermafleece - UltraWool	Sheeps wool & recycled polyester	0.1	0.71	0.071	14.98	21.16	211.60	0.035
Sisaltech - Sisalwool 100	Sisal & wool	0.1	0.70	0.070	15.06	21.64	216.40	0.041
Pavatex - Pavatherm	Wood fibre	0.1	0.66	0.066	20.56	13.57	311.52	0.038
MD Façade Cork Board - Amorim	Cork	0.1	0.50	0.050	44	88	880.00	0.043
Mean values	-	-	**0.79**	**0.08**	**15.94**	**16.45**	**221.78**	**0.04**

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