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Synergies, energy efficiency and circularity in the renovation wave

Bio-based products for the renovation wave

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Executive summary

While the European building sector is responsible for 40% of the energy consumption and 36% of the GHG emissions in the EU, only 25% of the building stock is energy efficient. The Renovation Wave Strategy has been launched by the European commission to boost the building stock energy performance. Bio-based products could help lower the overall carbon footprint of the construction sector. This work assesses the use of bio-based material for energy renovation.

Nowadays, bio-based materials represent 3% of the total mass of building material used in Europe and 10% of its volume, with wood covering respectively two third and half of these shares. Regarding insulation, bio-based products cover about 1% of the total market volume in Europe.

The bio-based material market is expected to gain importance in the years to come due to the stimulus coming from European policies like the bioeconomy strategy. However, this policy stimulus must be confronted with several barriers in the context of the renovation wave. The most important being the lack of economic competitiveness; the limited availability of biomass that, being a finite resource, cannot completely replace all other types of materials; the present lack of national norms promoting and facilitating the adoption of bio-based materials; the strong and often distorted competition with the bioenergy sector; the general lack of workers along the value chain skilled on bio-based materials (e.g. construction engineers, architects, building contractors etc.) and the limited size of the bio-based insulation material market compared to its competitors.

1 Introduction

The European building sector is responsible for 40% of the energy consumption and 36% of the emissions in EU (WEF, 2021). Considering that yearly only 1% of buildings in Europe undergo energy renovation, and that only 25% of the building stock is energy efficient, the European Commission launched the Renovation Wave Strategy to boost actions in the buildings sector and achieve climate-neutrality by 2050 (EU, 2020). This main goal of this strategy is to improve the energy performance of the European building stock by doubling the annual energy renovation rates in the coming 10 years. Of the total GHG (greenhouse gas) emissions in Europe, 12% is due to the material intensity of the building sector (EUROSTAT, 2021). Due to their lower carbon footprint (Hart et al., 2021), bio-based products represent a great alternative to GHG-intensive fossil-based construction materials that could help lowering the carbon footprint of the European building stock.

Bio-based materials are those materials wholly or partly derived from materials of biological origin, excluding materials embedded in geological formations and/or fossilised. The use of bio-based material in the renovation wave might represent a win-win solution that could both help increasing the energy efficiency of the European building stock and, at the same time, lower its embodied carbon footprint.

This work aims at exploring the role bio-based products can plain in the context of the renovation wave. More specifically, this report wants to give insights about:

- the market size and the different market sub-segments and their perspectives,
- the existing policies and measures EU and Member States level,
- the existing plans and strategies existing at Member State level to promote and incentivise the use of these products,
- the key barriers in the further development of these products, and
  the comparative advantages and disadvantages in terms of energy and CO_2 emission savings.

The main objective of the renovation wave is to foster deep energy renovation activities to achieve the goal of 35 million building units renovated by 2030, it wants also to achieve several other side-objectives. Aspects like the creation of more sustainable, circular, building aesthetic, high health and environmental standards in buildings are, for example, other side-objectives mentioned in the strategy. For this reason, the report will mostly focus on materials and applications that are directly relevant for energy renovation (i.e. insulation material) but will also touch upon other materials not directly relevant for this purpose which can still contribute to the side-objectives of the renovation wave.

2 State of play of bio-based materials

Key messages:

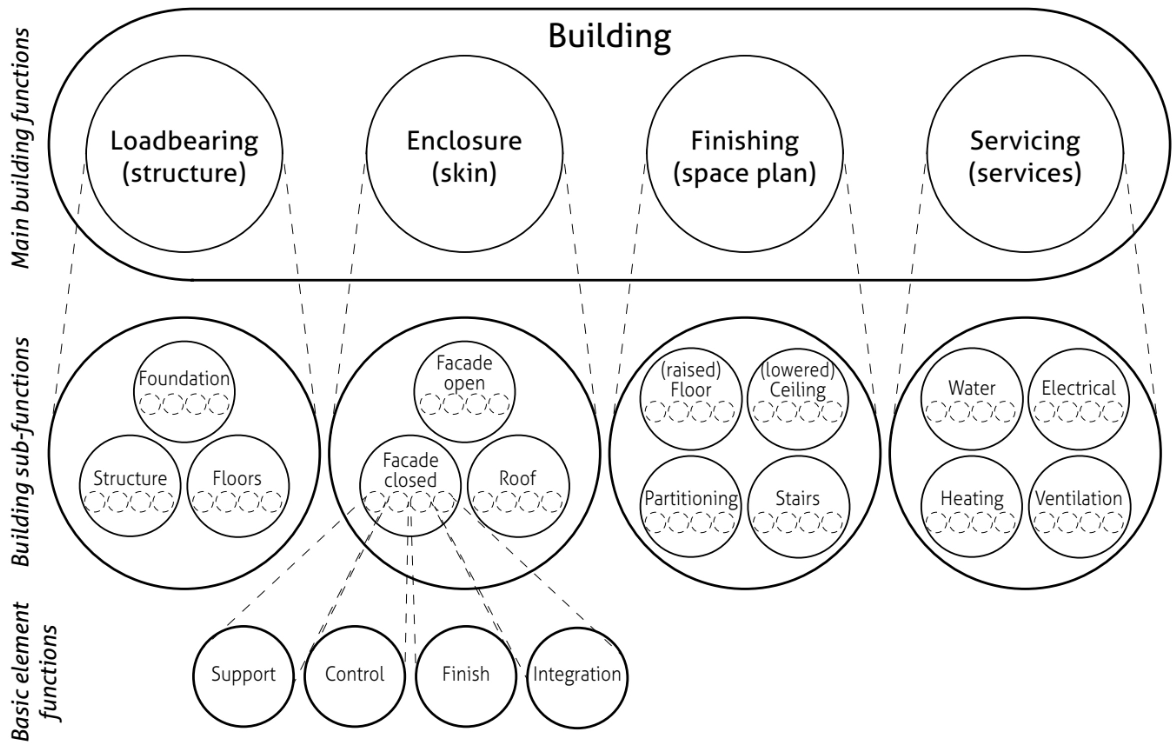
- Bio-based insulation materials represents about around 1% of the European market of insulation materials.
- Wood dominates the market of bio-based materials in the building sector, although other feedstock like straw, hemp, flax etc. are more and more being used.
- The bio-insulations research field has sensibly grown in the last decades, with Europe being the most active region of the world in this respect.
- The cost of bio-based insulation materials is generally higher than that of its traditional competitors (e.g. EPS).
- Bio-based insulation materials show, on average, better performances than their competitors from an environmental and health point of view, although the variability is high.

This chapter sets the scene by giving an overview about the use of bio-based materials in construction. The most important bio-based construction and insulation materials will be described in terms of size, sub-segments characteristics and its perspective will be outlined. Finally, the benefits and/or impact of using bio-based materials in the context of renovation, and more broadly in construction is summarised.

2.1 Bio-based materials in construction

Buildings consists of building elements that are generally classified on the basis of their function and the location in a building (Figure 2-1).

Figure 2-1 Functional decomposition of building elements.



Source: Beurskens (2021).

A literature review has been performed to identify those building elements that are relevant to be considered in the context of the study. The relevant works to be further reviewed were found using the so-called snowballing procedure (Wohlin, 2014). To identify the start set, the search engine LIMO ([1]) has been used to perform the initial literature search. For each of the above listed target *element,* the following search string has been used in LIMO: (bio-based OR bio based) AND building material AND construction AND *element*. Based on their title and the keywords, the resulting articles were reduced in a first iteration and, for those deemed relevant, the contents were read in the second iteration. The final set was further integrated with the (e.g. grey) literature already known from the authors for their relevance and not included in the performed search. Not only the building elements that directly or indirectly contribute to meet the objectives of the renovation wave, but also those where bio-based materials have a relatively important market share have been included in this section.

2.1.1 Insulation

Several bio-based insulation materials can already be found on the market or are being developed, with multiple methods (

([1]) https://limo.libis.be/index.html

Table 2-1) and feedstocks (Table 2-2) that can be used to create them.

Table 2-1 **Typical manufacturing methods used in bio-based insulation materials and frequency found in the literature.**

Manufacturing methods	Explanation	Number of applications found in the review
Bonding	By help of at least one binder, such as glue, to make one or more kinds of loose/particle materials to form a whole body.	85
Natural form	Biomasses are packaged directly from raw type (e.g. straws bales with tight or loose structures).	33
Pressing	By help of high pressing at environmental temperature, to make one or more kinds of loose materials to form a whole body.	26
Hot-pressing	By help of high pressing at a relative higher temperature, to make one or more kinds of loose materials to form a whole body.	18
Others	Such as needle-punching, hydro-entanglement, aerosol processing. etc.	3
Injection	A magma is first produced, and then the solution is injected into a mold at a specified pressure.	2
Foaming	Generate a porous structure in solid materials by physical or chemical foaming methods.	1

Source: Modified from Liu et al. (2017).

Feedstock like **(wood) cellulose fibre** (Cetiner & Shea, 2018; Foams et al., 2020; Hossain et al., 2018; Latif et al., 2015; Palumbo et al., 2016, 2018; Pavelek & Adamová, 2019; Romano et al., 2020; Segovia et al., 2020; Spirinckx et al., 2013; Tiso et al., 2016; Tumusiime et al., 2020), **paper flakes** (Spirinckx et al., 2013), **hemp** (Agliata et al., n.d.; Benfratello et al., 2013; Charai et al., 2021; Collet & Pretot, 2014; Costantine et al., n.d.; Crini et al., 2020; Degrave-lemeurs et al., 2018; Hussain et al., 2019; Kyma & Sjo, 2008; Marceau et al., 2017; Nguyen et al., 2016; Palumbo et al., 2016, 2018; Pittau et al., 2018; Pochwała et al., 2020; Rahim et al., 2016; Sinka et al., 2018; Somé et al., 2018; Spirinckx et al., 2013; Vėjelis et al., 2017; Viel et al., 2019; Zampori et al., 2013), **straw** (Blondin et al., 2020; Colinart et al., 2013; Latif et al., 2015; Lee & Yeom, 2015; Liu et al., 2019; Palumbo et al., 2016; Pittau et al., 2018; Platt et al., 2020; Rahim et al., 2016; Romano et al., 2020; Sabapathy & Gedupudi, 2019; Slaimia et al., 2017), **bamboo fibre** (Huang et al., 2018; Mao et al., 2017, 2018), **flax** (Benmahiddine et al., 2020; Codyre et al., 2018; Kyma & Sjo, 2008; Spirinckx et al., 2013), **sheep's wool** (Romano et al., 2020; Spirinckx et al., 2013), **cork** (Abu-Jdayil et al., 2019; Cascone et al., 2019; Dias et al., 2018; Limam et al., 2016), **reed** (Asdrubali et al., 2016), **algae** (Talaei et al., 2020), **agro waste** (Antunes et al., 2019; Barbieri et al., 2020; Brouard et al., 2018; Ismail et al., 2020; Karaky et al., 2018; Lee & Yeom, 2015; Maraveas, 2020; Palumbo et al., 2015, 2016; Panyakaew & Fotios, 2011; Pinto et al., 2011; Prajer & Trgala, 2018; Viel et al., 2019), **cotton waste** (Binici et al., 2012; Rajput et al., 2012), **waste paper** (Oriyomi et al., 2015; Rajput et al., 2012) and **leather scraps** (Marconi et al., 2020) have been used.

Table 2-2 **Top 5 countries with highest number of scientific papers published on bio-based insulation material and relative feedstock studies.**

Country	Feedstock and number of of papers
France	Sunflower (4), hemp (7), flax (5), wood (2), straw (1), bagasse (1), rice husk (1)
UK	Straw (4), wood (1), coconut husk (1), bagasse (1), hemp (6),
Italy	Kenaf (1), cork (1), carboard panels (1), hemp (4), reed (1), waste paper and textile (1), wood (1), Olive stone (1)
Turkey	Cotton (2), straw (3), rice husk (1), sunflower (3), Olive seed (1), textile waste (1), wood (1)
Algeria	Wood (3), straw (2), date palm (4)

Source: Modified from Liu et al. (2017).

The bio-based components can be formed into a soft malleable insulation material, or into hard panels. All mentioned bio-based elements can be filled in between two panels to serve as insulation. However, most research papers work with a composite panel with the bio-based element as first input, and a binder as a second input (e.g. glue, silica). Additionally, straw and hemp can be used as blocks as well, compared to the previously mentioned filling method and the formation of a panel. Straw bales on the one hand and hempcrete on the other hand can be used both as insulation and as structural component.

Figure 2-2 Example of bio-based insulation materials.

Source: Maskell et al. (2015).

As shown by Liu et al. (2017), research in bio-based insulation material has boomed in the last decade, especially in Europe (Table 2-2), in particular for hemp, straw, flax and wood based material (Liu et al., 2017).

2.1.2 Wall

Wall elements can be constructed out of **timber** (Corradini et al., 2019; Dong et al., 2020; Markström et al., 2019; Mathis, Blanchet, Lagière, et al., 2018; Mathis, Blanchet, Landry, et al., 2018; Nakano et al., 2020; Robertson et al., 2012; Santi et al., 2016; Singh et al., 2019; Švajlenka & Kozlovská, 2020; Werner & Richter, 2007; Winandy & Morrell, 2017; Zibell et al., 2011), **bamboo** (Ahmad & Kamke, 2011; Seixas et al., 2021), **hemp** (Crini et al., 2020; Moujalled et al., 2018; Piot et al., 2017; Pittau et al., 2018) and **straw** (Cascone et al., 2019; Pittau et al., 2018; Yin et al., 2020). Bio-based composites can be constructed as well, for example based on **agro-waste** (Liuzzi et al., 2017). In the case of a composite, fibre is used to add strength to a massive wall element.

Timber can used in wall elements, for example by creating a timber framework (Pittau et al., 2018), or load bearing walls, which would represent the load bearing component of the building. Generally speaking, timber can be used directly as beam or transformed into manufactured product, by e.g. laminating and/or pressing wood, products that are often referred also as engineered wood products. While the first is used typically as load-bearing element, engineered wood products can have different applications. Examples of such products are CLT (cross laminated timber), LVL (laminated veneer lumber), OSB (oriented strand board), MDF (medium density fibreboard), PSL (parallel strand lumber) and HDF (high density fibreboard) (Mathis, Blanchet, Lagière, et al., 2018; Singh et al., 2019).

Bamboo can be used directly in a round pole frame structure , but it can also be formed into more workable dimensions, similar to timber (Ahmad & Kamke, 2011; Seixas et al., 2021). It is possible to create PSL or

SWB (strand woven bamboo) from the bamboo material for example, similar to OSB and LVL. Hemp cannot be used as it is in construction. It is formed in hemp concrete or hempcrete blocks (Piot et al., 2017). This product is achieved by mixing hemp shives with a binder like cement or lime for example. It is possible to use straw bales as load bearing structure itself, or as infill for an existing framework. Timber frameworks are used frequently for this purpose (Cascone et al., 2019; Pittau et al., 2018). Note that a structural wall element will rarely be renovated since it is hard to access and is expected to have a life cycle of 100 years. Other construction elements will be changed out more regularly, like cladding and insulation.

2.1.3 Cladding, roofs and floors

Bio-based inputs used for cladding, roofs and floors can be **wood** (Friedrich, 2021; Friedrich & Luible, 2016; Lehmann, 2012; Mantanis et al., 2018; Markström et al., 2019; Valachova et al., 2021), **straw** (Brzyski et al., 2017), **flax** (Barnat-hunek et al., 2017; Betts et al., 2021; Brzyski et al., 2017; Codyre et al., 2018; Mak & Fam, 2019), **hemp** (Barnat-hunek et al., 2017) or other **residue products** (Pujadas-gispert et al., 2020). A common used wood composite in construction works is CLT (Lehmann, 2012), but new products like wood plastic composite (WPC), a composite material combining wood-based elements with polymers, are more and more being developed (Gardner et al., 2015).

Wood can be applied to a building to support both the roof, as well as the floor (Lehmann, 2012; Mantanis et al., 2018; Pujadas-gispert et al., 2020). Similar applications are found regarding flax panels (Mak & Fam, 2019).

2.2 Market size, perspective and natural capacity

2.2.1 Market size

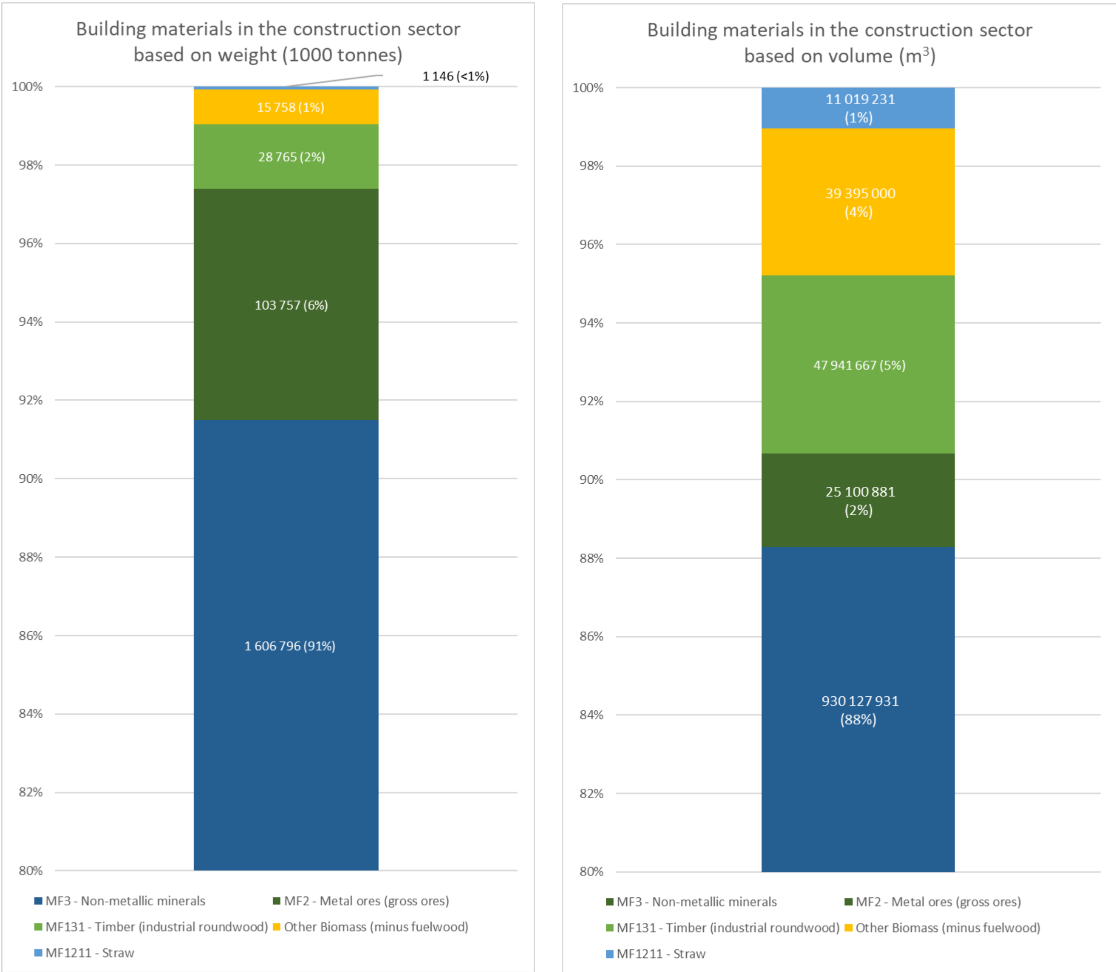
In this section, an overview of the current market size of bio-based materials in construction is given. To determine the market size of each bio-based construction material, the material consumption at EU level is analysed for the construction sector (NACE code F). This is achieved by considering the Raw Material Consumption (RMC) indicator for 2018, the latest year available. The RMC combines the amount of domestic, foreign, direct and indirect raw material necessary to satisfy the material need of a certain industry in a given geographical reference area. This means that the RMC includes both material used in new as well as renovated buildings and does not allow to clearly understand the amount of bio-based material consumed in the context of renovations. However, the analysis helps to understand the overall market characteristics and the role played from bio-based materials in the building sector.

The selected categories of primary raw materials for the construction industry are (Eurostat, 2020):

- Non-metallic minerals, which contains (but not limited to) litho-based inputs like marble, granite, clay, sand and gravel.
- Metal ores (gross ores), which includes all possible mineable metals (e.g. iron, copper, nickel, gold, silver).
- Timber (industrial roundwood), which is comprised of all roundwood, except for fuel wood. Both natural lumber and engineered products are included.
- Straw, which is part of the total biomass used for construction purposes.
- Other biomass. This category is created to scope the amount of bio-based construction material that is used, excluding the explicit available categories of timber and straw.

These materials are selected, as they are part of the final, physical construction work. Extractions of fuel, both renewable/bio-based as non-renewable to power the production of the final products are excluded from the calculations whenever possible.

Figure 2-3 **Raw material consumption in construction and construction works (NACE code F), 2018, EU 27. In thousand tonnes and percentages left and in cubic meter and percentages right.**



Note: y-axis not fully displayed.

Source: Based on Eurostat data (Eurostat, 2020).

Figure 2-3 on the left depicts the RMC for the construction sector in thousand tonnes. For each input category, the percentage of total material consumption is calculated. Non-metallic minerals dominate the construction sector by far, with a market share of 91%. Metal ores follow with a market share of 6%. The remaining 3% of the mass of building material used in Europe is due to bio-based construction product. Within this category, timber has the biggest market share, namely 2%, 1% of the mass is represented by "other biomass" and straw has a negligible market share of less than 1%.

While mass is the common unit used in such a type of material flow analysis, it must be noted that making the comparisons solely based on mass can give an incomplete picture of the relative market importance of each material. In fact, at least in the context of construction materials, it can also be relevant to know the relative volume occupied from a specific type of material in buildings to get an idea of its relative market importance. For this reason, in this work also the volume-based market shares in cubic meters (m^3) is calculated using the densities reported in Table 2-3.

- The category non-metallic minerals is assumed to consist of four main categories: (1) concrete (i.e. sand and gravel, MF38), (2) marble, granite and sandstone (MF31), (3) clay (MF37) and (4) limestone (MF36).
- Metal ores are split between (1) steel (i.e. iron, MF21) and (2) non-ferrous metal (MF22). Since it is not possible to calculate the density of the combined mix of non-ferrous metals, aluminium is taken as a proxy.
- The three bio-based inputs are kept separately to be able to analyse each of them separately.

Since the category "other biomass" consists of many different plant species, which are not defined in the Eurostat database, a gross estimation of 400 kg/m^3 is assumed. For this reason, the resulting estimate of the market share of the category "other biomass" has subject to higher uncertainty.

Table 2-3 Densities used for construction materials.

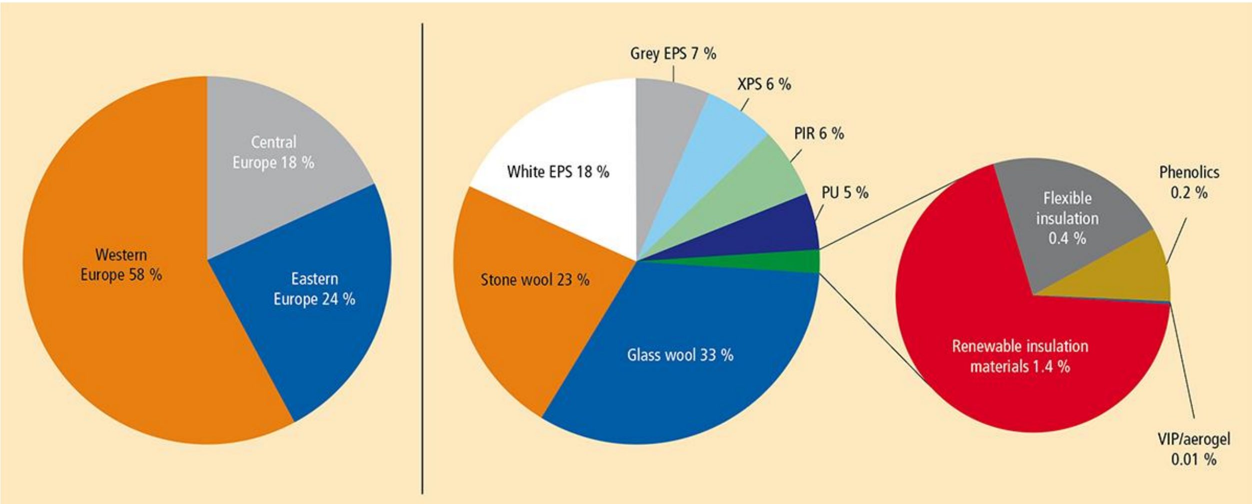
Material category	Material	Estimated share of category	kg/m^3
Non-metallic minerals	Concrete (sand and gravel)	72%	1 425
	Marble, granite and sandstone	11%	2 475
	Clay	8,5%	2 350
	Limestone	8,5%	2 700
Metal ores	Steel (iron)	28%	7 820
	Non-ferrous metals (aluminium)	72%	2 700
Timber	Wood	100%	600
Straw	Straw	100%	104
Other biomass	Various crops	100%	400

Source: Data retrieved from Engineering Toolbox (2020) and Sokhansanj (2013).

Figure 2-3 on the right shows the resulting market shares based on volume instead of weight. As one can see, the conventional categories of non-metallic minerals and metal ores decrease in relative market share to 88% and 2% respectively. The market share of the bio-based materials (with lower density compared to the conventional materials) increases. Timber increases from 2% to 5%, straw increases from less than 1% to 1% and the undefined "other biomass" increases from 1% to 4%. In this new calculation model, the bio-based materials account for 10% of the total raw material consumption in the European building sector.

As already mentioned, these data refer to the big family of bio-based materials. This means that they do not allow to distinguish neither which is the share used in new and renovated building nor which is the share that is used in those applications that are mostly relevant for the renovation wave (i.e. insulation) compared to the others (e.g. load-bearing elements).

Figure 2-4 European thermal insulation market by region (left) and product (right) in 2018 (total = 270 million m^3).



Source: https://www.gupta-verlag.com/news/industry/23659/ial-consultants-the-european-market-for-thermal-insulation-products (retrieved on 31/10/2021).

While, at least based on the authors' knowledge, there are no data available about this latest aspect, some conclusions can be drawn comparing the result our analysis with the characteristic of the market of insulation material (Figure 2-4). The family of renewable insulation materials account for 1,4% of the total market volume of insulation material in EU. Even assuming that insulation material volume in building is linearly proportional with the other building elements (which is clearly not being typically lighter) the fact that bio-based insulation material has a volume that is proportionally 10% of that used in the whole construction sector makes clearly understand that most of the bio-based material used in construction goes in other building elements like structural elements. It is thus evident from the analysis of previous sections that bio-based materials currently play a secondary, although still relevant, role in the construction sector, and that timber dominates this market segment.

2.2.2 Market perspective

It is evident from the analysis of section 0.1 that bio-based materials play a marginal market role in the construction sector and that timber dominates this market segment. Still, the bio-based material market is expected to gain importance in the coming years due to the stimulus from European policies such as the bioeconomy strategy (Kardung & Wesseler, 2019) as it happened over the last years. For example, between 2008 and 2018, the whole bio-based economy experienced an increased of its turnover of about

30%, with the highest increase in the the chemicals and plastics (+68 %) and the pharmaceutical (+42%) sectors (Porc et al., 2021).

It is thus important to look also at the market perspective and try to give answers to the following questions:

- What is the market potential considering their economic competitiveness and the overall consumer acceptance?
- What is the achievable sustainable supply of bio-based feedstock material?

With regard to the first questions, Schulte et al. (2021) compared the life cycle cost of different bio- and fossil-based insulation materials (
Table 2-4). They found that EPS (expanded polystyrene) is the cheapest and miscanthus, which still shows a limited market integration, being only about 10% more expensive. Hemp and wood-based insulation are the least cost-efficient.
Other studies come to the same conclusion that bio-based solutions tend to be slightly more expensive than their traditional competitors (see e.g. Barrio et al., 2021; Lazzarin et al., 2008; Saadatia, 2014). In another work, Göswein et al. (2019) explored the economic performances of building retrofitting and compared the cost per m^2 of EPS and cork-based insulation material. They found that, over the 30 years studied, retrofitting offers an economic advantage only in the case of relatively high energy consumption (or energy cost) in the building. This is because the savings are more than compensated by retrofitting costs. In addition, between the two insulation materials, the bio-based one results the most expensive due to its higher market price compared to the EPS-based solution (Figure 2-5).

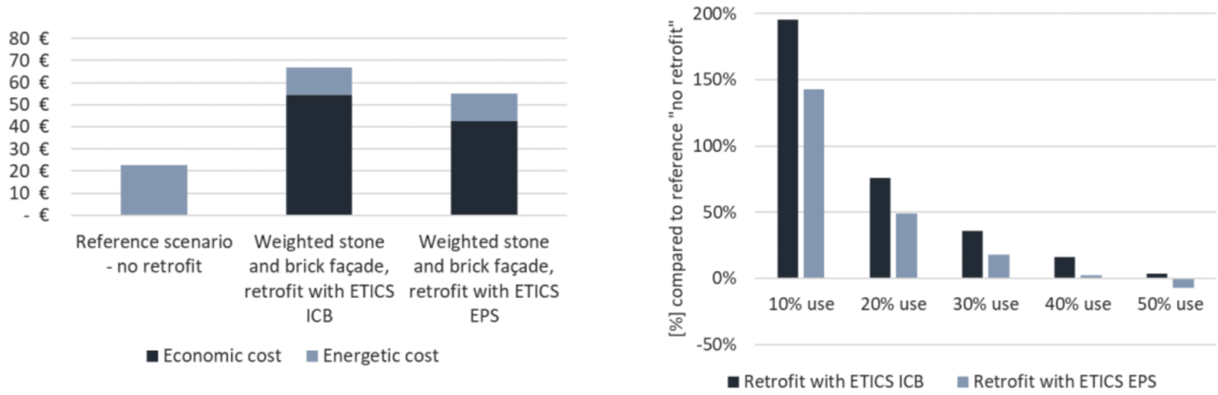
Table 2-4 Life cycle costs of insulating 1 m^2 of external wall of a residential building with 0.24 W/m^{2}K for 70 years with different materials.

	Costs in € per FU					
Life cycle stage	**Wood fiber**	**Hemp fiber**	**Flax**	**Miscanthus**	**EPS**	**Stone wool**
Cultivation system	1.51	2.21	2.79	0.90	0	0
Manufacturing system	10.33	9.19	6.35	2.76	4.13	8.35
Use phase system	0.81	3.70	0.81	3.74	3.70	3.64
End- of- life system	1.22	1.31	1.37	1.39	0.46	0.81
Transports	0.37	0.39	0.40	0.41	0.09	0.25
Total	**14.24**	**16.79**	**11.72**	**9.18**	**8.39**	**13.05**

Source: Adapted from Schulte et al. (2021).

It has also to be noted that, while EPS production is a relatively well-established and widespread technology (cfr. Figure 2-4), the insulation cork board use is rather limited due to the limited supply of cork, which is also due to the high intersectoral competition for the raw material cork with bottle cork stoppers industries. In practical terms, this means that while the former benefits from the positive effect on production costs of technological learning, process efficiency optimization and of the economies of scale, this is not the case for the latter. This applies to many bio-based materials that appeared on the market recently or are being developed, being the bio-based industries are a nascent sector. The fact that often they still represent a niche market, the technological readiness level it is relatively low and that the efficiency of the production processes is not yet optimized, makes bio-based products hardly economically competitive. At least in comparison with the more widespread products such as those based on mineral wool (glass and stone wool) and plastic foams (EPS, XPS, PUR). The fact that the bio-based sector is and will most probably continue to grow, can positively influence the cost competitiveness of at least those subsectors and products that will continue to grow reaching a certain market size and will thus benefit from the aforementioned effects.

Figure 2-5 Left: Comparison of the economic (production and installation) and energy consumption costs after 30 years for 1 m² of non-retrofitted, ICB (insulation cork board) and EPS-based insulated exterior wall. Right: Sensitivity analysis of heating and cooling needs based on the total economic cost.



Source: Göswein et al. (2019).

Consumer behaviour will play a critical role in supporting the uptake of bio-based materials. Consumers' purchasing choices can greatly influence the bio-based products demand and, consequentially, its supply and market price. Gaffey et al. (2021) reviewed the studies looking at the consumers perspective of bio-based products and, more specially their motivation, interest and knowledge related to bio-based product. The reviewed studies (see In the same work the authors studied the consumer drivers and motivations with regards to buying bio-based products in the Netherland and Ireland. They found that, in both countries, price is the key factor influencing the purchase of bio-based products (Figure 2-6) and that about half of the consumers are not willing to pay more for them.

To avoid unwanted effect, it is important that the increased demand of bio-based material does not lead to the unsustainable overexploitation of natural resources. It is thus crucial to understand what a future realistically achievable sustainable supply of bio-based feedstocks is.

Table 2-5 for their details and main findings) showed the relatively positive perceptions of consumer towards bio-based materials, mainly due to the sustainability benefits perceived, despite the relatively limited knowledge they have about them.

In the same work the authors studied the consumer drivers and motivations with regards to buying bio-based products in the Netherland and Ireland. They found that, in both countries, price is the key factor influencing the purchase of bio-based products (Figure 2-6) and that about half of the consumers are not willing to pay more for them.

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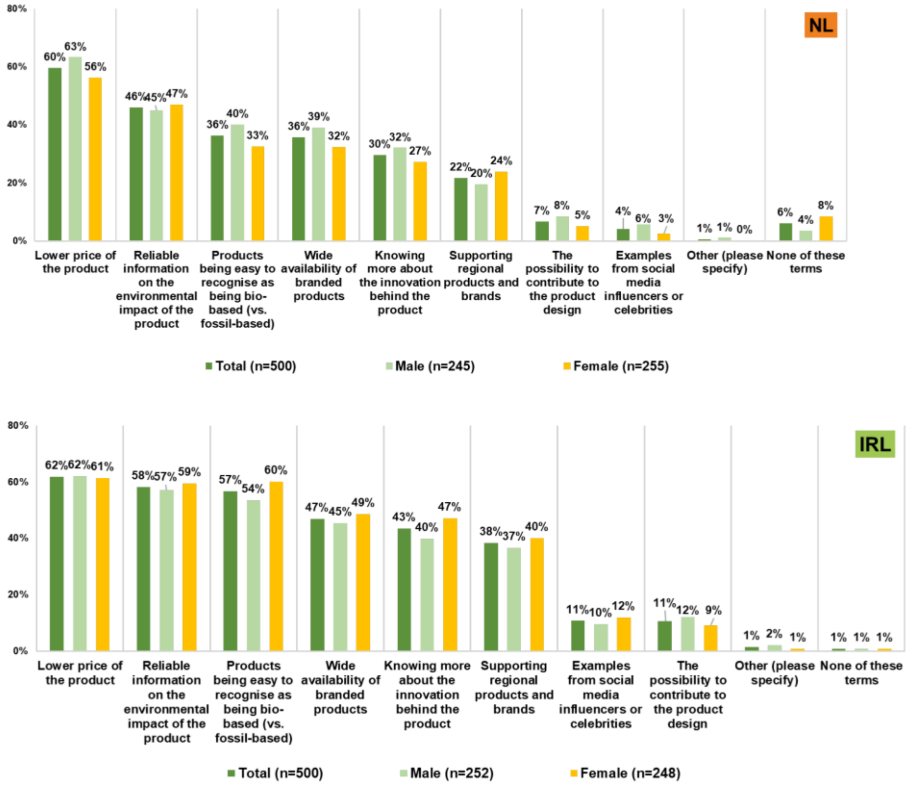
Table 2-5 Studies assessing consumer perspective on bio-based material.

Study Name and Year	Study Type	Study Region(s) and Size	Findings
Meeusen et al., 2015	Survey	Denmark (N = 1012), Germany (N = 1136), Italy (N = 1060), The Netherlands (N = 1016), Czech Republic (N = 1008), and Slovenia (N = 1011)	A high degree of unfamiliarity with the bio-based concept and bio-based products among consumers. They have positive associations linked to the environment. However, there are also mixed and negative feelings due to the lack of knowledge and arising questions about the bio-based concept and products.
Pfau Swinda, Vos John Vos, Dammer Lara, 2017	Literature Survey	17 relevant EU reports	While there is a general understanding among the public regarding what bio-based products are, specific knowledge about product characteristics is mostly missing and misconceptions occur. Various studies included in the meta-review show that people assume that bio-based production is aimed at finding environmentally friendlier solutions. This results in a positive attitude towards bio-based products, but also high expectations.
Delioglamnis et al., 2018	Two-round Survey	Round 1 (N = 452), Round 2 (N = 530) from 17 EU member states	Respondents have a positive attitude towards and interest in bio-based products. Consumers find them trustworthy in terms of their content, they recognize their potentially positive environmental impact and are willing to pay more for a bio-based product of the same functionality and properties than a fossil-fuel derived one. Nevertheless, the survey does indicate that limited market availability and high prices are important factors that inhibit the wider use of bio-based products.
Carus Michael,Partanen Asta,Piotrowski Stephan, 2019	Interviews	90-min in-depth psychological interviews (N = 60) in Germany, Italy and Poland	Most consumers had very little knowledge of concepts like “bio-based” and “biodegradable”. They (incorrectly) assume that all plant-derived products will be biodegradable. Consumers feel overwhelmed, not competent, and not responsible for the decision around which materials are good or bad. They want a simple, official, and trustworthy label to help them identify the “good” materials.
Ladu et al., 2019	Two-round Delphi Study Survey	Round 1 (N = 744), Round 2 (N = 341) from Germany, Italy, Spain, UK	The top three environmental issues for consumers were: (1) biodegradability; (2) recyclability; and (3) type and origin of raw material. For consumers, the top three social issues were: (1) impact of the product on people’s health; (2) no child labour; and (3) respect for human rights in the production of raw materials and products. The three most important aspects to be considered before buying a product in addition to sustainability related characteristics were: (1) price; (2) functionality/performance of the product; and (3) better performance than alternative fossil-based products.
Sabini Matteo, Cheren Serena, 2020	Survey	(N = 1014) from 37 countries (largely Mediterranean, but other EU and non-EU responses included)	Many misconceptions, lack of knowledge or understanding about what is bio-based, the origin, production and processing of bio-based products. Furthermore, customers have doubts about the trustfulness of the claims given by companies and brand owners. Clear labels are expected to answer the misconceptions, provide knowledge and more visibility for bio-based products.
Taufik et al., 2020	Lab-in-the -field study	(N = 281) German, French and US consumers	Focus on bio-based packaging. The results show that consumers only perceive compostable bio-based packaging to have more environmental benefits than fossil-based packaging. However, most consumers dispose of compostable bio-based packaging in an incorrect manner (not in line with what is communicated on the packaging label) relatively often.

Source: Adapted from Gaffey et al. (2021).

Figure 2-6 Motivations of consumer for buying bio-based products (NL= Netherlands, IRL= Ireland).



Source: Gaffey et al. (2021).

2.2.3 Market versus resources issues

With regard to timber, largest part of bio-based construction materials at the moment, an idea on the current intensity of forest management and harvesting can be obtained analysing the utilisation rate. The utilisation rate represents the ratio between the annual volume felled and the volume of annual growth (i.e. net annual increment NAI) in the stock of living trees. This ratio is an indicator of the sustainable forest management since it provides an overview of the net forest that remains after felling.

Values over 100% indicate a non-sustainable harvest process, where more trees exit compared to natural generation plus additional plantation. Values below 100% imply an increase in the standing volume of timber over time. The ratio indicator should obviously be considered only over large spatial areas and temporal timeframes. This is due to the spatio-temporal variability of growth and harvesting patterns influenced, for example by the necessary management decisions like evening out the age of the standing stock, or the impact of natural disturbances. It must be also underlined that the ratio of fellings per net annual increment reported in the statistics might be under-estimated when relative large areas of the forests are owned by small-scale owners exploiting the forest for self-consumption of firewood. This type of harvesting is not reported in official statistics.

In the latest report on the State of Europe's Forest (Forest Europe, 2020), these figures are provided by region (

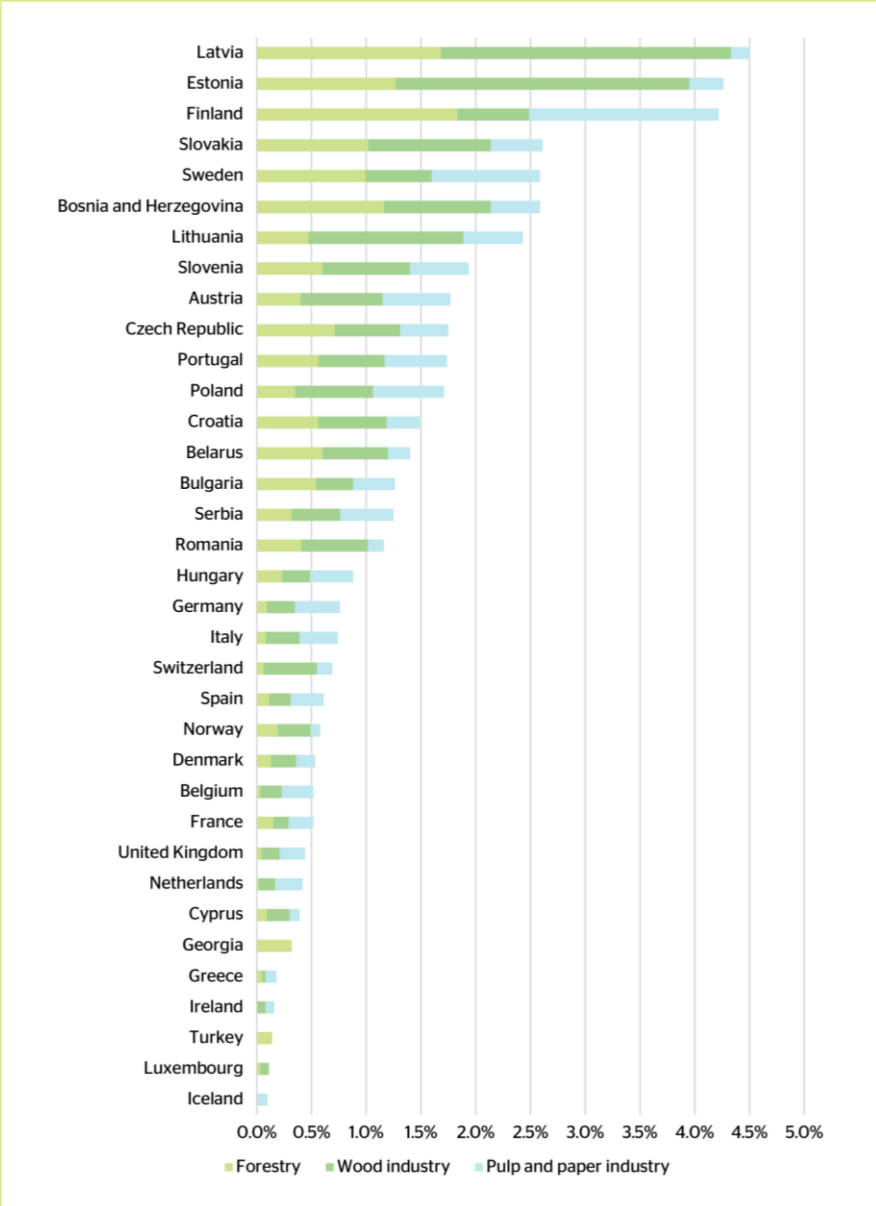
). The average utilisation rate is slightly above 70%, which implies a yearly increase in the overall standing stock of wood. It is interesting to know the descending gradient in the utilisation rate moving from the Nordic to the Southern European countries. This is certainly due to the higher relative importance of the forest sector in Nordic countries (cfr. Figure 2-7) but this is certainly also due to the fact that exploitation of forests for self-consumption of firewood is much more widespread in southern European countries. This means that, at the moment, European forests are not under pressure and that an increase in the supply wood can be also foreseen. It should ensure no further forest degradation and sustainable management at the supply side.

Table 2-6 Net annual increment (NAI), fellings, and utilisation rate by region (2015). Data coverage as % of total regional forests available for wood supply (FAWS) area: NE 94%, C-WE 100%, C-EE 34%, S-WE 0%, S-EE 61%, EU-28 67%, Europe 65% (23 countries).

Region	NAI		Fellings		Utilisation rate
	million m^3	m^3/ha	million m^3	m^3/ha	%
North Europe	249,1	4,8	205,8	3,9	82,6
Central-West Europe	259,1	7,3	184,7	5,2	71,3
Central-East Europe	86,6	8,1	53,6	5,0	61,9
South-West Europe	-	-	-	-	-
South-East Europe	57,5	4,8	33,3	2,8	58,0
EU-27+UK	**576,4**	**6,3**	**432,2**	**4,7**	**75,0**

Source: Based on State of Europe's Forests (Forest Europe, 2020).

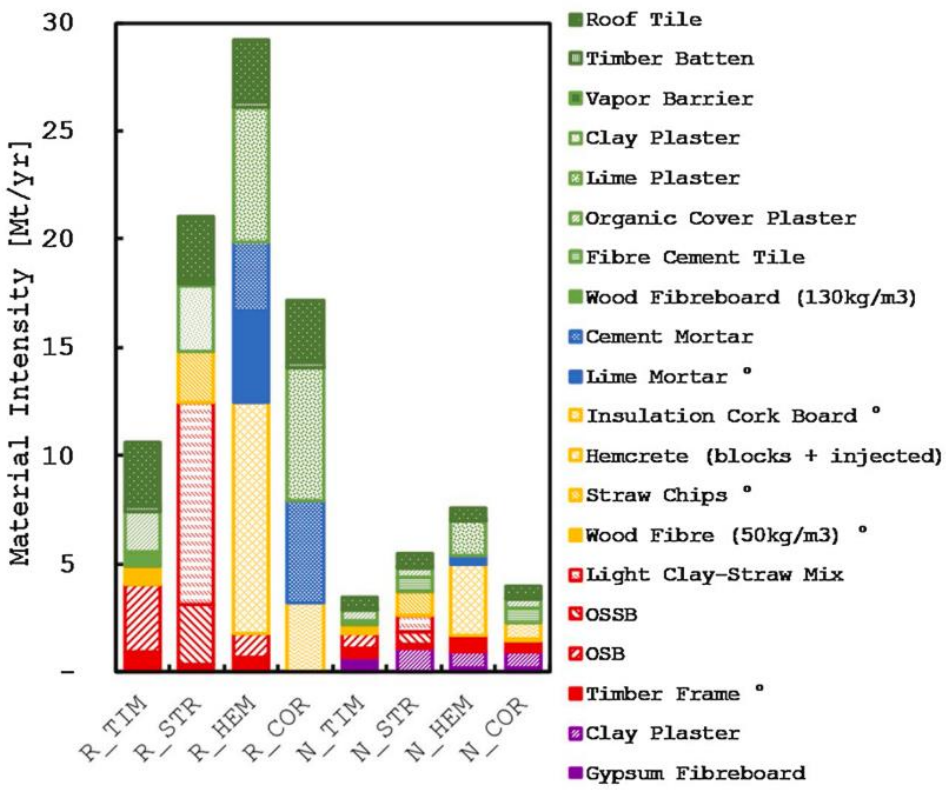
Figure 2-7 Contribution of the forest sector to gross domestic product, by country, 2015.



Source: State of Europe's Forests (Forest Europe, 2020).

Göswein et al. (2021) estimated the potential land requirements of a large-scale bio-based renovation of the building stock in Europe until 2050. Their research focused on four different materials, namely timber, straw, hemp and cork and considered only the building envelope components above the ground (exterior wall and roof). Using material flow analysis, the authors estimated the expected material intensity of such bio-based renovation strategy in the EU-27+UK (Figure 2-8).

Figure 2-8 Yearly material intensity for renovation and new construction, evaluated as mean value for the period 2020-2050, for exterior walls and roofs, per type of material.



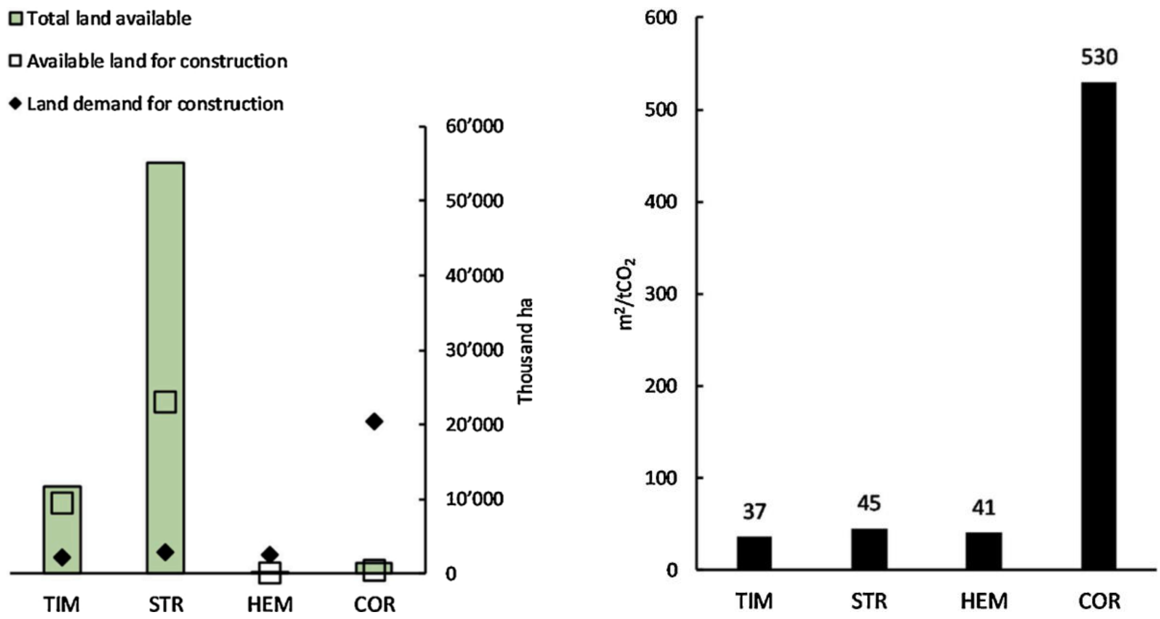
Note: The materials are color-coded depending on the functions of the main components: purple = interior finishing, red = structure, yellow = insulation, blue = adhesive, green = exterior finishing. "R" states for renovation, and "N" is for new construction. "TIM" states for timber, "STR" for straw, "HEM" for hemp and "COR" for cork.

Source: Göswein et al. (2021).

Consequently, the land that would be needed to fulfil the estimated demand of bio-based material has been based estimated (Figure 2-9 left). The authors conclude that straw represents the most promising feedstock to be used in large-scale bio-based renovation. This is both because of its carbon storage potential and low land use impact (Figure 2-9 right) coming from the fact that it is a by-product of wheat farming. In addition, its use would provide an additional source of income to farmers. Timber is found to be the most promising in terms of land availability. Considering also its carbon storage benefits and the fact that from a technological and logistical point of view the wood-based market is already developed, it is certainly going to be a fundamental bio-based resource in the near future.

The expectable increase in demand of the resource wood from other sectors as well is likely increasing the competition for this resource. Both hemp and cork do not have the capacity to satisfy the demand in the EU 27+UK at the moment, even though hemp was found to have the highest potential GWI (global warming impact) (see next section).

Figure 2-9 **Left: European land requirement vs availability to supply the annual demand of the four alternative feedstocks. Right: land efficiency coefficient measured as m[2] required to store 1 tonne CO_2 in the building stock.**



Source: Göswein et al. (2021).

Material Economics (2021) modelled the European demand for biomass feedstocks from all sectors by 2050 and compared this with the realistically achievable biomass supply in Europe. Nowadays' energy use is slightly over six exajoules (EJ) ([2]) in the EU, that is already 150% more than what was in 2000. Based on the proposal of e.g. think thanks and industries associations, bioenergy use could peak more than 20 EJ by 2050. Even if the EU Commission roadmaps and integrated scenarios are more conservative (see e.g. European Commission 2018a), they still expect 11 to 14 EJ of energy coming from bioenergy by 2050. These analyses generally neglect the biomaterial sector, which already consumes the equivalent of 4 EJ of biomass. This work does not indicate the share of this biomass used specifically in the construction sector, but solely that roughly two thirds of it consists of solid wood products, which is in line with other EU level estimates (Gurria et al., 2017). Sadly, this type of statistics is not available, but a substantial share of solid wood products is used in construction, and there are claims that about 70% of wood in Europe is used in construction and furnishings ([3]). Taking these aspects into consideration it can be guessed that probably between one third and half of the total biomass used for biomaterials and bioenergy together are absorbed by the construction sector. The bioeconomy and the development of novel bio-based materials that it is stimulating, can increase the demand for biomass of up to 5 EJ. Considering that an increased import of sustainable biomass is unlikely due to the already high competition for land and that the domestic supply from forest and waste streams can only partially contribute (see e.g. previous sector), the extra demand should come from dedicated energy crops which would require a profound modification of the EU agricultural sector and its landscapes. For example, the 5 EJ extra of bioenergy might require about 30 million hectares of land, which roughly the same size of Italy and represent 20% of EU cropland nowadays. All this means that the high reliance on biomass of current climate scenarios would require an increase from 70% to 150% of its use in both the material and energy sectors. This might bring to a demand of biomass that is from 40 % to 100 % higher than what is realistically available.

([2]) In the study 1 EJ is equivalent to 5 to7 million hectares of land used for energy crops or 55 million tonnes of wood.
([3]) https://ec.europa.eu/growth/sectors/raw-materials/related-industries/forest-based-industries/woodworking_en

The authors explicitly stated that, with some due exceptions (e.g. biofuels for aviation), biomaterials have to be prioritized over bioenergy due to their effectiveness. Nevertheless, the competition between the two sectors is high, and will probably remain so in the future, contributing to limit the potentiality of bio-based materials to play a leading role in the context of renovations. It is also evident that the increase in circular (also called cascading) practices and the more general valorisation of bio-waste streams potentially represents an important source of additional biomass supply since it can significantly decreases resource consumption (see e.g. Risse et al., 2017). The production of bioenergy mostly or even solely of second and third generation would, for example, help achieving the climate goals and, simultaneously, reduce the pressure on lands and increase virgin biomass availability for biomaterials.

The situation becomes even more complex when the European situation is seen from a global perspective and the potential indirect impact of the bioeconomy in other regions of the world is looked at. Europe is already now the sole region in the world acting as a net importer of the four major natural resources: materials, water, carbon and land (Tukker et al., 2016), and has a per capita cropland footprint of 40% higher than the global average (Tramberend et al., 2019). Bruckner et al. (2019) further assessed the European global cropland footprint of the non-food bioeconomy. The authors showed that Europe is the major consuming region of cropland-based non-food products worldwide and is highly dependent on imports being roughly two thirds of the cropland required to satisfy its non-food bioeconomy related demand. It is interesting to note that, on the contrary, three quarter of the cropland footprint of the European food consumption 2010 is coming from domestic land resources. These results show how high is the risk of land use displacement and leakage effects linked to an increased demand of biomass in Europe. All these aspects, although extremely difficult to be accounted for, should be taken into account to avoid unwanted negative side-effects.

2.3 Environmental and health impacts and benefits associated to bio-based products for renovation

In this section an overview on the environmental benefits and impacts of bio-based materials used in the context of renovation is given. The section aims at answering the following questions:

- What is the most effective bio-sourced renovation product to mitigate climate change?
- What is the broader impact of bio-based material other than that related to climate change?

2.3.1 Climate mitigation and bio-based material for renovation

Literature on GHG footprint of bio-based materials shows that, on average, they have a lower GHG footprint compared to their fossil counterpart. An nice overview is for example presented by Weiss et al. (2012), which reviewed the results of 44 LCA studies covering some 60 individual biobased materials and about 350 different scenarios. The same benefits are reported also more specifically the construction sector (see e.g. review in Trinomics et al., 2021) and for, more specifically, insulation materials (Cusenza et al., 2021).

Anyway, with regard to the first point, it is not easy to provide an answer because finding the best bio-based feedstock needs to take into consideration many aspects such as the application into which the material is turned to, its energy saving performance and its embedded carbon (i.e. GHG emission due to its production), the amount of biogenic carbon stored in the bio-based product, its lifetime, if the positive effect of the temporary carbon storage in biomaterials is accounted for and how. Studies with different approaches can lead to different results that thus need to be carefully interpreted.

Pittau et al. (2018), for example, investigated the climate change impact of five functionally equivalent (i.e. same area, U-value and lifetime) alternative exterior walls, three of which bio-based (hemp, straw and wood-based) and two fossil-based (brick and concrete).

The analysis looked at the life cycle emissions of the products and took into account also the temporary carbon storage effect of bio-based ones, which is typically not included in studies following the methodology outlined in LCA standards like the EN 15804. They found that, among the different materials studied, the fast-growing bio-based materials (i.e. hemp and straw) are the best to be used if one wants to minimize the impact in terms of CO_2 emissions. All the three bio-based materials exhibit a GWI lower than that of both fossil-based ones. However, while the cumulative GWI is still positive for timber, no matter the disposal scenario, for both straw and hemp the cumulative GWI is always negative over the time horizon considered (200 years).

Pittau et al. (2019) investigated also the European scale mitigation potential of storing carbon in bio-based materials used for the energy renovation (i.e. insulation) of existing facades. Three construction solutions based on fast-growing biogenic material, one wood-based and a synthetic (EPS) insulation solution were compared. They found that: (i) using straw as insulation material to renovate existing facades, by 2050 up to 3% of total anthropogenic emissions of 2015 could be offset; (ii) the hemp-based solution needs 28-40 years to yield net negative cumulative GWI; (iii) wood can store a large amount of carbon, but due to long rotations of forest stands, not all emissions can be compensated by 2050.

However, it has to be stressed here that two different approaches to account for the role of biogenic carbon sequestration exist. One assumes that forest occurrences are accounted for before harvesting (growth approach henceforth), following what happens in the natural cycle of carbon where the biomass has to grow before it harvested. The other (regrowth approach henceforth) accounts for the biogenic carbon dynamics after harvesting and describes a burden thinking where the harvested biomass creates a carbon debt caused by a time gap before the forest is regrown.

Peñaloza et al. (2018), for example, showed how the approach chosen to account for the temporary carbon storage effect of bio-based products can have a sensible impact on the results, especially for shorter time horizons. In comparing cross laminated timber with concrete, the former resulted 40% and 50% less impacting than the latter respectively over a 20- and 100-year time horizon when assessed with the growth approach, and 190% and 135% with the regrowth one. Peñaloza et al. (2018) also argued that, while the choice is subjective; the growth approach better represents the reality as the trees grow before they are harvested. On the contrary the regrowth one is mostly theoretical and generates the so-called temporal carbon debt that is attributed to the forest product. They further said that the former is more suitable for attributional LCA approach with the objective of knowing more about a product system, rather than to support decision-making, which is more suitable for the latter, when the aim of the study is to assess the impact of specific actions (i.e. consequential LCA). It can further be argued, following the previous logic, that the regrowth approach can logically make sense in the case of afforestation practices involving land use change (non-forested land turned to a forest), while the growth approach can better reflect situations without land use change i.e. forest area under (sustainable) forest management, which is also the most widespread case in the case of Europe.

When the temporary carbon storage effect is considered, also the rotation length chosen has an influence on the results. As shown in Trinomics et al. (2021), if the same amount of carbon is sequestered in 1 vs 100 years, the absolute results change of 44%, with a sign that depends on if the growth or regrowth approach is followed. If the first approach is used, slow-growing feedstocks are favoured (i.e. 100 years rotation length has an impact of -44% compared to that of 1 year for same amount of carbon), when the second is used, fast-growing ones are favoured (i.e. 100 years rotation length has an impact of +44% compared to that of 1 year for same amount of carbon).

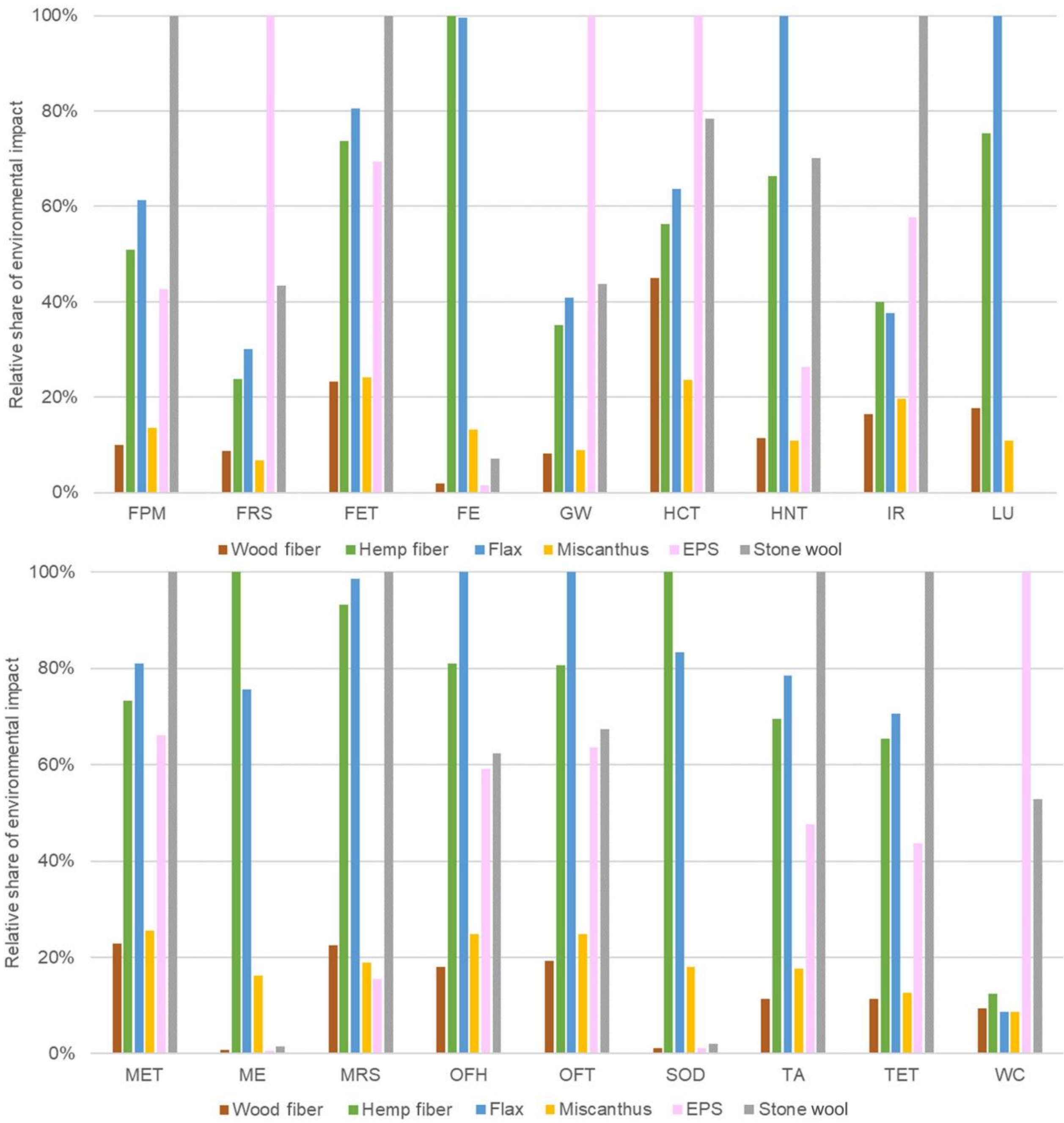
All this to say that great care has to be placed on drawing the conclusion that fast-growing plant-based bio-based materials contribute more to mitigate climate change than slow-growing ones based on the results of these studies. Different methodologies exist and they bring to opposite results. There is no scientific consensus on which one is the best since each approach can be more or less suitable depending on the overall goal and scope of the assessment.

2.3.2 Other environmental and health impacts

Concerning the broader impacts/benefits of bio-based material in the context of renovation, Schulte et al. (2021) calculated the life cycle impact of different insulation materials for 18 different impact indicators (Figure 2-10). In 11 impact categories the bio-based insulation materials performed better than EPS and stone wool-based, with the latter being the most impacting in seven categories. Overall, wood and miscanthus-based insulation materials were found to be the least environmental impacting, not showing the highest burden in any of the considered impact categories.

For those feedstocks sourced from agriculture (hemp and flax), the cultivation step is a critical hotspot, being the main contributor to the overall life cycle impact in 16 out of the 18 assessed impact categories. The main driver of these burdens is represented by the application of fertilizer, and the subsequent release of emissions in the form of nitrate, N_2O, phosphate and ammonia, of pesticides and, to a lower extent, of agricultural operations.

Figure 2-10 Comparison of the relative environmental burdens of the bio-based and fossil-based insulations. The material with the highest impact in a category represents 100%.



Note: Categories are fine particulate matter formation (FPM), fossil resource scarcity (FRS), freshwater ecotoxicity (FET), freshwater eutrophication (FE), global warming (GW), human carcinogenic toxicity (HCT), human noncarcinogenic toxicity (HNT), ionizing radiation (IR), land use (LU), marine ecotoxicity (MET), marine eutrophication (ME), mineral resource scarcity (MRS), ozone formation, human health (OFH), ozone formation, terrestrial ecosystems (OFT), stratospheric ozone depletion (SOD), terrestrial acidification (TA), terrestrial ecotoxicity (TET) and water consumption (WC).

Source: Schulte et al. (2021).

2.3.3 Health impacts (indoor air quality)

With regards to VOCs (volatile organic compounds) emissions, bio-based and synthetic or mineral insulation materials show similar performances, with the first showing in the first week noticeable emissions that drastically drops after one month (Maskell et al., 2017; Won et al., 2014). Important to note that some wood-based materials can contribute sensibly to the emissions of VOCs such as aldehydes and terpenes in indoor spaces. This is mainly caused by the formaldehyde-based binding resins used in some engineered wood products like plywood and MDF (Harb et al., 2018), but also, in part, to the organic nature of wood. However, the steady state VOCs emissions from wood-based products are comparable to other products: mostly below thresholds and emitted soon after renovation or construction. Interestingly, some of the VOCs naturally emitted from wood products like d-limonene and α-pinene contribute to lower blood pressure and to physiological relaxation and antimicrobial, anti-inflammatory antipruritic, analgesic and stress reducing properties that are attributed to monoterpenes (Son et al., 2013). These type of human health benefits can undoubtedly contribute to improve indoor air quality.

Bio-based materials prevent the condensation of water vapour by allowing for the diffusion of moisture. For this reason, they are often used in breathable assemblies. This water-permeability reduces the chance of growth of mould, that is known to be associated to higher risk of allergic reactions and asthma. Palumbo et al. (2018) showed that bio-based insulation materials can absorb up to seven times more moisture than EPS, provided that the assembly breathability, that depends on its composition (plasters, paints, coatings, etc.), is ensured. Although insulation materials are generally not exposed to indoor air directly, the inherent natural properties of some bio-based materials can be beneficial to improve air quality. The amine groups presented in wool insulation, which are highly reactive with VOCs, can contribute to purify indoor air (Won et al., 2014), and hemp is well known to have hypoallergenic properties. The moisture buffering capacity of bio-based materials, and all the other positive properties, are proportional to the surface area covered by these materials. To really influence indoor air quality, the bio-based materials should be exposed on the interior. Compared to insulation materials, bio-based plasters have a much higher potential to positively influence indoor air quality since, by occupying a bigger indoor surface area on walls, they have a more direct contact with indoor air. Similarly to the insulation materials, they would also contribute to buffer the indoor moisture level due to their breathability.

To sum up, of the four key factors to achieve good indoor air quality, namely: ventilating well, controlling humidity and moisture, reducing the indoor emissions and protecting against outdoor sources (Nazaroff, 2013). Bio-based materials can, to a certain degree, positively influence the last three.

3 Plans and strategy to promote and incentivise bio-based materials in Europe

Key messages:

- At European level, the role of bio-based products in contributing to reduce the whole life-cycle carbon emissions in buildings is acknowledged although there is no direct reference to the use of them for energy renovation.
- Member states are slowly starting to acknowledge the use of biomaterials as climate mitigators with some (e.g. France) also promoting their use in the construction sector, even if not specifically in the context of energy renovations.
- Wood is still being prioritised as bio-based construction material and limited references are made to other types of biomass.

The overall objective of this section is to provide an overview of actions, plans and strategies to promote bio-based material for the renovation wave both at the level of the European Union and of its member states. This has been achieved by screening relevant EU documents, plans, strategies etc. dealing with climate change, renovation and bio-based materials as well as all EU National Energy and Climate Plans (NECPs) and National Long Term Strategies (LTSs). Based on the findings of this literature research two case studies have been selected in which the member states have been described in more detail.

3.1 European policies and action plans

The most important European action plan related to climate change and sustainability in general is “The European Green Deal” (European Commission, 2019). It represents “a new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use” (European Commission, 2019).

The renovation wave initiative falls under the green deal, which singled out that the renovation of public and private buildings is the key initiative to deliver its objectives. The plan explicitly acknowledges the role of bio-based products in contributing to reduce the whole life-cycle carbon emissions in buildings. As already stressed, the renovation wave focuses on the reduction of the operational energy consumption. All references to the material use include reducing, reusing, recycling and their decarbonisation. Thus, a circular economy model is proposed, which is not solely applicable to bio-based materials but to all types of materials used. However, bio-based materials might have an advantage when a circular economy is the status-quo.

In a questionnaire as part of a stakeholder consultation regarding the “European Green Deal”, bio-based construction materials were mentioned in the section about the most promising approaches and best practices for targeting the residential sector (European Commission, 2020b). Respondents preached to define accurate accounting rules to measure and confirm the substitution effect of using bio-based products instead of carbon-intensive materials on construction sites. In this direction goes also the recent study promoted by the Directorate-General Climate Action of the European Commission that explores the challenges and opportunities of incentivising a higher uptake of wood products in construction together with a possible policy instrument to support it by remunerating the actors who employ wood materials in construction projects.

Also the “new Circular Economy Action Plan for a Cleaner and more Competitive Europe” recognizes the environmental impact of the construction sector (European Commission, 2020a). It names both construction and buildings as key product value chains and proposes a cooperation with the construction industry to reach circularity.

In March 2020 the European Commission committed itself to come forward with a sustainable built environment strategy, and the launching of a new and comprehensive “Strategy for a Sustainable Built Environment”. This strategy is supposed to ensure coherence across all relevant policy areas such as climate, energy and resource efficiency, management of construction and demolition waste, accessibility, digitalisation and skills. As preliminary indicated, the focus should be strongly on the creation of a circular economy through recycling and material recovery. Notably, carbon storage and support for the sustainable and circular bio-based sector are mentioned in the communication ([4]). Despite the ambitious intentions set out from the Commission, at the time of writing of this report (December 2021) the strategy has not been published yet, and there are concerns about its future delivery ([5]).

The main action of the European Commission to promote the use of bio-based materials is represented by the updated bioeconomy strategy (European Commission, 2018b), which pursues five main objectives:

- ensure food and nutrition security,
- manage natural resources sustainably,
- reduce dependence on non-renewable, unsustainable resources,
- limit and adapt to climate change,
- strengthen European competitiveness and create jobs.

This strategy is implemented by means of a dedicated action plan (European Commission, 2018c) consisting of 14 actions clustered into three main priorities that should promote bio-based material use through supportive measures such as funding, innovation and regulatory frameworks. This strategy is the most comprehensive with regard to the promotion of bio-based materials use and while it mentions the construction sector, it does not specifically mention renovation.

The newly launched “fit for 55%” package ([6]), aims to put Europe on track for a 55% reduction in emissions by 2030 by supporting its climate policy framework. The package comprises of eight revisions to existing laws and five new proposals covering areas of climate, land use, energy, transport and taxation. Although some relevant for bio-based materials and the renovation wave (e.g. new EU forest strategy and the revision of the Energy Performance of Buildings Directive), no direct reference to the use of bio-based materials for the renovation wave is made.

In general, it is clear that there is interest in promoting the bio-based sector in Europe. However, the use of these materials in the context of energy renovation is only mentioned, but not specifically tackled.

3.2 National Energy and Climate Plans & Long Term Strategy

All EU National Energy and Climate Plans (NECPs) have been screened searching for the keywords, “bio-based”, “wood”, “timber”, “straw”, “cork” “hemp” and “flax” so to find the potentially relevant section to further read. The same approach has been followed for the National Long Term Renovation Strategies (LTRSs), although it has been done only for the nine member states that provided their report in English.

As expected, very little was found on bio-based construction materials. Only nine out of 27 member states mention the word bio-based, but not necessarily linked to the building industry. Austria, Belgium, Bulgaria, Finland, France, Germany, Ireland, Netherlands and Sweden all mention the future development of bio-based fuel, products and a bio-based circular economy. Only France mentions bio-based materials as

([4]) https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-strategy-for-a-sustainable-built-environment
([5]) https://rreuse.org/stakeholders-call-for-delivery-of-eu-strategy-for-a-sustainable-built-environment/
([6]) https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/package-fit-for-55

environmentally high performing substitutes in the construction sector. They also plan to support innovation in the eco-material sectors, which includes the bio-based one, as well the use of wood residues to facilitate their National Energy Renovation Plan.

The search terms “wood” and “timber” did yield a substantial amount of hits. All 27 member states provide plans regarding the management of their wood and timber supply. Austria, Denmark, France, Germany, Latvia, Lithuania, Luxembourg, Portugal, Slovenia and Sweden (10 out of 27) include the (increased) use of wood in construction in the future. Others mention the increased production of wood-based products, because of its carbon sequestration potential and the fact that wood can be recycled following the cascading principle (e.g. construction beam, recycled to particle board, recycled to briquettes to be burnt). Straw is mentioned almost exclusively as a bio-based fuel source, and only Portugal recognizes the environmental benefits of cork in its NECP and LTS. This should not come as a surprise since Portugal is the biggest producer of cork in the world. For that reason, they do not have to cope with the above-mentioned supply problem of using cork as a construction material.

From this analysis, it is evident that in the EU member states, wood is being prioritized as bio-based construction material to (partly) substitute conventional materials like concrete and steel in the future. Other materials like straw, cork, hemp and flax that, as shown before, have potential, are not mentioned in the NECPs and LTRSs.

3.3 National case studies

3.3.1 France

France is selected since, although not explicitly for energy renovation (as all other member states), it is the only country explicitly proposing and stimulating the use bio-based materials in construction, inclusive but not restricted to the wood-based ones. Its NECP highlights the importance of substituting fossil-based materials with bio-based ones, promoting the use of harvested wood products, and temporary stocking carbon in bio-based materials. It has put in place other relevant initiatives, such as the new RE2020 (see below) to stimulate bio-based material use in construction. France has a relatively low market share of bio-based construction products, but relatively high potential in terms of domestic wood supply.

France not only mentions bio-based construction in its NECP, but also in other reports such as their “National Low Carbon Strategy” (Ministère de la Transition Écologique et Solidaire, 2020). The country highlights the use of bio-based materials in construction and renovation work to reduce the overall greenhouse gas emissions related to the construction sector. France also has its own Bioeconomy Strategy, that has been operationalized by the adoption in 2018 of its associated 2018 - 2020 Action Plan (Ministère de l’agriculture et de l’alimentation, 2018). With this strategy, the country provides a framework for the sustainable development of the bioeconomy as a whole, with the final goal of transitioning from a fossil-based to a bio-based economy.

RE2020 (Ministry of Ecological Transition, 2020), the new regulation on the climate and energy performance of new buildings, is expected to come into force in 2022 and is maybe the most important national policy measure that should positively influence the uptake of bio-based construction materials. This regulation has three main goals of reducing the GHG impact of buildings, stimulate the further improvement in their energy performance and ensure their freshness in summer periods. The long term goal is to progressively transform the industry as a whole, the involved construction techniques and the energy consumption of buildings.

The regulation takes into account the building's emissions over its entire life cycle to reduce the climate change impact. It will thus stimulate the use of materials with low embodied carbon and strongly emphasize the positive role bio-based material use in construction can have with this respect. This is done indirectly thanks to the calculation approach that is required to assess the life cycle impact of the building. The regulation, in fact, foresees the use of the dynamic LCA method, which weighs more the carbon that is emitted today than that is emitted in the future. This method thus acknowledges and gives value to the carbon sink effect of bio-based materials, thus indirectly stimulating its use in the construction sector. Despite RE2020 does not specifically mention the use of bio-based materials for energy renovation, it wants to improve the energy efficiency of both new and existing (i.e. to renovate) buildings and it promotes bio-based materials. This can thus be considered the most important policy measure, probably in the whole Europe to promote the use of bio-based materials for energy renovation.

As expected, wood is still the dominant bio-based construction material. In France forests covered roughly a third of France's territory (Forest Europe, 2020), with an area that increases of 85 000 thousands hectares yearly on average. According to the industry association, France Bois Forêt, the country has enough timber resources to increase the use of wood as construction material (France Bois Forêt, 2019). Although wood is not traditionally used as a main construction material in France, the RE2020 initiative is expected to change this in the future.

Table 3-1 lists the relevant policy measures in place to promote the use of bio-based construction materials in France. Most measures relate to wood-based construction. The scope of this study is more broad and encompasses other materials as well (e.g. straw, hemp, cork). For that reason, the wood-specific measures are combined at the bottom of the table.

Table 3-1 List of policy measures incentivizing the use of bio-based materials in construction in France.

Measure	Type	Geographic level	Timing	Description
"Bâtiment Biosourcé" (Bio-based Building) label	Label/certification	National	Since 2012	Buildings in France can receive this label, certifying that they have used bio-based material in their construction (Fillon, 2012). Several levels of certification are available, based on the amount of kilograms material per square meter used.
RE2020	Legislation	National	In the next few years	This is a national building regulation. It is supposed to provide requirements in terms of environmental performance for construction works. It considers both the energy performance and the environmental footprint of the buildings (Ministry of Ecological Transition, 2020).
France Relance	High-level strategy	National	2020-2022	This COVID-19 recovery plan includes three development areas: ecology, competitiveness and cohesion (Ministère de l'Économie des Finances et de la Relance, 2020). The plan encompasses bio-based construction in two ways. First, by promoting the use of bio-based materials in renovation. Second, it indirectly strengthens the wood-based construction material sector by aiming for reforestation and a general support for the timber industry.
Bas-carbone (Low carbon) label	Label/certification	National	Since 2019	This initiative provides funding for voluntary efforts to reduce climate impacts (Ministère de la Transition Écologique, 2021b). The label works as a signal to other funders and investors.
E+ C- label	Label/certification	National	Since 2016	The E + C- label was created to support the development and improvement of low-carbon buildings in France (Ministère de la Transition Écologique, 2021a). It was an experiment to test the ambition to build environmentally friendly with existing capacities and skills in the construction sector.
4e Programme d'investissements d'avenir (PIA4)	High-level strategy	National	2021-2026	20 billion euros investment over 5 years dedicated to innovation and support for the recovery plan. The building sector represents one of the three axes covered in the strategy.

Wood-specific measures:	Name
	• Plan "Immeubles de Grande Hauteur en bois" (High-rise Timber Building Plan) • Charte Bois – Construction – Environnement • "Plans bois" (Wood Plans) I, II and III • Campaign "Le bois – c'est essential" (Wood is essential) • Contrat stratégique de Filière Bois (Strategic Contract for the Wood-based value chain) • Decree n. 2010-273 • Pacte "Bois Biosourcés" (Biosourced wood pact) • Fonds Bois & Plan de relance de la compétivité des scieries (Timber Fund & Sawmill competitiveness revival plan) • "France Bois" (France Wood) • Filière forêt bois – plan recherche innovation (Forest-wood sector - innovation research plan)

France takes on great responsibility regarding the implementation of bio-based construction materials to reduce environmental impacts of the sector. They translate the general European Commission action plans well into regional measures. The country even takes it one step further and applies these measures to future legislation. The RE2020 national building regulation should deeply stimulate the use of bio-based building materials (not just wood) in the construction sector both in new and renovated buildings. France has also other measures into action to promote these bio-based materials, although they often focus only on wood.

Additionally, the country highlights the use of bio-based materials in the renovation context specifically in their NECP, but they do not specify critical details like which materials to use and where to apply them. It is expected that these details will follow after RE2020 is launched. In general, it can be said that France puts its goal of reaching an established bioeconomy into action quite well, with sufficient consideration for the construction sector.

3.3.2 Finland

Finland’s national plans and strategies do not mention the use of bio-based construction materials specifically. However, this does not mean the country does not use such materials in practice. In fact, Finland traditionally uses massive amounts of wood as a construction material. Today, wood accounts for about 40% of all construction materials used in Finland, which is some eight times more compared to the earlier calculated European average (Ministry of Agriculture and Forestry of Finland, n.d.). Roughly 71% of the land area of Finland is covered by forests (Eurostat, 2018), which makes wood an extremely important resource. Even if bio-based materials encompass a broader array of feedstocks, the massive availability of wood and the potential offered to use it in construction makes Finland an extremely important country to study further. For that reason, together with the fact that Finland is one of the European countries with the best average energy performance of buildings (European Commission, n.d.), Finland is selected as second case study.

Not surprisingly, the policy context of Finland focuses on stimulating and promoting the use of wood, with the country supporting its forest industry through public policies in the past decades. To do so Finland introduced public wood promotion campaigns and technology platforms, and they removed institutional obstacles (e.g. revision of fire safety regulations) (Ministry of Agriculture and Forestry of Finland, n.d.). This resulted in a doubling of sawnwood consumption per capita between 1995 and 2000 (Hurmekoski, 2016).

The main objectives to be achieved by the wood-based industries and activities until 2025 are described by Finland’s “National Forest Strategy” (Ministry of Agriculture and Forestry of Finland, 2015), which also emphasizes the importance on further promoting the use of wood in the construction sector in general. This strategy was adopted in 2015 and updated in 2019. In turn, this strategy was based on the “Government Report on Forest Policy”, which defines sustainable forest management as a source of growing welfare (Ministry of Agriculture and Forestry of Finland, 2014).

Similarly to France, Finland has its own “Finnish Bioeconomy Strategy” (LukeFinland, 2017). It is an overarching strategy to generate economic growth and support a sustainable bioeconomy. More specifically, the ministry proposes to stimulate the bio-based economy with an output of 100 billion euro by 2025 and 100 000 new jobs added. They plan to do this by increasing the bioeconomy business and from the development of high added value products and services, while securing the operating conditions for the nature’s ecosystems.

The Finish “National Energy and Climate Strategy for 2030” mentions specifically the promotion of the use of wood as construction material (Ministry of Economic Affairs and Emoloyment of Finland, 2017). They highlight the potential to store carbon long-term by using such materials. For this reason, wood-based construction materials are promoted to help reducing the carbon footprint of the entire construction sector.

Table 3-2 depicts all relevant measures to promote the use of wood-based construction materials in Finland. No specific bio-based measures are found.

Table 3-2 List of policy measures incentivising the use of wood-based materials in construction in Finland.

Measure	Type	Geographic level	Timing	Description
Strategic Programme for the Finnish forest sector	High-level strategy	National	2011 - 2015	The programme promotes the competitiveness and renewal of the Finnish forestry sector (Ministry of Employment and the Economy, 2015).
National wood construction / building programme	High-level strategy	National	2011 – 2015 and 2016 - 2022	The programme aims at increasing the use of wood in construction. It also covers the growth of internationally competitive wood construction know-how (Ministry of the Environment, 2019).
Aid scheme for growth and development from wood	Financial aid	National	2021	The scheme provides support and funding for various R&D projects (Ministry of the Environment, n.d.).
The Housing Finance and Development Centre of Finland (ARA)	Financial aid	National	Since 2013	The agency provides loans to public and private building projects. If they include the use of wood, the cost can be partly compensated by the government (ARA, n.d.).
Normative carbon limits for different building types	Legislation	National	In the next few years	Finland is developing a building code for low-carbon construction, including normative carbon limits for different building types. Wood-based buildings have an advantage because of their long-term carbon storage.

Finland tries to utilise the full potential of its abundance of natural, especially forest-related, resources. Even though no direct support measures for other bio-based materials in the context of energy renovation and more generally in construction are found, Finland does support the development of a bio-based economy. Given that the country has still some margins to increase its wood supply, it is expected that the use of wood as a construction material can still be increased, maintaining a level of demand that is sustainable. In addition, the country is planning to increase the amount of timber buildings by launching a building code to promote low-carbon construction. Due to the carbon sink effect of wood-based materials, they will have a competitive advantage over other materials when such legislation will be approved.

4 Key barriers

Key messages:

- Lack of economic competitiveness of bio-based products and concerns regarding fire security, sound insulation and durability are still common from users, although they like the perceived environmental friendliness of biomaterials.
- Difficult access to capital to develop and market new bio-based products due to high perceived risk.
- Biomass is a finite resource and, as such, cannot completely replace all other types of materials.
- Although things are changing in some countries, national norms are not yet bio-based product friendly e.g. due to conservativeness about fire safety and the lack of recognition of their environmental advantages.
- At continental level, the support of bioenergy creates a market distortion against the material sector and the lack of harmonisation in the national standards/certifications is a challenge.
- General lack of skilled workers and/or formal training programs about bio-based materials along the value chain, e.g. construction engineers, architects, building contractors etc.
- Many bio-based products are in initial development and the limited size of the bio-based market/industries makes it difficult to benefit from e.g. economies of scale and technological learning effects, which would augment the competitiveness of the bio-based products on the market.

Multiple potential barriers identified in the previous sections and in the literature are summarised in the following sub-sections.

4.1.1 Market conditions

- Bio-based materials are often not cost-competitive with their fossil-based competitors.
- Although bio-based materials are often seen positively from users due e.g. to their perceived environmental friendliness, still prejudices against their use and their safety and technical performance exists, although these concerns are often not justified. For example, concerns regarding fire security, sound insulation and durability are still common (Ranacher et al., 2020).
- Also due to its smaller size, the bio-based sectors spend much less on marketing than other competing markets does (Gustavsson et al., 2006).
- The cost of insuring bio-based building is often higher since this type of buildings are put in higher insurance premium classes from insurance companies (Mahapatra et al., 2012). This is due to the higher perceived fire risk and the costs of damages due to water and moisture that are higher for such a type of buildings (GLOBE Advisors, 2016).
- Investment barriers and the perception of high investment risk, which lead to difficult access of capital to develop and market new bio-based products.
- Although feedstock supply can be increased, biomass is a finite resource and, as such, cannot completely replace all other types of material.

4.1.2 Legal and regulatory

- Conservative regulations about fire safety in some places hinder the more widespread use of bio-based materials (Gustavsson et al., 2006).
- Norms often do not recognize the advantageous properties of bio-based materials, e.g. the environmental ones and those connected to moisture regulation for insulation materials (nova-Institut, 2015).
- The support for the energetic use of biomass, often in terms of subsidies for bioenergy, create a market distortion that makes feedstocks too expensive and/or difficult to source for the material sector (nova-Institut, 2015).
- Many different certifications exist on the market, with some that overlap and others that are issued only in specific regions. The often-missing harmonisation of standards and certifications can be a challenge for bio-based producers. For example, for the wood fibre insulation materials, the harmonized European Standard EN 13171 has been developed, but something similar does not exist for e.g. vegetable (flax, hemp, etc.) and animal (sheep wool) fibres (Bos et al., 2018).

4.1.3 Human capacity

- Bio-based materials still represent something unfamiliar to many construction engineers, architects, building contractors and other building consultants. This is often because their education and/or traditional practices are oriented towards the use of other, fossil-based, materials (Gustavsson et al., 2006).
- General lack of skilled workers and/or formal training programs along the value chain.

4.1.4 Technical

- Many bio-based products are in the initial development stage with a technological and market readiness that is still too low.
- Limited size of the bio-based market/industries makes it difficult to benefit from economies of scale and technological learning effects, which would in turn contribute to make products more cost-efficient.

5 Conclusions

The major conclusions that can be drawn from this report are the following:

- Bio-based products represent an important but still marginal market in the construction sector.
- Wood dominates the market of bio-based material in construction although, especially in the family of insulation materials, other feedstocks (e.g. hemp and flax) showing very good potentiality are being more and more used.
- Generally speaking, the environmental performances of bio-based materials tend to be better than their traditional, fossil-based, competitors, although there is a relatively important variability that depends on the product under consideration and the feedstock used.
- Cost-competitiveness of bio-based materials for renovation is still low compared to traditional products. This represents one of the main hurdles to its more widespread adoption. The fact that the bio-based sector is and will most probably continue to grow, can positively influence this aspect.
- Even if the supply of bio-based feedstocks can be increased and its use made more efficient with circular practices, the biomass resource is a scarce and finite resource. Considering also the strong competition with the bioenergy sector for biomass, bio-based products cannot, also in the best case, be consider to play a dominant role in the context of the renovation wave but rather a supporting one.
- The limited availability of biomass requires that those uses and products contributing the most to climate change mitigation or not having cost-effective alternatives are prioritised and that the potential indirect impact of increased biomass demand in other regions of the world is carefully considered to avoid burden-shifting.

List of abbreviations

Abbreviation	Name	Reference
CLT	Cross laminated timber	/
EEA	European Environment Agency	www.eea.europa.eu
EPS	Expanded polystyrene	/
ETC CM	European Topic Centre on Climate change mitigation	https://www.eionet.europa.eu/etcs/etc-cm
GHG	Greenhouse gas(ses)	/
GWI	Global warming impact	/
HDF	High density fibreboard	/
ICB	Insulation cork board	/
LTRS	Long term renovation strategy	/
LTS	Long term strategy	/
LVL	Laminated veneer lumber	/
MDF	Medium density fibreboard	/
NAI	Net annual increment	/
NECP	National Energy and Climate Plan	/
OSB	Oriented strand board	/
PSL	Parallel strand lumber	/
RMC	Raw material consumption	/
SWB	Strand woven bamboo	/
VITO	Vlaamse Instelling voor Technologisch Onderzoek	https://vito.be/en
VOC	Volatile organic compound	/
WPC	Wood plastic composite	/

References

Abu-Jdayil, B., Mourad, A. H., Hittini, W., Hassan, M., & Hameedi, S. (2019). Traditional, state-of-the-art and renewable thermal building insulation materials: An overview. *Construction and Building Materials*, *214*, 709–735. https://doi.org/10.1016/j.conbuildmat.2019.04.102

Agliata, R., Gianoglio, S., & Mollo, L. (n.d.). *Hemp-lime composite for buildings insulation : material properties and regulatory framework*.

Ahmad, M., & Kamke, F. A. (2011). Properties of parallel strand lumber from Calcutta bamboo (Dendrocalamus strictus). *Wood Science and Technology*, *45*(1), 63–72. https://doi.org/10.1007/s00226-010-0308-8

Antunes, A., Faria, P., Silva, V., & Brás, A. (2019). Rice husk-earth based composites : A novel bio-based panel for buildings refurbishment. *Construction and Building Materials*, *221*, 99–108. https://doi.org/10.1016/j.conbuildmat.2019.06.074

ARA. (n.d.). *ARA implements Finland's housing policy*. 2013.

Asdrubali, F., Bianchi, F., Cotana, F., Alessandro, F. D., Pertosa, M., & Pisello, A. L. (2016). Experimental thermo-acoustic characterization of innovative common reed bio-based panels for building envelope. *Building and Environment*, *102*, 217–229. https://doi.org/10.1016/j.buildenv.2016.03.022

Barbieri, V., Lassinantti, M., & Siligardi, C. (2020). Wheat husk : A renewable resource for bio-based building materials. *Construction and Building Materials*, *251*, 118909. https://doi.org/10.1016/j.conbuildmat.2020.118909

Barnat-hunek, D., Smarzewski, P., & Brzyski, P. (2017). Properties of Hemp – Flax Composites for Use in the Building Industry Properties of Hemp – Flax Composites for Use in the Building. *Journal of Natural Fibers*, *14*(3), 410–425. https://doi.org/10.1080/15440478.2016.1212764

Barrio, A., Francisco, F. B., Leoncini, A., Wietschel, L., & Thorenz, A. (2021). Life Cycle Sustainability Assessment of a Novel Bio-Based Multilayer Panel for Construction Applications. *Resources 2021, Vol. 10, Page 98*, *10*(10), 98. https://doi.org/10.3390/RESOURCES10100098

Benfratello, S., Capitano, C., Peri, G., Rizzo, G., Scaccianoce, G., & Sorrentino, G. (2013). Thermal and structural properties of a hemp – lime biocomposite. *Construction and Building Materials*, *48*, 745–754. https://doi.org/10.1016/j.conbuildmat.2013.07.096

Benmahiddine, F., Cherif, R., Bennai, F., Belarbi, R., & Tahakourt, A. (2020). Effect of flax shives content and size on the hygrothermal and mechanical properties of flax concrete. *Construction and Building Materials*, *262*, 120077. https://doi.org/10.1016/j.conbuildmat.2020.120077

Betts, D., Sadeghian, P., & Fam, A. (2021). Post-impact residual strength and resilience of sandwich panels with natural fiber composite faces. *Journal of Building Engineering*, *38*(November 2020), 102184. https://doi.org/10.1016/j.jobe.2021.102184

Beurskens, P. R. (2021). *The development of an evaluation method to support circular building design* [University of Twente]. https://doi.org/10.3990/1.9789036552042

Binici, H., Gemci, R., Kucukonder, A., & Solak, H. H. (2012). Investigating sound insulation, thermal conductivity and radioactivity of chipboards produced with cotton waste, fly ash and barite. *Construction and Building Materials*, *30*, 826–832. https://doi.org/10.1016/J.CONBUILDMAT.2011.12.064

Blondin, F., Blanchet, P., Triantafyllidis, Z., Bisby, L., & Dagenais, C. (2020). *Fire hazard of compressed straw as an insulation material for wooden structures*. *March*, 736–746. https://doi.org/10.1002/fam.2851

Bos, H., van den Oever, M., Dammer, L., Babayan, T., Ladu, L., Clavell, J., & Vrins, M. (2018). *STAR4BBI project. Deliverable 2.1: Market entry barriers*.

Brouard, Y., Belayachi, N., Hoxha, D., Ranganathan, N., & Méo, S. (2018). Mechanical and hygrothermal behavior of clay – Sunflower (Helianthus annuus) and rape straw (Brassica napus) plaster bio-composites for building insulation. *Construction and Building Materials*, *161*, 196–207. https://doi.org/10.1016/j.conbuildmat.2017.11.140

Bruckner, M., Häyhä, T., Giljum, S., Maus, V., Fischer, G., Tramberend, S., & Börner, J. (2019). Quantifying the global cropland footprint of the European Union's non-food bioeconomy. *Environmental Research Letters*, *14*(4), 045011. https://doi.org/10.1088/1748-9326/AB07F5

Brzyski, P., Barnat-hunek, D., Fic, S., Szeląg, M., Barnat-hunek, D., & Szel, M. (2017). Hydrophobization of Lime Composites with Lignocellulosic Raw Materials from Flax Hydrophobization of Lime Composites with Lignocellulosic Raw Materials from Flax. *Journal of Natural Fibers*, *14*(5), 609–620. https://doi.org/10.1080/15440478.2016.1250024

Carus Michael,Partanen Asta,Piotrowski Stephan, D. L. (2019). *Market analysis. BIOFOREVER project. D7.2*. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c7086741&appId=PPGMS

Cascone, S., Rapisarda, R., & Cascone, D. (2019). Physical properties of straw bales as a construction material: A review. *Sustainability (Switzerland)*, *11*(12). https://doi.org/10.3390/SU11123388

Cetiner, I., & Shea, A. D. (2018). Wood waste as an alternative thermal insulation for buildings. *Energy and Buildings*, *168*, 374–384. https://doi.org/10.1016/j.enbuild.2018.03.019

Charai, M., Sghiouri, H., Mezrhab, A., & Karkri, M. (2021). Thermal insulation potential of non-industrial hemp (Moroccan cannabis sativa L .) fi bers for green plaster-based building materials. *Journal of Cleaner Production*, *292*, 126064. https://doi.org/10.1016/j.jclepro.2021.126064

Codyre, L., Mak, K., & Fam, A. (2018). *Flexural and axial behaviour of sandwich panels with bio-based flax fibre-reinforced polymer skins and various foam core densities*. https://doi.org/10.1177/1099636216667658

Colinart, T., Glouannec, P., Pierre, T., Chauvelon, P., & Magueresse, A. (2013). *Experimental Study on the Hygrothermal Behavior of a Coated Sprayed Hemp Concrete Wall*. 79–99. https://doi.org/10.3390/buildings3010079

Collet, F., & Pretot, S. (2014). Thermal conductivity of hemp concretes: Variation with formulation, density and water content. *Construction and Building Materials*, *65*, 612–619. https://doi.org/10.1016/j.conbuildmat.2014.05.039

Corradini, G., Pierobon, F., & Zanetti, M. (2019). Product environmental footprint of a cross-laminated timber system: a case study in Italy. *International Journal of Life Cycle Assessment*, *24*(5), 975–988. https://doi.org/10.1007/s11367-018-1541-x

Costantine, G., Maalouf, C., Moussa, T., & Polidori, G. (n.d.). *Monitoring of a Hemp Lime External Building Insulation*. *6*(201 9), 6–11.

Crini, G., Lichtfouse, E., Chanet, G., & Morin-Crini, N. (2020). Applications of hemp in textiles, paper industry, insulation and building materials, horticulture, animal nutrition, food and beverages, nutraceuticals, cosmetics and hygiene, medicine, agrochemistry, energy production and environment: a review. *Environmental Chemistry Letters*, *18*(5), 1451–1476. https://doi.org/10.1007/s10311-020-01029-2

Cusenza, M. A., Gulotta, T. M., Mistretta, M., & Cellura, M. (2021). Life Cycle Energy and Environmental Assessment of the Thermal Insulation Improvement in Residential Buildings. *Energies 2021, Vol. 14, Page 3452*, *14*(12), 3452. https://doi.org/10.3390/EN14123452

Degrave-lemeurs, M., Glé, P., Hellouin, A., & Menibus, D. (2018). Acoustical properties of hemp concretes for buildings thermal insulation : Application to clay and lime binders. *Construction and Building Materials*, *160*, 462–474. https://doi.org/10.1016/j.conbuildmat.2017.11.064

Delioglamnis, I., Kouzi, E., Tsagaraki, E., Bougiouklis, M., & Tollias, I. (2018). Public Perception of Bio-Based Products—Societal Needs and Concerns (Updated Version). In *BIOWAYS Deliverable D2.3* (Vol. 2).

Dias, S., Tadeu, A., António, J., Almeida, J., Pedro, F., Martins, S., & Serra, C. (2018). Experimental study of expanded cork agglomerate blocks – Compressive creep behavior and dynamic performance. *Construction and Building Materials*, *181*, 551–564. https://doi.org/10.1016/j.conbuildmat.2018.06.021

Dong, Y., Qin, T., Zhou, S., Huang, L., Bo, R., Guo, H., & Yin, X. (2020). Comparative whole building life cycle assessment of energy saving and carbon reduction performance of reinforced concrete and timber stadiums-a case study in China. *Sustainability (Switzerland)*, *12*(4), 1–24. https://doi.org/10.3390/su12041566

Engineering Toolbox. (2020).

EU. (2020). *A Renovation Wave for Europe – Greening our buildings, creating jobs, improving lives*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662

European Commission. (n.d.). *EU Buildings Factsheets | Energy*. Retrieved November 5, 2021, from https://ec.europa.eu/energy/eu-buildings-factsheets_en

European Commission. (2018a). *A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*.

European Commission. (2018b). *A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment : updated bioeconomy strategy*.

European Commission. (2018c). *Bioeconomy: the European way to use our natural resources. Action plan 2018*. https://doi.org/10.2777/79401

European Commission. (2019). *The European Green Deal*. https://doi.org/10.1017/CBO9781107415324.004

European Commission. (2020a). *A new Circular Economy Action Plan For a cleaner and more competitive Europe*.

European Commission. (2020b). *Stakeholder Consultation on the Renovation Wave Initiative*.

Eurostat. (2018). *Over 40% of the EU covered with forests*.

Eurostat. (2020). *Material flow accounts in raw material equivalents by final uses of products - modelling estimates (env_ac_rme)*.

EUROSTAT. (2021). *Eurostat, Greenhouse gas emission statistics - carbon footprints*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Greenhouse_gas_emission_statistics_-_carbon_footprints#Carbon_dioxide_emissions_associated_with_EU_consumption

Fillon, F. (2012). *Décret n° 2012-518 du 19 avril 2012 relatif au label « bâtiment biosourcé » Dernière mise à jour des données de ce texte : 22 avril 2012*.

Foams, B., Augaitis, N., Vaitkus, S., & Członka, S. (2020). *Research of Wood Waste as a Potential Filler for Loose-Fill Building Insulation : Appropriate Selection and Incorporation into Polyurethane*.

Forest Europe. (2020). *State of Europe's Forests*.

France Bois Forêt. (2019). *Le Bois dans la construction*.

Friedrich, D. (2021). Attitude of building experts towards novel biobased wood-polymer façades under various properties : A choice-based experiment and impact analysis. *Journal of Building Engineering*, *35*(September 2020), 102079. https://doi.org/10.1016/j.jobe.2020.102079

Friedrich, D., & Luible, A. (2016). Investigations on ageing of wood-plastic composites for outdoor applications : A meta-analysis using empiric data derived from diverse weathering trials. *Construction and Building Materials*, *124*, 1142–1152. https://doi.org/10.1016/j.conbuildmat.2016.08.123

Gaffey, J., McMahon, H., Marsh, E., Vehmas, K., Kymäläinen, T., & Vos, J. (2021). Understanding Consumer Perspectives of Bio-Based Products—A Comparative Case Study from Ireland and The Netherlands. *Sustainability 2021, Vol. 13, Page 6062*, *13*(11), 6062. https://doi.org/10.3390/SU13116062

Gardner, D. J., Han, Y., & Wang, L. (2015). Wood–Plastic composite technology. *Current Forestry Reports*, *1*(3), 139–150. https://doi.org/10.1007/S40725-015-0016-6/FIGURES/4

GLOBE Advisors. (2016). *Study of Insurance Costs for Mid-Rise Wood Frame and Conrete Residential Buildings*. Jan.

Göswein, V., Dinis Silvestre, J., Freire, F., & Habert, G. (2019). Fleet-based LCA applied to the building sector – Environmental and economic analysis of retrofit strategies. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012172. https://doi.org/10.1088/1755-1315/323/1/012172

Göswein, V., Reichmann, J., Habert, G., & Pittau, F. (2021). Land availability in Europe for a radical shift toward bio-based construction. *Sustainable Cities and Society*, *70*(January). https://doi.org/10.1016/j.scs.2021.102929

Gurria, P., Ronzon, T., Tamosiunas, S., Lopez, R., Condado, S. G., Guillen, J., Cazzaniga, N., Jonsson, R., Banja, M., Fiore, G., Camia, A., & M'Barek, R. (2017). Biomass flows in the European Union: The Sankey biomass diagram - towards a cross-set integration of biomass. *JRC Working Papers*. https://ideas.repec.org/p/ipt/iptwpa/jrc106502.html

Gustavsson, L., Madlener, R., Hoen, H. F., Jungmeier, G., Karjalainen, T., Klöhn, S., Mahapatra, K., Pohjola, J., Solberg, B., & Spelter, H. (2006). The Role of Wood Material for Greenhouse Gas Mitigation. *Mitigation and Adaptation Strategies for Global Change 2006 11:5*, *11*(5), 1097–1127. https://doi.org/10.1007/S11027-006-9035-8

Harb, P., Locoge, N., & Thevenet, F. (2018). Emissions and treatment of VOCs emitted from wood-based construction materials: Impact on indoor air quality. *Chemical Engineering Journal*, *354*, 641–652. https://doi.org/10.1016/J.CEJ.2018.08.085

Hart, J., D'Amico, B., & Pomponi, F. (2021). Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. *Journal of Industrial Ecology*, *25*(2), 403–418. https://doi.org/10.1111/JIEC.13139

Hossain, U., Wang, L., Yu, I. K. M., Tsang, D. C. W., & Poon, C. (2018). Environmental and technical feasibility study of upcycling wood waste into cement-bonded particleboard. *Construction and Building Materials*, *173*, 474–480. https://doi.org/10.1016/j.conbuildmat.2018.04.066

Huang, Z., Sun, Y., & Musso, F. (2018). Hygrothermal performance of natural bamboo fiber and bamboo charcoal as local construction infills in building envelope. *Construction and Building Materials*, *177*, 342–357. https://doi.org/10.1016/j.conbuildmat.2018.05.071

Hurmekoski, E. (2016). Long-term outlook for wood construction in Europe. *Dissertationes Forestales*. https://doi.org/10.14214/df.211

Hussain, A., Calabria-holley, J., Lawrence, M., & Jiang, Y. (2019). Hygrothermal and mechanical characterisation of novel hemp shiv based thermal insulation composites. *Construction and Building Materials*, *212*, 561–568. https://doi.org/10.1016/j.conbuildmat.2019.04.029

Ismail, B., Belayachi, N., & Hoxha, D. (2020). Optimizing performance of insulation materials based on wheat straw , lime and gypsum plaster composites using natural additives. *Construction and Building Materials*, *254*, 118959. https://doi.org/10.1016/j.conbuildmat.2020.118959

Karaky, H., Id, C. M., Bliard, C., Moussa, T., Wakil, N. El, Lachi, M., & Polidori, G. (2018). *Hygrothermal and Acoustical Performance of Starch-Beet Pulp Composites for Building Thermal Insulation*. https://doi.org/10.3390/ma11091622

Kardung, M., & Wesseler, J. (2019). EU Bio-Based Economy Strategy. In J. Dries, Liesbeth Heijman, Wim Jongeneel, Roel Purnhagen, Kai Wesseler (Ed.), *EU Bioeconomy Economics and Policies: Volume II* (pp. 277–292). Springer International Publishing. https://doi.org/10.1007/978-3-030-28642-2_15

Kyma, H., & Sjo, A. (2008). *Flax and hemp fibres as raw materials for thermal insulations*. *43*, 1261–1269. https://doi.org/10.1016/j.buildenv.2007.03.006

Ladu, L., Wurster, S., Clavell, J., Iersel, S. van, Ugarte, S., Voogt, M., Falcone, P. M., Imbert, E., Tartiu, V. E., Morone, P., Crêpy, M., & Fedrigo, D. (2019). Acceptance factors among consumers and businesses for biobased sustainability schemes. STARProBio. Deliverable D5.1. In *STAR-ProBio - Sustainability Transition Assessment and Research of Bio-based Products (727740)*. https://doi.org/10.5281/ZENODO.3741850

Latif, E., Anca, M., Tucker, S., Chitral, D., & John, D. (2015). Hygrothermal performance of wood-hemp insulation in timber frame wall panels with and without a vapour barrier. *Building and Environment*, *92*, 122–134. https://doi.org/10.1016/j.buildenv.2015.04.025

Lazzarin, R. M., Busato, F., & Castelloti, F. (2008). Life cycle assessment and life cycle cost of buildings' insulation materials in Italy. *International Journal of Low-Carbon Technologies*, *3*(1), 44–58. https://doi.org/10.1093/IJLCT/3.1.44

Lee, K., & Yeom, D. (2015). *Indoor and Built Experimental research on the indoor environment control of natural insulation materials : Carbonized rice hull and straw bales*. *24*(6), 729–739. https://doi.org/10.1177/1420326X14534866

Lehmann, S. (2012). *Sustainable Construction for Urban Infill Development Using Engineered Massive Wood Panel Systems*. https://doi.org/10.3390/su4102707

Limam, A., Zerizer, A., Quenard, D., Sallee, H., & Chenak, A. (2016). Experimental thermal characterization of bio-based materials (Aleppo Pine wood , cork and their composites) for building insulation. *Energy & Buildings*, *116*, 89–95. https://doi.org/10.1016/j.enbuild.2016.01.007

Liu, L., Li, H., Lazzaretto, A., Manente, G., & Tong, C. (2017). The development history and prospects of biomass-based insulation materials for buildings. *Renewable and Sustainable Energy Reviews*, *69*(October 2016), 912–932. https://doi.org/10.1016/j.rser.2016.11.140

Liu, L., Zou, S., Li, H., Deng, L., Bai, C., Zhang, X., Wang, S., & Li, N. (2019). Energy & Buildings Experimental physical properties of an eco-friendly bio-insulation material based on wheat straw for buildings. *Energy & Buildings*, *201*, 19–36. https://doi.org/10.1016/j.enbuild.2019.07.037

Liuzzi, S., Sanarica, S., & Stefanizzi, P. (2017). Use of agro-wastes in building materials in the Mediterranean area: A review. *Energy Procedia*, *126*, 242–249. https://doi.org/10.1016/j.egypro.2017.08.147

LukeFinland. (2017). *Finnish Bioeconomy Strategy | Biotalous - Bioeconomy*. https://www.bioeconomy.fi/facts-and-contacts/finnish-bioeconomy-strategy/

Mahapatra, K., Gustavsson, L., & Hemstrm, K. (2012). Multi-storey wood-frame buildings in Germany, Sweden and the UK. *Construction Innovation*, *12*(1), 62–85. https://doi.org/10.1108/14714171211197508/FULL/XML

Mak, K., & Fam, A. (2019). Performance of flax-FRP sandwich panels exposed to different ambient temperatures. *Construction and Building Materials*, *219*, 121–130. https://doi.org/10.1016/j.conbuildmat.2019.05.118

Mantanis, G. I., Athanassiadou, E. T., & Barbu, M. C. (2018). *Adhesive systems used in the European particleboard , MDF and OSB industries*. *0272*. https://doi.org/10.1080/17480272.2017.1396622

Mao, D., Grillet, A., Bui, Q., My, T., Diep, H., & Woloszyn, M. (2018). Building bio-insulation materials based on bamboo powder and bio-binders. *Construction and Building Materials*, *186*, 686–698. https://doi.org/10.1016/j.conbuildmat.2018.07.153

Mao, D., Grillet, A., My, T., Diep, H., Nhan, C., Thuc, H., & Woloszyn, M. (2017). Hygrothermal properties of bio-insulation building materials based on bamboo fibers and bio-glues. *Construction and Building Materials*, *155*, 852–866. https://doi.org/10.1016/j.conbuildmat.2017.08.075

Maraveas, C. (2020). Production of sustainable construction materials using agro-wastes. *Materials*, *13*(2). https://doi.org/10.3390/ma13020262

Marceau, S., Glé, P., Guéguen-minerbe, M., Gourlay, E., Moscardelli, S., Nour, I., & Amziane, S. (2017). Virtual Special Issue Bio Based Building Materials Influence of accelerated aging on the properties of hemp concretes. *Construction and Building Materials*, *139*, 524–530. https://doi.org/10.1016/j.conbuildmat.2016.11.129

Marconi, M., Barbanera, M., Calabrò, G., & Baffo, I. (2020). Reuse of leather scraps for insulation panels: Technical and environmental feasibility evaluation. *Procedia CIRP*, *90*, 55–60. https://doi.org/10.1016/J.PROCIR.2020.01.053

Markström, E., Kuzman, M. K., Bystedt, A., & Sandberg, D. (2019). Use of wood products in multi-storey residential buildings: views of Swedish actors and suggested measures for an increased use. *Wood Material Science and Engineering*, *14*(6), 404–419. https://doi.org/10.1080/17480272.2019.1600164

Maskell, D., da Silva, C. F., Mower, K., Rana, C., Dengel, A., Ball, R. J., Ansell, M. P., Thomson, A., Peter, U., & Walker, P. J. (2015). Properties of bio-based insulation materials and their potential impact on indoor air quality. *Academic Journal of Civil Engineering*, *33*(2), 156–163. https://doi.org/10.26168/ICBBM2015.24

Maskell, D., da Silva, C. F., Mower, K., Rana, C., Dengel, A., Ball, R. J., Ansell, M. P., Thomson, A., Peter, U., & Walker, P. J. (2017). Bio-based plaster for improved indoor air quality. *Academic Journal of Civil Engineering*, *35*(2), 637–642.

Material Economics. (2021). *EU Biomass Use In A Net-Zero Economy - A Course Correction for EU Biomass*. https://www.climate-kic.org/wp-content/uploads/2021/06/MATERIAL-ECONOMICS-EU-BIOMASS-USE-IN-A-NET-ZERO-ECONOMY-ONLINE-VERSION.pdf

Mathis, D., Blanchet, P., Lagière, P., & Landry, V. (2018). Performance of wood-based panels integrated with a bio-based phase change material: A full-scale experiment in a cold climate with timber-frame huts. *Energies*, *11*(11), 1–15. https://doi.org/10.3390/en11113093

Mathis, D., Blanchet, P., Landry, V., & Lagière, P. (2018). Impregnation of wood with microencapsulated bio-based phase change materials for high thermal mass engineered wood flooring. *Applied Sciences (Switzerland)*, *8*(12). https://doi.org/10.3390/app8122696

Meeusen, M., Peuckert, J., & Quitzow, R. (2015). Acceptance factors for bio-based products and related information systems. In *Open-Bio Deliverable D* (Vol. 9).

Ministère de l'agriculture et de l'alimentation. (2018). *Stratégie Bioéconomie pour la France*.

Ministère de l'Économie des Finances et de la Relance. (2020). *France Relance*.

Ministère de la Transition Écologique. (2021a). *Bâtiment à énergie positive et réduction carbone*.

Ministère de la Transition Écologique. (2021b). *Label bas-carbone : récompenser les acteurs de la lutte contre le changement climatique*.

Ministère de la Transition Écologique et Solidaire. (2020). *Stratégie nationale bas-carbone*.

Ministry of Agriculture and Forestry of Finland. (n.d.). *Wood construction is being promoted in Finland*. https://mmm.fi/en/en/forests/use-of-wood/wood-construction

Ministry of Agriculture and Forestry of Finland. (2014). *Government Report on Forest Policy 2050*.

Ministry of Agriculture and Forestry of Finland. (2015). *National Forest Strategy 2025*.

Ministry of Ecological Transition. (2020). *RE2020 : Une nouvelle étape vers une future règlementation environnementale des bâtiments neufs plus ambitieuse contre le changement climatique*.

Ministry of Economic Affairs and Emoloyment of Finland. (2017). *Government report on the National Energy and Climate Strategy for 2030*.

Ministry of Employment and the Economy. (2015). *Finland: Strategic Programme for the Forest Sector reached its targets*.

Ministry of the Environment. (n.d.). *Aid Scheme for Growth and Development from Wood*. https://ym.fi/en/aid-scheme-for-growth-and-development-from-wood

Ministry of the Environment. (2019). *Wood Building Programme*. https://ym.fi/en/wood-building

Moujalled, B., Aït Ouméziane, Y., Moissette, S., Bart, M., Lanos, C., & Samri, D. (2018). Experimental and numerical evaluation of the hygrothermal performance of a hemp lime concrete building: A long term case study. *Building and Environment*, *136*(December 2017), 11–27. https://doi.org/10.1016/j.buildenv.2018.03.025

Nakano, K., Karube, M., & Hattori, N. (2020). Environmental impacts of building construction using cross-laminated timber panel construction method: A case of the research building in Kyushu, Japan. *Sustainability (Switzerland)*, *12*(6), 1–14. https://doi.org/10.3390/su12062220

Nazaroff, W. W. (2013). Four principles for achieving good indoor air quality. *Indoor Air*, *23*(5), 353–356. https://doi.org/10.1111/INA.12062

Nguyen, S. T., Tran-le, A. D., Vu, M. N., To, Q. D., Douzane, O., & Langlet, T. (2016). *Modeling thermal conductivity of hemp insulation material : A multi- scale homogenization approach*. *107*, 127–134. https://doi.org/10.1016/j.buildenv.2016.07.026

nova-Institut. (2015). *KBBPPS project. Deliverable 5.3: Market entry barriers*.

Oriyomi, M. O., David, A. O., & Khatib, J. (2015). A review of recycled use of post consumer waste paper in construction. *Academic Journal of Civil Engineering*, *33*(2), 711–717. https://doi.org/10.26168/ICBBM2015.111

Palumbo, M., Formosa, J., & Lacasta, A. M. (2015). Thermal degradation and fire behaviour of thermal insulation materials based on food crop by-products. *Construction and Building Materials*, *79*, 34–39. https://doi.org/10.1016/j.conbuildmat.2015.01.028

Palumbo, M., Lacasta, A. M., Giraldo, M. P., Haurie, L., & Correal, E. (2018). Bio-based insulation materials and their hygrothermal performance in a building envelope system (ETICS). *Energy and Buildings*, *174*, 147–155. https://doi.org/10.1016/j.enbuild.2018.06.042

Palumbo, M., Lacasta, A. M., Holcroft, N., Shea, A., & Walker, P. (2016). Determination of hygrothermal parameters of experimental and commercial bio-based insulation materials. *Construction and Building Materials*, *124*, 269–275. https://doi.org/10.1016/j.conbuildmat.2016.07.106

Panyakaew, S., & Fotios, S. (2011). New thermal insulation boards made from coconut husk and bagasse. *Energy and Buildings*, *43*(7), 1732–1739. https://doi.org/10.1016/J.ENBUILD.2011.03.015

Pavelek, M., & Adamová, T. (2019). Bio-waste thermal insulation panel for sustainable building construction in steady and unsteady-state conditions. *Materials*, *12*(12), 1–17. https://doi.org/10.3390/ma12122004

Peñaloza, D., Røyne, F., Sandin, G., Svanström, M., & Erlandsson, M. (2018). The influence of system boundaries and baseline in climate impact assessment of forest products. *The International Journal of Life Cycle Assessment 2018 24:1*, *24*(1), 160–176. https://doi.org/10.1007/S11367-018-1495-Z

Pfau Swinda, Vos John Vos, Dammer Lara, A. O. (2017). *Public perception of bio-based products. RoadToBio Deliverable D2.2*. https://roadtobio.eu/uploads/publications/deliverables/RoadToBio_D22_Public_perception_of_bio-based_products.pdf

Pinto, J., Paiva, A., Varum, H., Costa, A., Cruz, D., Pereira, S., Fernandes, L., Tavares, P., & Agarwal, J. (2011). Corn's cob as a potential ecological thermal insulation material. *Energy and Buildings*, *43*(8), 1985–1990. https://doi.org/10.1016/J.ENBUILD.2011.04.004

Piot, A., Béjat, T., Jay, A., Bessette, L., Wurtz, E., & Barnes-Davin, L. (2017). Study of a hempcrete wall exposed to outdoor climate: Effects of the coating. *Construction and Building Materials*, *139*, 540–550. https://doi.org/10.1016/j.conbuildmat.2016.12.143

Pittau, F., Krause, F., Lumia, G., & Habert, G. (2018). Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. *Building and Environment*, *129*(August 2017), 117–129. https://doi.org/10.1016/j.buildenv.2017.12.006

Pittau, F., Lumia, G., Heeren, N., Iannaccone, G., & Habert, G. (2019). Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. *Journal of Cleaner Production*, *214*, 365–376. https://doi.org/10.1016/J.JCLEPRO.2018.12.304

Platt, S., Maskell, D., Walker, P., & Laborel-préneron, A. (2020). Manufacture and characterisation of prototype straw bale insulation products. *Construction and Building Materials*, *262*, 120035. https://doi.org/10.1016/j.conbuildmat.2020.120035

Pochwała, S., Makiola, D., & Anweiler, S. (2020). *The Heat Conductivity Properties of Hemp – Lime Composite Material Used in Single-Family Buildings*. 1–14.

Porc, O., Hark, N., Carus, M., Dammer, L., BIC, D. C., & Knapsack, C. (2021). *European Bioeconomy in Figures 2008-2018*.

Prajer, M., & Trgala, K. (2018). *Static and Dynamic Thermal Characterization of Timber Frame / Wheat (Triticum Aestivum) Chaff Thermal Insulation Panel for Sustainable Building Construction*. https://doi.org/10.3390/su10072363

Pujadas-gispert, E., Alsailani, M., Koen, K. C. A. V. D., Annine, A. D. K. R., Puck, J. P. H., Carmen, C. C. K., & Faas, S. P. G. M. (2020). Design , construction , and thermal performance evaluation of an innovative bio-based ventilated facade. *Frontiers of Architectural Research*, *9*(3), 681–696. https://doi.org/10.1016/j.foar.2020.02.003

Rahim, M., Douzane, O., Le, A. D. T., Promis, G., & Langlet, T. (2016). *Characterization and comparison of hygric properties of rape straw concrete and hemp concrete*. *102*, 679–687. https://doi.org/10.1016/j.conbuildmat.2015.11.021

Rajput, D., Bhagade, S. S., Raut, S. P., Ralegaonkar, R. V., & Mandavgane, S. A. (2012). Reuse of cotton and recycle paper mill waste as building material. *Construction and Building Materials*, *34*, 470–475. https://doi.org/10.1016/J.CONBUILDMAT.2012.02.035

Ranacher, L., Sedmik, A., & Schwarzbauer, P. (2020). Public perceptions of forestry and the forest-based bioeconomy in the European Union. *EFI Knowledge to Action; European Forest Institute: Joensuu, Finland*.

Risse, M., Weber-Blaschke, G., & Richter, K. (2017). Resource efficiency of multifunctional wood cascade chains using LCA and exergy analysis, exemplified by a case study for Germany. *Resources, Conservation and Recycling*, *126*, 141–152. https://doi.org/10.1016/J.RESCONREC.2017.07.045

Robertson, A. B., Lam, F. C. F., & Cole, R. J. (2012). A comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: Laminated timber or reinforced concrete. *Buildings*, *2*(3), 245–270. https://doi.org/10.3390/buildings2030245

Romano, A., Grammatikos, S., Riley, M., & Bras, A. (2020). Physicochemical characterisation of bio-based insulation to explain their hygrothermal behaviour. *Construction and Building Materials*, *258*, 120163. https://doi.org/10.1016/j.conbuildmat.2020.120163

Saadatia, S. (2014). *Integrated life-cycle analysis of six insulation materials applied to a reference building in Portugal* [University of Coimbra]. https://estudogeral.uc.pt/bitstream/10316/39028/1/Integrated life cycle analysis of six insulation materials applied to a reference building in Portugal.pdf

Sabapathy, K. A., & Gedupudi, S. (2019). Straw bale based constructions: Measurement of effective thermal transport properties. *Construction and Building Materials*, *198*, 182–194. https://doi.org/10.1016/j.conbuildmat.2018.11.256

Sabini Matteo, Cheren Serena, B. S. (2020). *Biobridges Action Plan for raising consumers' awareness. D6.2*.

Santi, S., Pierobon, F., Corradini, G., Cavalli, R., & Zanetti, M. (2016). Massive wood material for sustainable building design: the Massiv–Holz–Mauer wall system. *Journal of Wood Science*, *62*(5), 416–428. https://doi.org/10.1007/s10086-016-1570-7

Schulte, M., Lewandowski, I., Pude, R., & Wagner, M. (2021). Comparative life cycle assessment of bio-based insulation materials: Environmental and economic performances. *GCB Bioenergy*, *13*(6), 979–998. https://doi.org/10.1111/GCBB.12825

Segovia, F., Blanchet, P., Auclair, N., Geraud, G., & Essoua, E. (2020). *Thermo-Mechanical Properties of a Wood Fiber Insulation Board Using a Bio-Based Adhesive as a Binder*.

Seixas, M., Moreira, L. E., Stoffel, P., Bina, J., Ripper, J. L. M., Ferreira, J. L., & Ghavami, K. (2021). Analysis of a self-supporting bamboo structure with flexible joints. *International Journal of Space Structures*, *36*(2), 137–151. https://doi.org/10.1177/09560599211001660

Singh, T., Page, D., & Simpson, I. (2019). Manufactured structural timber building materials and their durability. *Construction and Building Materials*, *217*, 84–92. https://doi.org/10.1016/j.conbuildmat.2019.05.036

Sinka, M., Pina, A., Ferrão, P., Fournier, J., Lacarrière, B., & Corre, O. Le. (2018). In-situ measurements of hemp-lime insulation materials for energy efficiency improvement. *Energy Procedia*, *147*, 242–248. https://doi.org/10.1016/j.egypro.2018.07.088

Slaimia, M., Belayachi, N., & Hoxha, D. (2017). *In Situ Performance Assessment of a Bio-Sourced Insulation Material from an Inverse Analysis of Measurements on a Demonstrator Building*. *21*, 460–467. https://doi.org/10.4028/www.scientific.net/AEF.21.460

Sokhansanj, S. (2013). *Biomass densification - Cubing operations and costs for corn stover*. *July 2004*. https://doi.org/10.13031/2013.16480

Somé, S. C., Fraj, A. Ben, Pavoine, A., & Chehade, M. H. (2018). *Modeling and experimental characterization of effective transverse thermal properties of hemp insulation concrete*. *189*, 384–396. https://doi.org/10.1016/j.conbuildmat.2018.08.210

Son, Y.-S., Lim, B.-A., Park, H.-J., & Kim, J.-C. (2013). Characteristics of volatile organic compounds (VOCs) emitted from building materials to improve indoor air quality: focused on natural VOCs. *Air Quality, Atmosphere & Health 2013 6:4*, *6*(4), 737–746. https://doi.org/10.1007/S11869-013-0207-X

Spirinckx, C., Peeters, K., de moortel, E. Van, Thoelen, P., Troyer, F. De, Norton, A., Schmidt, Y., & Leemput, S. Van. (2013). *Product Category Rules for Environmental Product Declarations for Thermal Insulation Materials on the Belgian Market*. *March*, 77.

Švajlenka, J., & Kozlovská, M. (2020). Analysis of the energy balance of constructions based on wood during their use in connection with CO2 emissions. *Energies*, *13*(18). https://doi.org/10.3390/en13184843

Talaei, M., Mahdavinejad, M., & Azari, R. (2020). Thermal and energy performance of algae bioreactive façades: A review. *Journal of Building Engineering*, *28*, 101011. https://doi.org/10.1016/J.JOBE.2019.101011

Taufik, D., Reinders, M. J., Molenveld, K., & Onwezen, M. C. (2020). The paradox between the environmental appeal of bio-based plastic packaging for consumers and their disposal behaviour. *Science of The Total Environment*, *705*, 135820. https://doi.org/10.1016/J.SCITOTENV.2019.135820

Tiso, M., Just, A., & Nele, K. (2016). Behavior of wooden based insulations at high temperatures. *Energy Procedia*, *96*(October), 729–737. https://doi.org/10.1016/j.egypro.2016.09.135

Tramberend, S., Fischer, G., Bruckner, M., & van Velthuizen, H. (2019). Our Common Cropland: Quantifying Global Agricultural Land Use from a Consumption Perspective. *Ecological Economics*, *157*, 332–341. https://doi.org/10.1016/J.ECOLECON.2018.12.005

Trinomics, VITO, Wageningen University & Research, Technische Universität Graz, & Ricardo. (2021). *Evaluation of the climate benefits of the use of Harvested Wood Products in the construction sector and assessment of remuneration schemes*. https://doi.org/10.2834/421958

Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., Stadler, K., & Wood, R. (2016). Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. *Global Environmental Change*, *40*, 171–181. https://doi.org/10.1016/J.GLOENVCHA.2016.07.002

Tumusiime, E., Kirabira, J. B., & Musinguzi, W. B. (2020). Performance evaluation of cellulose fiber ' s effectiveness as a thermal insulation material for productive biogas systems. *Energy Reports*, *6*, 3390–3398. https://doi.org/10.1016/j.egyr.2020.12.014

Valachova, D., Badurova, A., & Skotnicova, I. (2021). *Thermal Technical Analysis of Lightweight Timber-Based External Wall Structures with Ventilated Air Gap*.

Vėjelis, S., Lekūnaitė, L., & Šeputytė, J. (2017). *Loose Fill Material from Hemp Shives and Binding Material for Thermal Insulation and Structural Use*. *908*, 134–138. https://doi.org/10.4028/www.scientific.net/MSF.908.134

Viel, M., Collet, F., & Lanos, C. (2019). Development and characterization of thermal insulation materials from renewable resources. *Construction and Building Materials*, *214*(x), 685–697. https://doi.org/10.1016/j.conbuildmat.2019.04.139

WEF. (2021). *https://www.weforum.org/agenda/2021/01/here-s-how-to-decarbonize-the-eu-s-building-stock/*. https://www.weforum.org/agenda/2021/01/here-s-how-to-decarbonize-the-eu-s-building-stock/

Weiss, M., Haufe, J., Carus, M., Brandão, M., Bringezu, S., Hermann, B., & Patel, M. K. (2012). A Review of the Environmental Impacts of Biobased Materials. *Journal of Industrial Ecology*, *16*(SUPPL.1), S169–S181. https://doi.org/10.1111/J.1530-9290.2012.00468.X

Werner, F., & Richter, K. (2007). Wooden building products in comparative LCA: A literature review. *International Journal of Life Cycle Assessment*, *12*(7), 470–479. https://doi.org/10.1065/lca2007.04.317

Winandy, J. E., & Morrell, J. J. (2017). Improving the utility, performance, and durability of wood- and bio-based composites. *Annals of Forest Science*, *74*(1), 1–11. https://doi.org/10.1007/s13595-017-0625-2

Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering - EASE '14*, 1–10. https://doi.org/10.1145/2601248.2601268

Won, D., Nong, G., Yang, W., & Collins, P. (2014). *Material emissions testing: VOCs from wood, paint, and insulation materials*. https://doi.org/10.4224/23002015

Yin, X., Dong, Q., Zhou, S., Yu, J., Huang, L., & Sun, C. (2020). Energy-Saving Potential of Applying Prefabricated Straw Bale Construction (PSBC) in domestic buildings in Northern China. *Sustainability (Switzerland)*, *12*(8). https://doi.org/10.3390/SU12083464

Zampori, L., Dotelli, G., & Vernelli, V. (2013). *Life Cycle Assessment of Hemp Cultivation and Use of Hemp-Based Thermal Insulator Materials in Buildings*.

Zhang, Y., Ghaly, A. E., & Li, B. (2014). *Physical Properties of Wheat Straw Varieties Cultivated Under Different Climatic and Soil Conditions in Three Continents*. *5*(2), 98–106. https://doi.org/10.3844/ajeassp.2012.98.106

Zibell, L., Forestier, O., Beznea, A., Hereford, J., Finesso, A., Trinomics BV, Schelhaas, M.-J., Lernink, B., Garcia Chavez, L., & Wageningen University & Research. (2011). *Market Analysis Final Report*.

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