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# WHERE DO BUILDINGS COME FROM? PROSPECTIVE LIFE CYCLE ASSESSMENT OF FAST-GROWING BIO-BASED INSULATION MATERIALS AND THEIR TRANSPORT

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## ABSTRACT

The construction industry’s high contribution to global greenhouse gas emissions is well documented. This has driven many countries to develop strategies aiming to achieve net-zero emissions in their built environments. Currently, the development of near-zero construction materials is still a niche, especially for insulation materials. In this paper, we explore the environmental impacts from the production of fast-growing bio-based construction materials and their potential transport at regional, national and international scales with the use of prospective life cycle assessment.

## KEYWORDS

LCA; $CO_2$; straw; hemp; grass; biogenic

## 1. INTRODUCTION

The relevance of the construction industry is undeniable; its role of delivering buildings and infrastructure can be directly connected to both economic dynamics and environmental degradation issues. The industry’s high contribution to global greenhouse gas emissions, from the production of mineral construction materials and the operation of buildings in temperate climates, is well documented (Dean et al., 2016). This has driven many countries to develop strategies aiming to achieve net-zero emissions in their built environments. In order to achieve such ambitious target, sectors within the construction industry need to develop to be able to deliver materials and systems with near-zero or net-zero carbon footprints. For the last four decades, great efforts have been put in the development of systems to achieve energy efficiency in buildings, especially in building envelopes(Rock et al., 2020). On the contrary, the development of near-zero construction materials is still a niche, especially for insulation materials (Pittau et al., 2019). Considering that near-zero materials might not be available in many regions in the near future poses a challenging decision between local availability and near-zero production of materials.

The context and trends in the sector vary greatly depending on geographic location; hence, the appropriate solutions and strategies to make the best out of it are not the same everywhere in the world. In developing urban areas in Asia and Africa, where ninety percent of the projected world population growth by 2050 will take place, solutions to prevent spikes of embodied GHG emissions from manufacturing of building materials, especially load-bearing materials, will be extremely important (Nagendra et al., 2018). In regions where most of the building stock has already been built, for example in Europe, retrofitting solutions which reduce operational emissions without costing high embodied emissions are the most important (Habert et al., 2020). Thanks to plants’ valuable $CO_2$ capturing and renewable properties, the use of fast-growing bio-based building materials offers an opportunity to store captured carbon in buildings delaying the natural GHG cycle. This opens the opportunity of designing for climate regeneration with bio-based building materials (Pittau et al., 2018; Zea Escamilla et al., 2016). An increased use of bio-based materials in construction can only be successful if does not lead to negative land use competition with other sectors or loss of biodiversity, in other words it must be supported with sustainable agricultural production and forestry (Goswein et al., 2021). The necessary land to support increased production of bio-based building materials is not equally distributed. Therefore, in a large-scale implementation of bio-based materials the question of transportation is of great relevance.

Freight transportation accounts for around 7% of global energy-related $CO_2$ (IEA, 2022; OECD/ITF, 2015). Direct and indirect emissions and other environmental impacts of transportation result from vehicle operation, fuel production, construction and maintenance of infrastructure and vehicle production. When environmental impacts of freight transportation are quantified, a reference unit of ton-kilometre is commonly used. This reference unit indicates impact of transporting one ton of goods one kilometre with a certain transportation mode. It is important to note that a detailed transportation impact analysis requires considerations of carrying capacity, for instance when transporting goods with a wide range of densities. Voluminous goods need more transport vessels and more trucks for road transport. Moreover, the fuel consumption increases with higher total weight of trucks but when everything is added, low density goods lead to more fuel consumption over one ton-kilometre than bulk goods (CLECAT, 2012; EcoTransIT World Initiative, 2020).

Life cycle assessment (LCA) is the most recognized methodology not only to assess whole life environmental impacts of products and services but also to support decision making processes (Hellweg & Mila i Canals, 2014). LCA is methodologically described on the ISO14040 (ISO14040, 2007) and has been implemented in several countries. LCA proposes an input-output relation between human activities and the environment. LCA has been used to evaluate construction materials; building products; buildings; and infrastructures. The most commonly used frame work for these assessment is described in the norm EU15978 (Standards, 2011). In recent years, researchers in the field of LCA have pointed out the importance of time-distributed fluxes of greenhouse gas emissions and removals. In the current LCA practice which is based on an IPCC method (Edenhofer et al., 2014), the timing of emissions is not considered, and the same importance with regards to global warming potential (GWP) is given to emissions regardless of their timing even though an LCA study is done with a specific time horizon (Levasseur et al., 2010).

The main objective of the research presented in this paper was to calculate the environmental saving potential of using innovative nearly zero carbon materials in renovation in Switzerland. Moreover, the objective was to assess the relevance of transportation of construction materials in the whole life environmental impacts of materials and buildings.

## 2. DATA AND METHODS

In this paper, we explore the environmental impacts from the production of fast-growing bio-based materials and their potential transport at regional, national and international scales with a case study in Zürich, Switzerland. To do so, life cycle assessment models of two conventional insulation materials and five bio-based insulation materials were developed. Moreover, the models consider the transport of materials from production facility to the construction site. Furthermore, prospective assessment models for potential transportation ranges were developed using the georeferenced location of production facilities of the studied products and the city, Zürich, as target destination. Using these results, we prepared a comparative assessment for a typical multi-storey building where the amount of insulation material required to fulfil the energy efficiency in Swiss building. The biogenic carbon storage of these materials was calculated in order to establish the materials' carbon balance.

### 2.1. Case Study

The case study was a typical four storey building in Zürich, in need of a building envelop renovation. Producers of insulation materials were identified and the distance from their production, facilities to the site were measured. Based on these distances, a maximum transportation range of 1000km was defined. The amount of insulation materials for each product was calculated based on the Swiss energy efficiency norm.

### 2.2. Insulation Material Data

The first step of the work was to collect information on non-conventional building material products and choosing a selection of products to use as a base for the study. The search for information was made through producers' websites, literature and the ecoinvent (Ecoinvent, 2020) LCA database. The main types of information searched were: (1) product function, properties and material composition; (2) information on production processes; (3) existing LCA results.

A summary of the materials studied, and their basic characteristics is presented in Table 1. From this table we can see that most of the studied materials, bio-based and conventional, have similar densities ranging from 30 – 45 kg/m$^3$. From this table it is also possible to observe that the transport capacity utilizations for most products fall within similar ranges. Finally, volumes of insulation materials required, which are calculated based on the insulating properties of the materials and the benchmarks for energy efficiency defined in the Swiss norms, can be seen in the table.

Table 1 Materials basic characteristics

| Product | Density of product [kg/m3] | Material volume in building [m3] | Capacity utilization | Thermal conductivity [W/m*K] |
|---|---|---|---|---|
| Grass fibre | 40 | 353.6 | 0.080 | 0.041 |
| Hemp fibre | 35 | 353.6 | 0.070 | 0.041 |
| Wood fibre | 150 | 349.1 | 0.302 | 0.04 |
| Cellulose fibre | 45 | 340.0 | 0.091 | 0.038 |
| Straw | 100 | 403.3 | 0.201 | 0.052 |
| XPS | 30 | 312.9 | 0.060 | 0.036 |
| Glass wool | 40 | 331.0 | 0.080 | 0.032 |

### 2.3. LCA methodology

The material level LCA starts with mass and energy flow analysis (MEFA) where mass flow models for each product are developed to get an overview of material and energy inputs for the production of the products. The collected data on the products lay the foundation for the MEFA models, which are constructed in harmony with the ecoinvent datasets that are used in the LCA modelling. The LCA on the material level follows the framework in the international ISO standards for LCA (ISO 14040-14043) (ISO, 2007) which consists of goal and scope definition, inventory analysis and impact assessment (Baumann & Tillman, 2004). Figure 1 gives an overview of the LCA procedure framework.

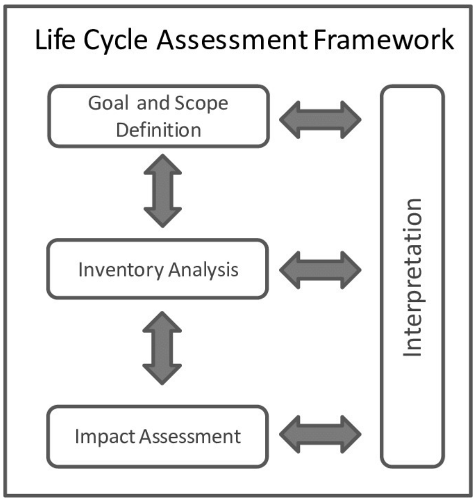

**Figure 1.** ISO 14040-14043 LCA procedure framework (ISO, 2006; Simonson Mcnamee et al., 2011).

### 2.4. Biogenic carbon content

The sequestered $CO_2$ in the bio-based products is calculated according to European Standard EN 16449 for wood and wood-based products. Equation 1 was used for calculations and it is based on the atomic weights of carbon (12) and $CO_2$ (44):

$$S_{CO_2} = \frac{44}{12} \times cf \times bc \times \rho_{0\%} \qquad \text{Eq. 1}$$

where
$S_{CO_2}$ is the biogenic $CO_2$ that is stored in the building material [$kg/m^3$];
$cf$ is the carbon fraction of the biomass in each product (approx. 0.40 – 0.54) [no unit];
$bc$ is the biomass content of the product (fully bio-based products have $bc = 1$) [no unit];
$\rho_{0\%}$ is the density of the product's biomass at moisture content of 0% [$kg/m^3$] (CEN, 2014).

To account for the effect of biogenic $CO_2$ storage in the building level LCA, the $GWP_{bio}$ index method is used (Cherubini et al., 2013). This semi-static method is able to assess time dependent $CO_2$ flows of biogenic $CO_2$ and therefore quantify the benefits of delayed GHG emissions in the natural $CO_2$ cycle. The time horizon used in the $GWP_{bio}$ index method is 100 years, which are presented on the same unit than IPCC 2013 LCA calculations of this study ($kgCO_2$.eq), and therefore the $GWP_{100a}$ and the $GWP_{bio}$ calculations can be combined (Equation 2). By adding the biogenic aspect into the standard LCA, it is for example possible to determine whether a certain use of a bio-based material in construction is carbon neutral or if the renovation is climate neutral. The two key parameters in the $GWP_{bio}$ index method are 1) the storage time of a bio-based material in the building and 2) the rotation period of the bio-based material. A rotation period of 1 year was used for the fast-growing plants that are studied in this study; straw, hemp and grass.

$$GWP_{net} = GWP_{100a} + I_{GWP_{bio}} \times S_{CO_2} \qquad \text{Eq. 2}$$

where
$GWP_{net}$ is the net global warming potential of a material (biogenic $CO_2$ effect included);
$GWP_{100a}$ is the standard LCA (IPCC 2013) global warming potential of a material;
$I_{GWP_{bio}}$ is the index depending on the storage and rotation time of the material;
$S_{CO_2}$ is the total sequestered $CO_2$ in the bio-based product.

Under these parameters, a $GWP_{bio}$ index of zero means a carbon neutral use of a bio-based material. $GWP_{net}$ of the particular material use equals the $GWP_{100a}$ calculated with standard IPCC 2013 LCA method, whereas, a negative $GWP_{bio}$ index indicates beneficial use of a bio-based material in terms of delayed GHG emissions. $GWP_{net}$ is less than $GWP_{100a}$ and can be negative. For example, if a building is built only with materials with $GWP_{net} < 0$, it has a positive effect on the climate (cooling effect). Finally, a positive $GWP_{bio}$ index indicates that the use of a bio-based material speeds up natural biogenic $CO_2$ emissions, which means that the specific use cannot be considered carbon neutral as assumed in standard LCA. The $GWP_{net}$ is therefore larger than $GWP_{100a}$.

### 2.5. Transport of low-density goods

Previous research has shown that the transportation of low density construction materials incurs on transportation inefficacies, due to the fact that the volume capacity of vehicles is reached before their weight carrying capacity (Zea Escamilla & Habert, 2014). Therefore, for this paper a special evaluation of transport related emissions of low-density cargo was used. The load capacity of vehicles transporting low-density cargo is limited by the volume capacity of the vehicle. For this evaluation, a 20-26 t diesel truck with payload capacity of 15 t is assumed. The transportation emission impact per ton-kilometre for each low-density product is calculated with a methodology developed by EcoTransIT Initiative (EWI) (EcoTransIT World Initiative, 2020). Equation 5 was used to calculate density dependent transportation impact per ton-kilometre. Equation 3 and 4 are descriptors for inputs of Equation 5.

$$LF_j = \frac{m_{full,j}}{CP} \qquad \text{Eq. 3}$$

where
$LF_j$ is the load factor of transportation of product $j$ [no unit];
$m_{full,j}$ is the total mass of product $j$ in a fully loaded truck of product $j$ [t];
$CP$ is the payload capacity of the vehicle [t].

$$CU_j = \frac{LF_j}{1+ET} \qquad \text{Eq. 4}$$

where
$CU_j$ is the capacity utilization in the transport of product j [no unit];
$LF_j$ is the load factor of transportation of a product j [no unit];
$ET$ is the empty distance factor (km empty/km loaded), assumed to be 10% for low-density products [no unit].

$$EMV_{tkm,j} = \frac{EMV_{km}}{CP \times CU_j} \qquad \text{Eq. 5}$$

where
$EMV_{tkm,j}$ are the density dependent $CO_2$emissions per ton km for a product j [kg/tkm];
$EMV_{km}$ is an average combustion related vehicle emission factor of vehicle per km [kg/km];
$CP$ is the payload capacity of the vehicle;
$CU_j$ is the capacity utilization in the transport of product j (EcoTransIT World Initiative, 2020).

## 3. RESULTS

The LCA results of the insulation materials from cradle to gate are presented in Figure 2. On this figure, the values for the environmental impact of production of each material as well as the transportation from factory to construction site are shown. From the figure it can be observed that most of the bio-based insulation materials have an environmental savings potential of up to 90% when compared to XPS and 76% when compared to glass wool. Moreover, the nominal impact form transport is very similar for all of the studied materials ranging from 28 to 32 $tCO_2eq$. This is related to the very similar densities and u-values of the studied materials.

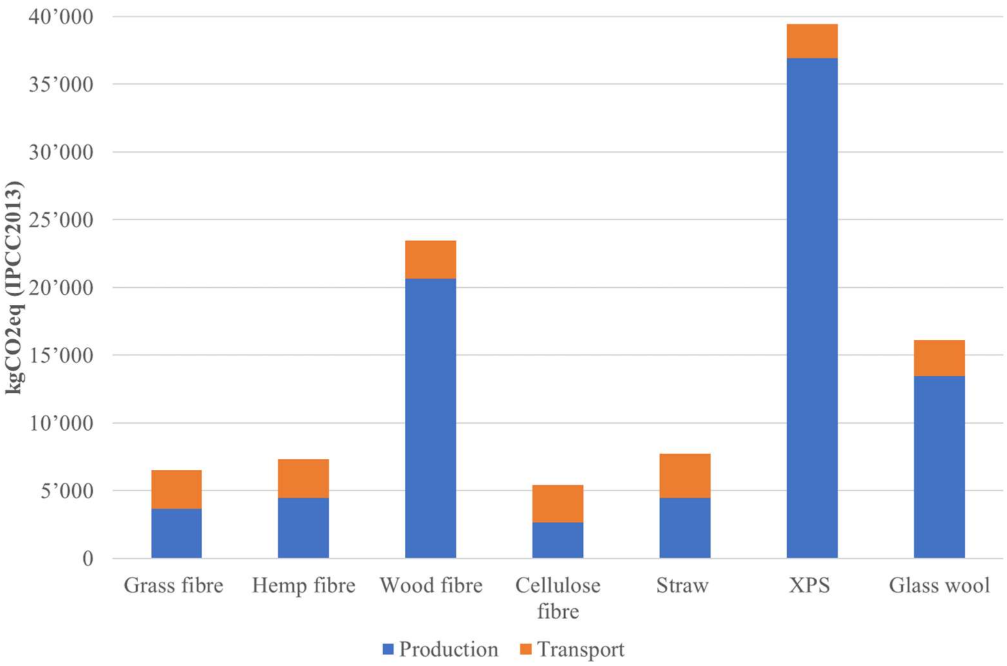

**Figure 2.** LCA results of materials’ production and transportation from producer to the building site.

The results for the storage of biogenic $CO_2$ are presented in figure 3. Moreover, the carbon balances are presented, showing the difference between emissions from production and biogenic $CO_2$ stored in the materials. From this figure, we can observe that all the bio-based insulation materials have a significant capacity for biogenic carbon storage. Furthermore, under the studied conditions three out of five materials can be considered as carbon negative materials, while the remaining two can be considered near-zero. It is important to note that the biogenic carbon storage is strongly related to the service life of the product. Thus, the carbon balances will be significantly affected by the durability of the materials during the service life of the buildings.

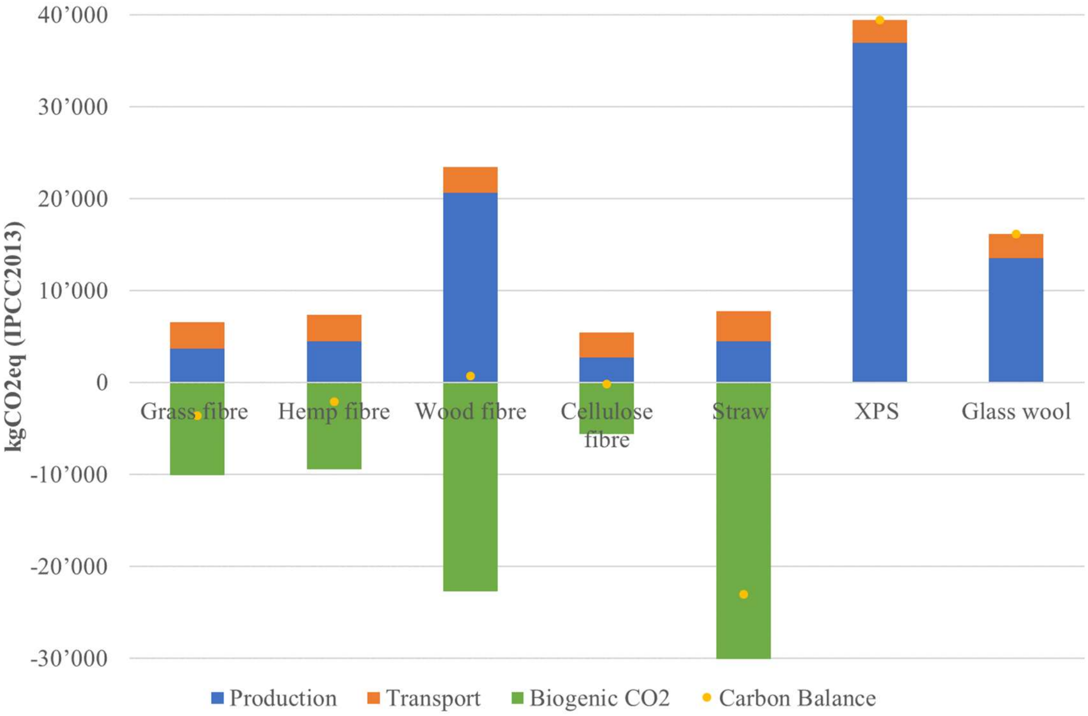

**Figure 3.** LCA Results - Biogenic carbon and $CO_2$ balance, assuming 60-year service time.

In order to better understand the contribution of transportation to the total environmental impacts of the studied materials a transportation analysis was carried out. The summary of carbon balances under different transportation regimes is presented on figure 4. The results on this figure show that all the bio-based insulation materials can be considered as carbon negative if they are transported under 400km. Nevertheless, it important to note that all the bio-based insulation material offer a low carbon alternative to conventional insulation materials under the proposed transportation distances. It is also possible to note that the environmental savings potential of bio-based materials in relation to conventional materials is maintained at all transportation distances.

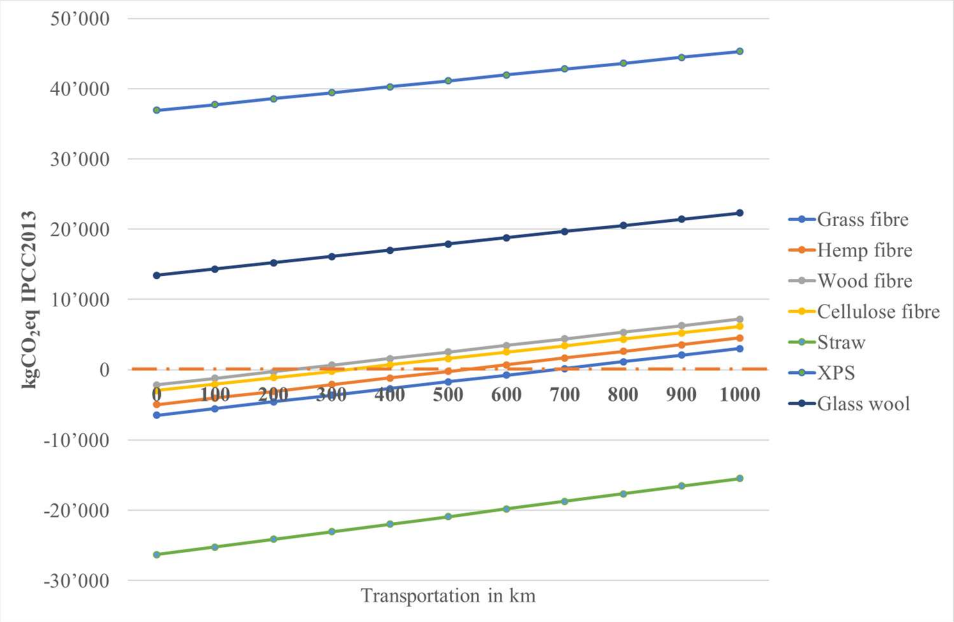

**Figure 4.** LCA Results - $CO_2$ balance under transportation regimes

## 4. CONCLUSIONS

Bio-based insulation materials made from hemp fibre, straw, grass fibre and cellulose fibre (recycled paper) have significantly lower embodied emissions than conventional insulation materials such as glass wool and XPS. Furthermore, the results show that bio-based insulation materials are not necessarily better in terms of upfront emissions, like the example of wood fibre vs glass wool; this underlines the importance of doing LCA to support decision making processes. The main contributor of emissions in the production of bio-based insulation materials is most often activities, which belong to the cultivation of the plants. Another significant contributor for these materials is often the energy use in the production of the insulation product. However, the bio-based insulation materials offer a huge opportunity to increase the biogenic $CO_2$ storage in buildings, especially straw and grass based insulation materials. It is important to remark that for the assessment transportation impacts of low-density materials, calculation methods with a fixed $CO_2$ intensity value per ton-kilometre should be avoided and instead capacity utilization should be considered. Furthermore, transportation analysis showed that most of the bio-based materials could be transported over long distances and still remain carbon negative. From the results of this research, it is possible to conclude that a quick implementation of renovation using bio-based insulation can truly be a way to reduce atmospheric $CO_2$ and have a positive impact on the climate, opening new market opportunities for the agricultural sector and business dynamics for the construction sector in Europe.

## CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

## DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.

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