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HEALING THE EUROPEAN BUILDING STOCK WITH BIO-BASED MATERIALS: DO WE HAVE ENOUGH AVAILABLE LAND?

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Abstract

The use of biomass for construction is a promising strategy to store carbon and decrease the construction sector's carbon footprint. This paper aims to determine how much biomass - namely timber for new structures and biogenic fibers for thermal insulation - and the relative land occupation would be needed to satisfy the material demand of the EU residential building stock up to 2050. Based on present land occupation, the potential for biogenic material use was determined and applied on four alternative insulation types: wood fibers, cork panels, straw fibers and hempcrete. The comparison of existing cultivation area and demanded land suggests possible land scarcities for the respective raw materials. Resource scarcity and abundance, as well as material-based practicability for the technology options, could therefore be determined. Finally, a traditional LCA (cradle-to-gate) was conducted to measure the carbon storage and $CO_{2\text{-eq}}$ emissions. The results indicate that the existing forests and fields used for cereal production are more than sufficient for supplying straw and timber-based construction materials. Cork is only favorable for turning buildings into carbon sinks at the local scale in Southern dry countries and the current legal limitations for hemp cultivation hinder this material's potential at a large scale.

Keywords:

Land use; Embodied land; Carbon storage; Biobased materials; MFA

1 INTRODUCTION

In the European Union (EU) buildings contribute 40% to the energy consumption and 36% of fossil carbon emissions (European Commission, 2018). Current EU legislation requires all new buildings to be nearly-zero energy buildings (nZEB) by next year (European Parliament and the Council of the European Union, 2010) and the revised Energy Performance of Buildings Directive (EPBD) demands a decarbonization of the national building stocks by 2050 (European Parliament and Council, 2018). 75% of the EU building stock qualifies as energy inefficient (European Commission, 2018). Future construction activities can be expected to require massive amounts of materials, based on past estimates of material stocks and flows (Wiedenhofer et al., 2015).

The production of common construction and thermal insulation materials is intense in fossil fuel consumption (Tettey et al., 2014). To avert exceeding climate tipping points, the building sector needs to become carbon neutral, which requires an immediate drastic shift in the design, production and use of construction materials (Nichols, 2019). Some authors indicate that regenerative design of buildings allows for an even more drastic solution by turning buildings into climate positive carbon pools (Churkina et al., 2020). Pittau et al. (2018) studied exterior walls made with straw, hemp, and timber, and benchmarked them with conventional wall systems using clay bricks or concrete. The authors found promising results: the fast-growing materials straw and hemp make carbon-negative construction a possibility, while timber construction is less efficient in terms of carbon storage due to the long rotation period of forests. The same authors (Pittau et al., 2019) conducted another study focusing on the carbon storage potential for the renovation of Europe's building stock, emphasizing at a large scale their finding that fast-growing biogenic materials offer a promising strategy towards reaching the climatic goals of the Paris climate agreement (UNFCCC, 2015).

Recently, more and more bio-based construction materials are emerging as new frontiers for the construction market. There has been an ongoing scientific discussion regarding if and how to account for biogenic carbon (Demertzi et al., 2018; Hafner and Schäfer, 2017).The use of bio-based materials in construction can potentially lead to negative carbon solutions. There is a wide range of bio-based materials available for construction. However, the materials do not only vary in their structural and thermal properties but also in processing and, most importantly, in the availability of raw material. Their manufacturing depends on agricultural or forest management, and questions related to land use and land competition between sectors lead to critical issues that need to be investigated. For this study, four different biogenic materials are selected, namely: straw from cereal production, wood from coniferous forests, cork from oak savannas, and hemp shives from hemp cultivations. Available land used for each specific cultivation is shown in the following Fig. 1.

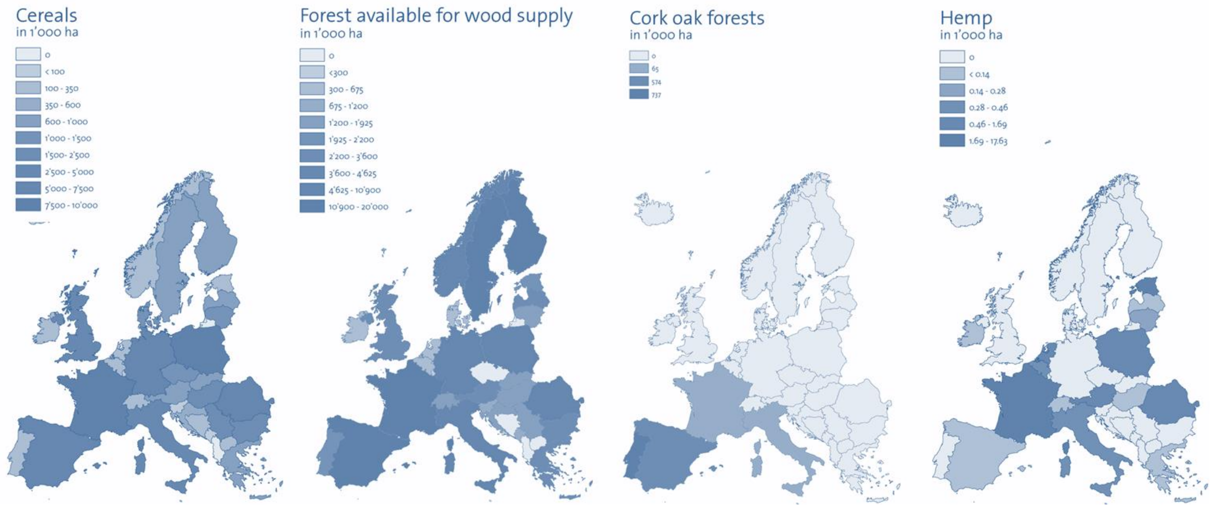

Fig. 1: Existing land for the cultivation, harvest and production of different types of biomass in Europe. Sources: Cereals (Eurostat, 2017) , Forest (Eurostat, 2015), Cork oak forests (APCOR, 2013), Hemp (Eurostat, 2017)

2 GOAL AND SCOPE

This paper aims to investigate possible implications and limits from a large implementation of biobased materials in construction at the pan-European level. The main research question wants to answer which bio-based materials are most promising at present conditions to store carbon in construction without requiring additional land for raw material supply and production. The prism of land use is employed to better understand how much material can be supplied at present conditions, considering plant growth rates, land requirements for different types of raw materials and cross-sectorial competition.

3 METHOD

3.1 Material flow analysis for residential building stock model

A specific material flow analysis (MFA) model was developed to simulate the material intensity expected in the next years in EU-28, as well as the raw bio-based materials which the natural systems (forest, crops, plantations) need to supply. The model was applied to the EU-28 member states, sorted into seven geographical clusters according to their climatic conditions as was proposed by Birchall et al. (2014), called "Geoclusters" (Sesana et al., 2015). The analysis was performed from present day until 2050. The model is demand-driven and only considers energy-retrofit and new construction of exterior walls and roofs of the residential building stock. A summary of all input parameters can be seen in Tab. 1. The model is based on the standard stock dynamics model as proposed by Müller (2006) and later adapted by Göswein et al. (2018).

Tab. 1: Input data for the residential building stock model

	Existing Building Stock & Renovation	New Construction	Dynamics
Existing Floor Area	x		No
Building Typology	x		No
Renovation Rate	x		No
Population Growth		x	Yes
People per Dwelling		x	No
Area per person		x	No
Wall Geometry (S_w/S_f)	x	x	No
Roof Geometry (S_r/S_f)	x	x	No
Thermal Performance of the Envelope & Building Energy Codes	x	x	No

For each geocluster, different reference residential building typologies collected in the TABULA catalogue (IEE, 2012) were aggregated and sorted into two categories: i) single-family houses (SF), and ii) multi-family houses (MF). Data on the country-wise distribution of these two typologies were obtained from the EU Buildings Observatory (Eurostat, 2018). Per each geocluster, a category share was evaluated on the basis of the built floor area and for each reference building typology a wall geometry factor and a roof geometry factor were calculated.

The driver of the renovation activity is the renovation rate (RR), while the driver of the construction activity is population growth and its lifestyle habit, expressed through persons per dwelling and area per person, which results in additional need for shelter. A mean constant *RR* was defined for each geocluster for walls and roofs based on Toleikyte et al. (2016) and a yearly renovated area was calculated accordingly.

The difference between the current U-value and the U-value target, per geocluster, was used to estimate the quantity of insulation material required for renovation of exterior walls. The majority of recently published national building codes have introduced a minimum U-value for walls that needs to be achieved with the design of a renovated or newly constructed building (Mazzarella, 2015). The incremental thermal resistance required to achieve the U-value target was calculated considering an incremental factor equal to 2, which takes into account future limitation of minimum U-value in energy regulations.

Tab. 2: Overview of the bio-based technology options sorted by structural elements and construction activity

			wood fiber board	straw chips	hempcrete (blocks or injected)	cork board	timber structure	structural	non-structural	lime plaster	clay plaster	organic cover plaster	roof tiles (vapor barrier, battens)	gypsum fiberboard	clay plaster	prefabrication	on-site	average thickness [mm]
			Insulation Type				Structure Type			Exterior Finishing				Interior Finishing		Type of construction		Ins.
WALL	renovation	TIM	x				x		x			x				x		67
		STR		x			x		x		x					x		87
		HEM			x				x	x							x	158
		COR				x			x	x							x	90
	new construction	TIM	x				x	x				x		x		x		160
		STR		x			x	x				x			x	x		168
		HEM			x		x	x		x					x	x		250
		COR				x	x	x				x			x	x		120
ROOF	renovation	TIM	x				x		x				x			x		102
		STR		x			x		x				x			x		138
		HEM			x		x		x				x			x	x	166
		COR				x			x				x				x	128
	new construction	TIM	x				x	x					x	x		x		167
		STR		x			x	x					x		x	x		242
		HEM			x		x	x					x	x		x		269
		COR				x	x	x					x	x		x		200

New construction is driven by population growth, which is a time-dependent function, while the parameters “persons per dwelling” and “area per person” are considered constant. The two latter parameters are multiplied together to obtain the per-capita floor area and then the yearly newly constructed area. Additional information about the building stock model can be found in Göswein et al. 2021 (Göswein et al., 2021).

3.2 Reference construction technologies

Four alternative bio-based construction technologies were considered in this paper, based on four different insulation materials: wood fiber (TIM), straw (STR), hempcrete (HEM) and cork (COR). A specific assembly for each alternative was developed, based on the proposition (renovation or new construction), and element (roof or exterior wall). Only the building envelope components above the ground were included into the analysis. Thus, resulting in sixteen slightly different technology options, eight for new construction and eight for renovation, as summarized in Tab.2. All new construction technology options require a timber frame as load-bearing structure, while in case of renovation a timber frame is used in TIM and STR (and HEM for roof) as a non-structural element to assembly the component. All the alternative technologies for renovation were assumed to be directly installed from the outer side of the envelope directly on existing support, either fixed with mortar or glue, or fixed through metallic fasteners. Most of the technology options are prefabricated panels, only some are mounted directly on-site. The average insulation thickness is an average all over EU member States, calculated for each of the technology options based on the materials' thermal properties. For new construction, a minimal thickness was defined due to structural requirements.

3.3 Material processing

Built environment and natural environment models were connected with an industrial processing model, which takes into account the mass flow changes of bio-based products before and after industrial processes. The processed biogenic material was connected to the raw material flow by single or multiple intermediate production process for highly industrialized final products (e.g., oriented strand boards (OSB), oriented strand straw boards (OSSB), etc.). For less engineered products (e.g., straw, hemp shives, etc.), the mass flow entering in the final product was assumed to be equal to the mass flow coming from the natural environment, depending on the nature of the treated material.

In a production process, often the material flow, which enters the system is not equal to the outflow. Especially in bio-based processes, a large share of biogenic residues can be generated during manufacturing, by lamination, cutting, drilling, planning, etc. The in- and out-flows was evaluated for each bio-based material to model the raw material need to supply the demand according to the following Tab. 3.

Tab. 3: Raw material (inflow) needed to produce the different bio-based construction products

Bio-based product	Inflow/outflow factor	Unit	Type	Ref.
Sawn Timber	2.94	m^3/m^3	LCA	(Puettmann et al., 2013)
OSB	1.52	m^3/m^3	LCA	(Puettmann et al., 2016).
Hempcrete (injected)	0.38	kg/kg	LCA	(Arrigoni et al., 2017)
Hempcrete (block)	0.38	kg/kg	LCA	(Arrigoni et al., 2017)
Cork Board	1.060	kg/kg	Losses	(Moreno Ruiz et al., 2015)
All others	1.053	kg/kg	Losses	(Assumption 5% mass losses)

3.4 Bio-systems model

Bio-systems modelling is a complex research field. Especially for forest-modelling, different dynamics should be included in the analysis: the rotation period of trees, tree species, type of soil and the local climate influence the harvest potential (Ramage et al., 2017) and global warming potential (GWP) due to CO_2 emitted from biomass (Cherubini et al., 2011). A simplified approach is to include forest growth in a model through statistics.

The land required to meet the biogenic raw material demand was calculated by extracting the average yield for the four biogenic raw materials of most present supply data and dividing the annual biogenic raw material demand by the yield (kg/ha) calculated from the current harvest and land use. The actual yearly required biomass is the driver of yearly required land to grow the different types of biomass, which is dependent on biomass density and considers a factor for material losses during cultivation.

Wood from coniferous forests

According to Ramage et al. (2017) mostly coniferous and thus softwood is used for construction. Therefore, this study only considered coniferous roundwood, making up about two-thirds of the total roundwood available for wood supply. It should be noted that a considerable additional potential could be found in non-coniferous wood.

Straw from cereal production

Cereal production statistics area used for cultivation of cereals were derived from Eurostat (Eurostat, 2017). The amount of cereal produced each year was translated into amount of straw, through the straw-to-corn ratio, which is 0.848 based on Hartmann, Kaltschmitt, and Thrän (2016). A German study (Münch, 2008) compared different recommendations and came to the conclusion, that on average one third of the straw can be taken out of the agricultural cycle/system and is hence available for all types of applications. Currently most of the straw is left on the field after the harvest to provide nutrients for soil regeneration or used as animal bedding and feed. Other secondary usages of straw are in horticulture and gardening and for energy production, which account for 1% of the current EU-28 straw production (Hartmann et al., 2016).

Hemp shives from Cannabaceae crops

Eurostat data for hemp production was used (Eurostat, 2016). The hemp production was multiplied by a hemp straw to hemp shives ratio suggested by Zampori, Dotelli, and Vernelli (2013). A share of 16% of hemp shive production was assumed to be available for construction based on the years 2010 and 2013 as suggested by Carus and Sarmento (2016). Uses in other sectors are not necessarily dependent on hemp shives and alternative raw materials could be used. This is because hemp shives are still considered a waste product, meaning it is realistic to allocate the entire production of hemp shives to the construction sector.

Cork from oak savannas

The model considers that to harvest the bark of cork oaks, which grow in large cork savannahs mainly in the western Mediterranean Basin, specific harvest cycles need to be followed (Gil, 2015). The regional share of cork production was derived from Aronson, Pereira, and Pausas (2009) and multiplied with the annual cork production for the EU stated by Bugalho et al. (2011). Currently 72 % of produced cork is used in the wine industry, followed by the construction sector, with 25 % where cork is used to manufacture products for floors, thermal insulation and coverings (APCOR, 2019).

3.5 Carbon uptake in biogenic materials

To estimate the carbon uptake through plant growth, the carbon content of the biomass (hemp, straw, cork, and timber) was multiplied with the amount of biogenic raw material demanded by the construction activities of the EU. The raw material demand is limited by the available raw material supply. For this purpose, the cumulative CO_2 uptake from biomass regrowth until 2050 was calculated.

4 RESULTS

The cumulative mass of CO_2 that can be potentially stored in wood and bio-based construction products by 2050 was estimated for the four alternative construction solutions in EU-28, as well as the corresponding land required to grow the biomass and fulfil the annual demand of biobased construction materials.

Fig. 2 shows the land available and required to supply the annual material demand, as well as the total cumulative mass of CO_2 that can be stored in construction products by 2050. The land available to supply wood and straw is more than sufficient to fulfill the full demand from construction. In particular, the land needed to supply roundwood for timber, sawn wood and insulation is 23% of the total land available for construction, meaning that neither land pressure nor cross-sector competition is expected if the TIM construction alternatives are largely used to fully supply the construction demand. Similarly, straw is largely available in Europe, and the construction sector requires only 12% of the land today available for construction if STR construction alternatives are used. Contrary, the current land to supply both hemp and cork insulation in HEM and COR solutions are far to be sufficient to fully supply the material demand. Namely, in case of HEM only 1% of the land needed for material supply is available for construction, while for COR the available land for oak savannas covers 2.2% of the land demand.

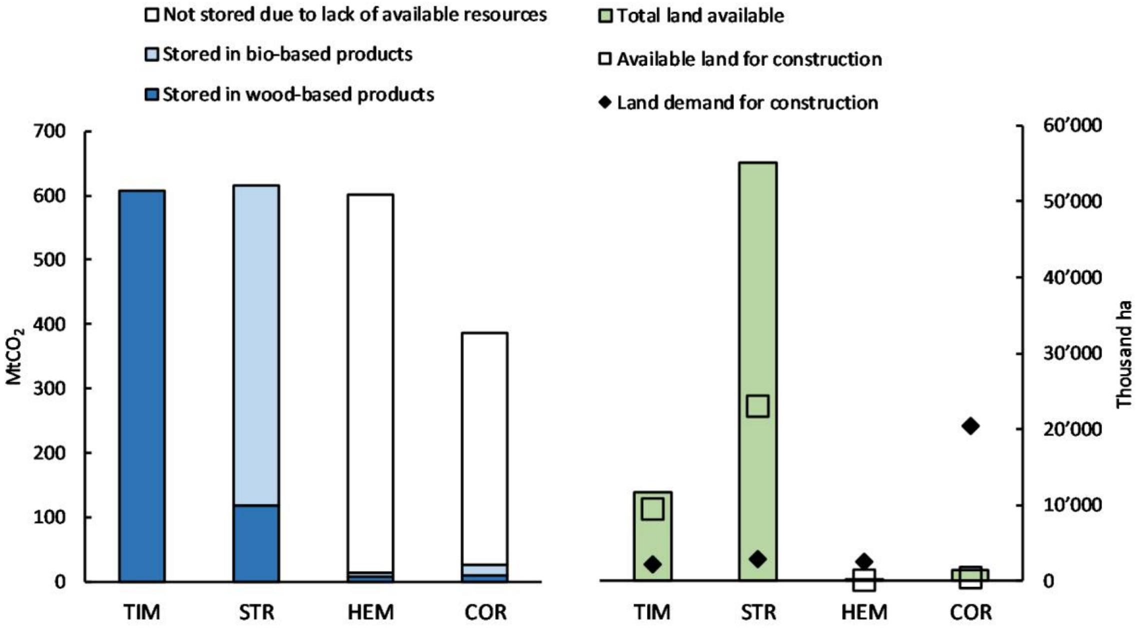

Fig. 2: Land requirement and land availability in Europe to supply the annual demand of biogenic resources for the four alternative construction solutions under study and cumulative carbon storage potential for the four alternative construction solutions under study by 2050.

In case of TIM, STR and HEM, roughly the same amount of CO_2, between 602 and 616 Mt CO_2, can be ideally stored, while a slightly lower value is expected for COR, 386 Mt CO_2, due to the higher thermal proprieties of cork insulation, which, compared to alternative insulations, requires less material to reach the same U-value. Contrary to TIM and STR, the cumulative mass of CO_2 ideally stored in HEM and COR is strongly limited by the availability of land for growing the resources, since only 2% and 4% respectively of bio-based material can be supplied for construction, limiting the possibility to effectively store the carbon in construction products.

5 CONCLUSIONS

This paper investigates the land use consequences of adopting four alternative construction technologies, based on wood (TIM), straw (STR), hemp (HEM) and cork (COR), for new construction and renovation in EU by 2050. For this purpose, the evolution of the EU building stock was modeled and the consequences from the annual material requirement on availability of raw resources and land pressure was evaluated. Moreover, the cumulative mass of CO_2 that can be potentially stored in the stock was calculated and linked to the relative land occupation, in order to estimate the space efficiency of each alternative. The analysis showed that the amount of land currently available for growing wood and straw is sufficient to fulfil the whole material demand for construction in EU. Moreover, both TIM and STR do not contribute to generate land competition with other industrial sectors since an advanced infrastructure network is already developed for timber supply and a large share of straw is currently without a value. Contrarily, the availability of land for growing raw materials for HEM and COR is far to meet the future construction demand. In particular, the land needed for hemp shives production covers only 2% of the whole demand and its future development is currently limited in many Countries by the stringent legislations. Similarly, only 4% of cork can be supplied for building insulation due to the low coverage of oak savannas, mostly located in southern dry regions. Even if TIM showed the best space efficiency coefficient, STR appears as the most promising solution since a slightly higher amount of carbon can be stored in the structures, and especially in the thermal insulation. Contrarily, only a marginal amount of carbon can be stored in HEM and COR solutions, due to the lack of available land for growing biobased materials.

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