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Negative Emission Potentials Using Biogenic Building Materials - A Case Study from Denmark

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Abstract. *Significant reductions in carbon footprint can be achieved by increasing the use of biogenic materials in construction. In biogenic materials, carbon is embedded as long as the materials are not biologically degraded, and they consequently act as carbon reservoirs that keep* CO_2 *out of the atmosphere. The reservoirs of carbon are maintained if the biogenic materials during maintenance and renovation are replaced by similar ones. Buildings containing more wood, straw, and other biogenic materials and less concrete, steel, and mineral wool are therefore part of the way forward for a sustainable restructuring of the construction industry. Until now, the main focus has been on reducing energy consumption of buildings, while less focus has been on energy consumption and the climate impact from the production of materials and the construction process itself. This paper examines the potential carbon reservoir in the building stock in Denmark for the next 100 years. In detail the paper describes potential building components made from biogenic resources, outlines the necessary amounts and qualities of biogenic materials, and summarizes the available biogenic resources. The article is based on the conditions for construction in Denmark and the opportunities Denmark has as an industrialized agricultural country with a long coastline, which can be utilized in the production of biogenic resources for manufacturing of building materials.*

Keywords: *Negative Emissions, Negative Emission Technology (NET), Carbon Dioxide Removal (CDR), Carbon Sink, Reservoir, Biogenic materials, Building stock, Resources, Building components.*

1 Introduction

The climate crisis is created by the human needs for materials, energy, and food for a continuously growing global population. The production of these goods has resulted in increasing emissions of greenhouse gases (GHG) from especially the combustion of fossil fuels such as coal, oil, and gas (Friedlingstein 2022). To avoid the most pessimistic future climate scenarios, it is necessary to reduce GHG emissions from society and to capture CO_2 and keep it out of the atmosphere by storage.

Buildings containing more wood, straw and other biogenic materials and less concrete, steel, and mineral wool are part of the way forward for a sustainable restructuring of the construction industry. As the world's population increases and more people move into cities, the need for new housing increases. Until the year 2050, approximately 50,000 new homes will have to be built globally every day to meet the need (Smith 2010). This corresponds to 550 million new homes in the next 30 years, in addition to office buildings, schools, and hospitals. Until now, the main political focus has been on reducing energy consumption of buildings, while there has been less focus on energy consumption and the climate impact from the production of materials and the construction process itself. This despite the fact that 50-70% of a new building's climate impact over its lifetime has been inflicted during the building process and prior to its use (Andersen et al. 2021).

Significant reductions of the carbon footprint can be achieved by increasing the use of biogenic materials in construction (Churkina et al. 2020, Hafner and Schäfer 2017, Himes and Busby 2020). Procurement and processing of biogenic materials is typically less energy intensive than for materials such as steel or concreate leading to significant potential emission reductions when substituting such materials e.g. with wood (Leskinen et al. 2018). Furthermore, plants absorb CO_2 by photosynthesis when they grow. They fix carbon from CO_2 in their chemical building blocks, e.g., cellulose, hemicellulose, and lignin while emitting oxygen (O_2). Thus, plant-based resources consist of approximately 50% (wt.) carbon captured from atmospheric CO_2. In this way, biogenic resources can help change the construction sector from being a significant emitter of CO_2eq to constitute a reservoir of carbon captured from the atmosphere (Churkina et al. 2020). If the biogenic materials during maintenance and renovation are replaced by similar ones, the reservoir is maintained and carbon is kept away from the atmosphere.

The built environment is a significant part of society's assets, both in terms of the value of the buildings and employment in the construction sector, including maintenance and renovation. There are also many additional occupations linked to the built environment, and there are many people who makes a living from being part of the construction industry. This applies, among other things, to material producers, subcontractors, craftsmen, engineers, architects, clients, and the financial markets in connection with priorities, mortgages, and transfers of property. A change in construction to increased use of biogenic materials thus relates to changes in several sectors of society, including changes in the provision of the necessary resources, which in the future will involve the cultivation and harvesting of biomass from agriculture, marine resources, and forestry.

This paper examines the potential carbon reservoir in the Danish building stock for the next 100 years. The calculated potential is based on that of an industrialized agricultural country with a long coastline, and a construction practice configured around the intensive use of concrete, brick, tails, steel, and mineral wool.

2 Biogenic Material Requirements for Low- and High-Rise Buildings

The material requirement per square meter of floor area for low-rise and high-rise buildings, see Table 1 was based on data for a single-family house. The house was examined for possibilities to be built by known biogenic materials meeting similar properties (Rasmussen et al. 2022).

For high-rise buildings, it was assumed that the material requirements for thermal insulation, facade cladding, internal partitions, and floors was the same as for low-rise buildings, whereas the material requirement for the load-bearing structure was based on results from D'Amica and Pomponi (2020). Material requirements are shown in Table 1 (Rasmussen et al. 2022).

Table 1. Material requirements for low-rise and high-rise buildings in mass per square metre of floor area.

Component	Low-rise [kg/m^2]	High-rise [kg/m^2]
Facade cladding	8	8
Fiber insulation	48	48
Board materials	28	28
Construction wood	41	90
Wooden floor	9	9

3 Biogenic Resources

Denmark is located in a temperate climate zone characterized by relatively moderate mean annual temperatures, with average monthly temperatures above 10 ˚C in their warmest months and above −3 ˚C in their colder (Trewartha and Horn 1980). Most regions with a temperate climate present four seasons, and temperatures can change greatly between summer and winter (McColl 2005). The Danish geography is characterized by flat, arable land, sandy coasts, low elevation, and a long coastline of 8593 kilometer compared to the relatively small size of the country of 43.098 sq. kilometer. Agricultural land takes up 61% of the total land area while forest land take up 15%. The main agricultural crops include grain, silage-maize and rape seed (Statistics Denmark 2023).

Biogenic resources relevant for manufacturing building materials in Denmark include the annual biomass crop from agriculture such as straw, reeds, flax, and hemp and perennial woody forest biomass as wood as well as marine resources such as eelgrass, seaweed, and shells from shrimps, mussels, and fish bones.

4 Needed Biogenic Material

Based on the amount of material required for low-rise and high-rise buildings per floor area (Table 1), material requirements at component level were determined. Numbers were based on data from Statistics Denmark (BYGB34), which showed that between the year 2000 and 2022, the total floor area, excluding basement area, grew with an average of 4.6 and 1.9 million m^2/year for low-rise and high-rise buildings, respectively. Assuming the average increase in future floor area will be constant, the annual material requirement for the substitution of conventional building materials with biogenic materials, based on current technologies, was estimated at a total of 978,000 tons/year, fiber insulation and structural parts taking up the lions share (Table 2).

The use of marine resources and its potential for the build environment are not known. Currently, the foot protein, MFP is extracted from the staple threads (byssus) of mussels, which is the basis for the development of different types of glue (Fan *et al.* 2021). Byssus makes up for approximately 14% of a mussel's weight. Furthermore, chitosan can be used as a non-toxic, antimicrobial and biodegradable biopolymer, i.e., as a binder in bio-based thermal insulation material (Mati-Baouche *et al.* 2014).

Table 2. The annual requirement for materials on a component-level to replace conventional building materials with biogenic materials based on current, known use of materials (Rasmussen et al. 2022).

Component	Materials needed [Tons per year]	Suitable biogenic materials
Facade cladding	~51,000	Wooden boards, reed
Fiber insulation	~320,000	Wood fibers, flax, hemp, straw, paper
Board materials	~190,000	Wood, flax, hemp, straw in the form of fibres, shavings or veneers
Structural system	~360,000	Wood, glulam, CLT[1], LVL[2]
Flooring	~57,000	Wood

[1] Cross Laminated Timber [2] Laminated Veneer Lumber

5 Carbon Sink Potential

The change from conventional building materials to biogenic materials in the specified construction parts does not happen suddenly. Assuming the transition to biogenic materials, is linear over a ten-year period, biogenic materials are fully phased in by the year 2032. After 2032, new constructions will store carbon equivalent to 1.8 million tons of CO_2eq/year. The following decades, stored carbon will drop to 1.7 million tons of CO_2eq/year over the next 30-50 years, depending on the lifespan of the main structure. Hereafter, the annual carbon storage will decline as a result of a balance between the supply of biogenic carbon from new constructions and the diffusion and combustion of biogenic carbon from demolition, after end of life. Assuming the lifespan of the facade materials to be 20 years and the end of life of the main constructions to be 50 years, the carbon sink will store an amount equivalent to approximately 88 million tons of CO_2eq. Assuming end of life of the main constructions to be 75 years, the carbon sink will store approximately 130 million tons of CO_2eq, see Figure 1 (Rasmussen et al. 2022).

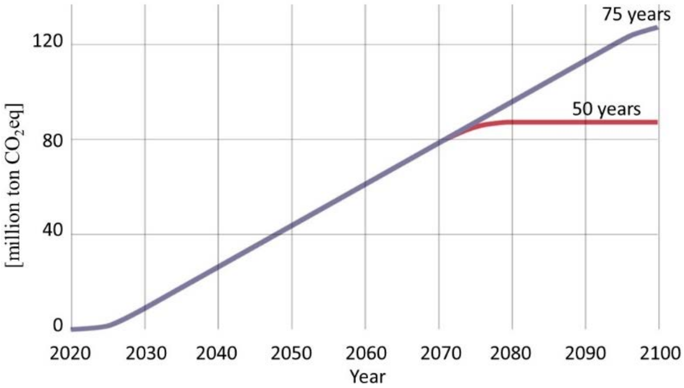

Figure 1. Carbon storage in new construction in Denmark from 2020 to 2100 using biogenic materials based on current, known use of materials.

For the calculations, it is assumed that carbon makes up for approximately half of the dry plant material. Since the plants only utilize the carbon from captured CO_2 and releases the oxygen (O_2) again, the mass of a plant material's carbon corresponds to approximately 3.7 times more CO_2. Thus, a plant absorbs approximately 1.8 kilograms of CO_2, utilizes 500 grams of carbon and releases 1.3 kilograms of oxygen when it produces 1.0 kilogram of plant material from water (H_2O) and CO_2.

6 Available Biogenic Material

Table 3 shows the approximate current national production of materials used in construction and the estimated potential increase related to components, mainly based on wood and straw. The figures do not cover the total production, as some wood materials are used in other sectors of the industry, e.g., furniture production and packaging. The production of boards for facade cladding is not known, whereas it was estimated that a third of the sawn softwood becomes strength-graded structural wood. The rest that goes into construction as non-structural wood, amounts to approximately 72,000 tons per year, a figure not accounted for in Table 3. The potential increase of the production of wood was based on the refinement of existing resources, only (Rasmussen et al. 2022).

Table 3. Current Danish production of wood materials used in construction, as well as potentials to increase this production from various material streams without reducing the supply of materials to other parts of society (Rasmussen et al. 2022).

Component	Production [Tons per year]	Increase potential [Tons per year]	Suitable biogenic materials
Facade cladding	Not known	~22,000	Roundwood that is exported
Fiber insulation	0	~225,000	Fibers from offcuts at sawmills[1]
		~42,000	10% of energy wood from forestry
		~340,000	10% of unused straw
Board materials	~50,000	~100,000	Pure recycled wood for energy
		~340,000	10% of unused straw
		~22,000	Mountain eelgrass
Construction wood	~36,000	~22,000	Roundwood that is exported
Wooden floor	~28,000	~4,000	Roundwood exported[2]

[1] Assumed material loss of 10% when cutting sawmill logs of softwood and hardwood.

[2] Assumed material loss of 30% when converting from sawn hardwood to flooring material.

For structural wood and facade cladding, an increased production can come from the net export of non-processed conifer roundwood, which constitute 39% of the Danish production of roundwood. For wooden floors, an increased production can come from the corresponding net export of hardwood logs, which constitutes 14%. Offcuts from the production of sawn wood constitute a large resource of high-quality wood fibers for e.g., fiber thermal insulation or board materials. Only about half of a piece of roundwood ends up as sawn wood, while the offcuts are often used for energy or fiber boards. In addition, there are around 100,000 ton of reclaimed wood waste annually, which is turned into energy, even if it has a quality that can be reused, e.g., for sheet materials (Rasmussen et al. 2022).

Towards the year 2050, there is a potential to increase the aquaculture production of mussels up to between 275,000 and 400,000 ton per year (Petersen *et al.* 2021a), which constitutes an available resource of mussel shells of up to between 110,000 and 160,000 ton per year.

Beachcast eelgrass as a resource is expected to be unchanged in Denmark in the future (Petersen *et al.* 2021b), as is chitosan.

7 Discussion

An overview of available biogenic resources, Table 3 shows a great potential for a considerable production of biogenic building materials from forestry, agriculture, and marine environments. Since the biogenic resources are renewable and can be cultivated, this resource will not be depleted, but be available recurringly from the same land area, as long as the area is managed sustainably. The analysis shows that pure fractions of wood biomass can fulfill a large part of the material requirement for all other product types than materials for load-bearing constructions. Supplemented with biogenic resources from agriculture such as straw, the need for sheet materials and fiber for thermal insulation material for the low- and high-rise buildings could be met by the Danish production alone. In order to meet the need for materials for load-bearing structures, imports of i.e., construction wood are necessary, see Table 2, but can be reduced by greater Danish processing of lower quality assortments of wood, for use in e.g., glulam or CLT elements.

Based on the material requirement for a full biogenic construction practice, the building stock could store carbon equivalent to 1.8 million tons of CO_2eq/year from 2032 and in the following decade, declining to 1.7 million tons of CO_2eq/year over the next 30-50 years. In comparison, the current consumption of concrete in Danish constructions causes a CO_2 emission of 1.5 million ton of CO_2eq/year (Thrane *et al.* 2019). However, this carbon emission will decrease in a biogenic construction practice as a result of the reduced use of concrete. Currently, 57% of the emissions from Danish concrete use derives from buildings, whereas the rest comes from infrastructure (Thrane *et al.* 2019). A greater use of biogenic materials will thus be able to significantly reduce and store carbon captured from atmospheric CO_2 in new constructions, corresponding to slightly more than the total CO_2eq emissions from the current Danish consumption of concrete.

The total carbon storage capacity was found to be 88 to 130 million tons of CO_2eq depending on the lifetime of the main constructions.

On top of that, there is a potential for further use of marine resources, which are currently not particularly known or used. In particular, the shells from common blue mussel (*Mytilus edulis*) can be used, as gravel, as the capillary breaking layer at the lower part of the slab on ground (Martínez-García *et al.* 2020). With a resource of mussel shells of up to between 110,000 and 160,000 tons per year, and estimated that around 38 tons of shells are required for the ground cover for a single-family house, the resource can, if fully exploited, support op to 3-4,000 houses per year.

8 Conclusions

Buildings containing more wood, straw or other biogenic materials and less concrete, steel and mineral wool are part of the way forward for a sustainable restructuring of the construction industry. Significant reductions of carbon footprints can be achieved by increasing the use of biogenic materials. Examining, under Danish conditions, the opportunities of using biogenic material from forestry, agriculture and marine environments for manufacturing of building materials, the potential carbon reservoir in the building stock was shown to be between 88 and

130 million tons CO_2eq by 2100. This assumes that the average growth in the floor space is constant, and that conventional building materials are substituted with biogenic materials by 10% every year over a 10-year period. The amount of stored carbon depends on the life span of the main constructions, with the low estimate referring to a life span of 50 years and the high to a life span of 75 years. By 2032, with the transition to biogenic building material completed, the new constructions will store an amount of carbon equivalent to 1.8 million tons of CO_2eq per year, declining to 1.7 million tons of CO_2eq per year over the following 30-50 years. The estimated amounts of stored carbon build on the assumption that the lifespan of the facade materials was 20 years.

As carbon is embedded in biogenic materials, and as long as the materials are not combusted or otherwise decayed, the carbon remains embedded, acting as a carbon reservoir keeping CO_2 out of the atmosphere.

The reservoir of carbon is maintained as long as the biogenic materials during maintenance and renovation are replaced by similar ones.

National biogenic resources can meet a major part of the material demand required for all other types of building products than material for load-bearing constructions. In order to meet the need for materials for load-bearing structures, imports of construction wood may be necessary but can be reduced by greater Danish processing of lower quality assortments of harvested wood, for use in e.g., glulam or CLT elements.

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