Material diets for Climate-Neutral Buildings

Olga Beatrice Carcassi[1], Guillaume Habert[2*], Laura Elisabetta Malighetti[1], Francesco Pittau[1,2]

[*] Corresponding author: Institute of Construction & Infrastructure Management, Chair of Sustainable Construction, ETH Zurich, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland , mail: habert@ibi.baug.ethz.ch, phone: +41 44 633 0560

[1] Department of Architecture, Built environment and Construction engineering (ABC), Politecnico di Milano, Via G. Ponzio 31, 20133 Milan, Italy

[2] Institute of Construction & Infrastructure Management, Chair of Sustainable Construction, ETH Zurich, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland

Abstract

The climate crisis is urging us to act fast. Buildings are a key leverage point to reduce greenhouse gas (GHG) emissions, but the embodied emissions related with their construction remain often the hidden challenge of any ambitious policy. Since a complete material substitution is not possible, we explore in this paper a material greenhouse gas (GHG) compensation where fast growing bio-based insulation materials are used to compensate building elements which necessarily release GHG. Different material diets as well as different building typologies are modelled to assess the consequences in term of bio-based insulation requirement to reach climate-neutrality. Our results show that it is possible to build climate-neutral buildings with sufficient energy performance to fulfil current standards and with building components thickness within the range of current construction practices. This paper evidences that it is technically feasible and that climate-neutrality in construction sector without a radical technology breakthrough.

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1. Introduction

The climate crisis is prompting an intensive examination into the reduction of anthropogenic greenhouse gas (GHG) emissions [1]. Since government agreed to keep Global Warming “well below” 2 degree Celsius [2], the question of budgets and orientations for future industries have become more stringent [3]. The new Green Deal in EU [4] and many national carbon-neutral initiatives have been engaged [5,6]. Although current efforts are still clearly not in line with planetary boundaries [1], the objective of a net-zero emissions target by mid-century is an accepted goal.

Buildings are clearly identified by policy makers as a key leverage point to reduce GHG emissions [7]. However, the different stakeholders such as portfolio managers, national political leaders, heads of industry, civil and building engineers, and designers do not include the same activities under the topic called “buildings”. Sometimes only the emissions related with the use of buildings are included, e.g. C40cities strategies [8], also called operational emissions. Sometimes emissions related to cement and steel production are targeted, e.g. European Trading Scheme—ETS, but this will include building construction along with other activities such as infrastructure or automobile production [9,10]. Sometimes, the production of goods related to construction and operation of buildings within a Country are included but the imports are excluded, e.g. UK carbon roadmap [11]. This creates confusion as it is difficult to grasp the boundaries of what is considered [12]. The prevailing confusion becomes an obstacle, because actors do not have a complete picture of the field of action corresponding to their perspective and their tasks. This leads to an increased risk of lock-in for the building sector which could achieve a carbon-neutrality target for the operation of building [13] but exceed emissions budgets due to the use of materials of these very same energy efficient buildings [14,15]. Here we explore the consequences in term of material choices in order to reach climate-neutrality at the building scale.

2. Existing climate-neutral strategies in the built environment

Strategies for mitigating embodied building emissions currently focus on the reduction of building construction and demolition waste, i.e. extending the existing building life and reuse of existing structures [16], on the enhancement of the material efficiency, i.e. using less of the same material while providing the same service [17], or material substitution, i.e. using alternative materials with lower embodied emissions [18]. Although these strategies could reduce by 50% the emissions for construction, they cannot reach net-zero emissions [19]. For example, most buildings require cement for concrete foundation or structure and a complete decarbonization is not possible due to energy intensive processes for manufacturing and emissions related to calcination reaction

[20,21]. New frontiers for carbon-neutral concrete solutions have been explored [22,23], but cannot cope with the scale of construction boom due to future urbanization [24] and the pace of decarbonization required to stay within planetary boundaries [25]. A replacement of concrete by timber in construction is an interesting option as it simultaneously reduces the emissions coming from concrete production and allows to store carbon in the building stock. Buildings can then be considered as a global carbon sink [26], but the question of resource availability limits the extend of a full transition from concrete to timber for structural materials [27]. Actually, depending on the local condition, on the economic constraints and the resource availability, timber cannot be imposed everywhere in the World without the risk of reducing carbon sink from forests as it is already observed in Europe over the last 5 years [28]. In the Global South, bamboo is a promising solution to avoid massive deforestation of tropical forest [26,29]. Nevertheless, concrete will remain the reference material for a majority of construction even though low carbon concrete can be implemented [19]. Definitely, most of carbon intensive materials currently used in construction will be adopted in future, with a influence on the whole building mass sometimes significant [30].

Looking for analogies with other human activities [31], we would like to position the debate in this current paper on the appropriate material *diet* required to build climate-neutral buildings. Since a complete structural *material substitution* is not possible, what we suggest here is rather a *material GHG compensation*. In fact, recent studies demonstrated the efficiency of substituting carbon intensive materials with fast-growing, or herbaceous, bio-based ones, e.g. hemp, straw, etc., due to their carbon removal potential and reduced life-cycle emissions [32]. The advantage of choosing these biomass instead of wood ones is that they exhibit a shorter rotation period to regrow (1 year), hence an higher yield [27]. They are usually by-products of croplands that can be transformed in high-value applications [33], which avoid a land use competition between buildings and food production. Moreover, inside the controversy either to consider or not the biogenic carbon in the different bio-based product life-cycle stages [34], Guest and co-authors showed that by adding the time factor with the regrow of plants and considering the temporary carbon storage during building's life cycle, the herbaceous biomass are the most promising to regenerate the climate [35]. To calculate this potential, they defined an index, the biogenic global warming potential (GWP_{bio}), which is based on the storage period of harvested biomass in the building and the rotation of the species needed to restore the carbon in the land. Herbaceous biomass exhibit great potentials as insulation material [36–38] and, by promoting their use, we can couple the need to lower the operational emissions in buildings today while reducing the building embodied ones [39]. Unfortunately, not all the construction materials can be substituted with the herbaceous ones. Here, we propose a new way of approaching the design of climate-neutral buildings based on the use of the adequate amount of herbaceous materials, or climate negative, as insulation to compensate the emissions resulting from the GHG source ones, or climate positive, rather than designing the amount of insulation material to reach a given energy performance. We design for climate-neutrality rather than for energy efficiency as it is clear that in the current situation GHG emissions has to be the primary objective [40].

3. Climate-neutrality at building scale using climate negative materials

In this paper, we assess three different material diets by decomposing the building in the elements that play the major role in building embodied emissions [41], namely above ground and underground structure, windows, water proofing membranes, finishing – internal pavement, wall and ceiling and exterior wall – and insulation. By mixing more conventional, e.g. concrete, and unconventional, e.g. bamboo, ingredients as building materials, we design different material diets to achieve the climate-neutrality. The material diets are defined according to the gradual use of herbaceous materials, from the insulation up to the structural level: mineral, woody and herbaceous (Figure 1a). Each material is classified as *climate positive* or *climate negative* (Figure 1b) according to the Net-GWP calculated that is used in the climate-neutrality equation (see Methods).

For all the diets, the insulation materials were the herbaceous ones, in particular cotton stalks, straw and hemp characterized by different carbon removal capacity (see Methods). By leveraging their negative GWP_{bio}, this research aims at quantifying the herbaceous biomass needed to bring to net-zero the total embodied emissions of buildings. This original approach differs radically from conventional design logic as the insulation thickness is dimensioned in order to compensate emissions from other building components.

We test the climate-neutrality of the three material diets on new residential buildings in the European context. We focus on Europe because the European Union aims to become the first climate-neutral continent by 2050 with the “Green Deal for Europe” in line with the Paris Agreement [4]. However, the building decomposition we use (namely structure, finishing and insulation), with insulation designed to compensate emissions and not to fulfil the energy requirements of building codes, makes theses building typologies much more appropriate to a wider context than Europe. This aspect is discussed later. In particular, we use the four typical Building Typologies (BT), namely single-family house (SFH), terraced house (TH), multi-family house (MFH) and apartment block (AB), to create the geometrical reference buildings form the Tabula/Episcope database [42]. We report the results only for the statistically significant values of these data sets, which are the Lower Whisker (0^{th} quartile), Upper Whisker (4^{th} quartile) and Median (2^{nd} quartile) (see figure SI 1 and Table SI 1 in Extended methods in SI) to obtain three geometrical configurations representative of the whole dataset. For these geometrical configurations, we compute the material quantity needed and the related GHG emissions (kg CO_{2e} /kg) which is depending on the potential carbon uptake of materials. After having calibrated the climate-neutrality for the three diets, we evaluate the architectural feasibility of having these buildings in the urban context in terms of volume of materials that will occupy the city spaces and resulting wall thicknesses that should also respond to the operational energy targets.

4. Which material diet for climate neutral buildings

4.1. Material quantities

The climate-neutrality assessment is based on the logic of defining the material intensity, here expressed per mass basis and normalized according the Reference Energy Surface (RES) (kg/m^2_{RES}), to achieve net-zero GWP for buildings.

Figure 2 shows material quantities required for climate-neutral buildings depending on the diet choice and the building typology. *Mineral* diets are the most mass-intensive ones for all the building typologies. The insulation required to bring to zero the total building emissions ranges between 102 and 238 kg/m^2_{RES} depending on the BT when straw is used as insulation. On the contrary, the *Woody* diets are the least mass-intensive ones and require between 48 to 102 kg/m^2_{RES} of straw insulation to reach climate neutrality. The *Herbaceous* are closer to the woody ones (85 to 132 kg/m^2_{RES}) but the engineered bamboo still exhibits high GWP due to the material transportation from the Asiatic counties [43]. Note that that future local cultivation of bamboo in some southern European regions could contribute to decrease the current carbon intense profile of Asian laminated bamboo products and would bring the bamboo buildings closer to woody diet. Structure and foundation are controlling building weight, regardless the diets. On the contrary, the windows and the membrane have small influence to balance the diets.

4.2. A ratio between climate positive and climate negative materials per building

To make a selection of climate negative materials for building envelopes, we perform an architectural feasibility analysis. First, we convert the mass quantities in volumetric ones to define the spatial footprint that designing climate-neutral buildings would demand. Secondly, to compensate the use of climate positive materials with the climate negative ones, we calculate necessary volumetric ratios among these two material families (Figure 3a). The more the value is close to 1, the more the two material volumes (positive vs. negative) are similar. The values are usually smaller than 1, except the low Whisker geometrical configuration for the MFH in the *Herbaceous* diet. It means that climate negative materials volumes are larger than climate positive ones. Depending on structural choices, an average ratio is ranging between 0.16 to 0.36, meaning that every cubic meter of a carbon emitting material, e.g. glass, concrete, etc. should be compensated by 2.5÷6 m^3 of climate negative materials, i.e. bio-based ones.

Additionally, results highlight that, for each diet, the insulation material choice is controlling climate negative over climate positive ratio whatever structural choice or building typology (Figure 3b). In fact, if straw is used as insulation a factor 3.2 will be required between the volume of carbon emitting materials and the volume of straw required to reach climate neutrality. A factor close to one cubic meter of climate positive for one cubic meter of climate negative can be reached for very efficient bio-based materials such as cotton, while a factor nearly 7 is required for bio-based materials such as hemp.

4.3 Climate neutral for construction and energy efficiency for operation

Besides the construction feasibility in urban context, another important issue is the operational energy requirements verification. Thus, with the bio-based insulation volumes, we calculate the resulting envelope thicknesses and assess the thermal performances obtained by inserting the insulation materials in the building envelopes (façade, roof and basement) to check the operational performance. Accordingly, we evaluate if the U-value of the three different material diets' wall assembly fulfils the European high/median limit (U/value ≤ 0,35 W/m^2K [44]) (see Methods). The results (Table 1) show two possible situations. The first one is when the building respects the median U-value defined for the different European Countries and fulfil the operational energy requirements with the established envelope thickness. The second one is when building does not cope with the energy requirement and therefore it would require a higher insulation level. This would contribute to an additional increment of the carbon removal potential and this extra contribution can be spent for other building component or installations, e.g. PV systems, energy storage, etc. The latter appears in very few cases, mainly for woody diets, as the demonstration that the envelope composition obtained with climate-neutral building design strategy in most of the case able to meet the energy requirements. Consequently, designing for climate-neutrality with material GHG compensation allows to reach also energy efficient buildings standards.

4.4 Envelope thickness of climate neutral buildings

We made an additional comparison (Figure 4), where we show the relationship among the ratio of climate positive and climate negative materials, and the wall thickness by varying the herbaceous insulation materials. For the hemp fibers (with the worse Net-GWP value) the wall thicknesses can reach unfeasible values as high as 4.5m depending on structural choices and building typology. The straw values stay for most of the construction solutions within an acceptable range for the wall thickness, smaller than 1 m, but can reach higher values for some AB and MFH made with a concrete structure. The use of cotton stalk results always in wall thicknesses smaller than 1 m whatever structure and BT is chosen. In Northern Europe, current constructions usually account for a wall thickness of 40/50 cm (20 cm concrete or brick and 20 cm insulation). In this paper, we show that with straw or cotton insulation, it would be possible to build similar wall dimension with timber structure. Concrete structure will require to double the insulation size (40 cm) and use efficient biobased insulation materials. A medium performance such as straw would lead to 1 m thick walls with 20 cm concrete and 80 cm straw.

5. Recommendations for immediate climate neutrality in new buildings

Our findings demonstrate that it is possible to build climate-neutral buildings thanks to the use of herbaceous bio-based materials applied as insulation. The building element dimensions can be controlled, and the thermal performance is for the majority of cases satisfied in accordance with high energy efficiency standard. As a matter of fact, contemporary buildings built with straw have similar thickness (e.g. Architect Werner Schmidt's Straw-Bale Construction with 0,80 m thick walls [45]). Hence, new climate neutral buildings would have a similar appearance as the conventional buildings currently built in Northern Countries and construction technologies already available on the market can be used. The only exception is the cross-laminated bamboo (CLB), which use as structural material for tall buildings, i.e. more than 3 storeys, is limited so far [46]. We included the scenario of having multi-story buildings with CLB in the perspective that the market will move in this direction in the near future.

According to our results, we can then build climate-neutral buildings which comply with the operational energy requirements. This avoid the lock-in situation that is feared when energy saving requirements are implemented without considering the consequential embodied emissions [12].

Regarding the structural and acoustic design, we neither dimensioned the timber and bamboo elements according to the fire safety requirements, nor checked the sound insulation of the envelope materials. Nevertheless, a passive approach has been considered by protecting walls and ceilings with gypsum fiberboards and clay plaster [47]. Another assumption we made is the possibility to adopt bio-based insulation for basement insulation, which is not recommended due to high water absorption risk and consequential fast decay. In order to reduce the risk, we added a waterproofing membrane which increase embodied emissions but remove high moisture content risks. An alternative bio-based solution would be cork due to its non-putrescible properties, but costs and availability make it difficult to reach the full European market [48,49].

Finally, it's important to mention that the GHG-fossil emission linked to the use of concrete could be further reduced by implementing low-carbon concrete. We used in this paper conventional concrete emissions but available alternatives allow to reduce by a factor-two these emissions [19,50]. This would reduce by the same order of magnitude the insulation volume and therefore lead to the possibility of building concrete climate-neutral buildings with similar wall dimension as current construction.

Our work gives a practical approach that can be used by policy makers to propose incentives for promoting climate negative technologies for the building and construction industry. Moreover, thanks to this concept, designers can be assisted during the early-design phase and become aware of the embodied GHG emissions resulting from their construction material choices and the physical ratios among the carbon positive and carbon negative ones. These preliminary considerations could guide them in the choice of the structural solutions and the resulting envelope dimensions that could be limited by urban planning regulations.

6. Methods

The study is subdivided in five main phases. First, we define the main geometric parameters of each building typologies. Secondly, we quantify the mass incidence of the structures. Thirdly, Net-GWP values of each construction materials is calculated. Fourthly, by joining all the three phases together, we perform the climate-neutrality assessment at a building level. To accomplish that goal, bio-based materials are implemented as insulation in the building envelopes, and the quantity needed to be found is its total volume and the related envelope thickness. Finally, the U-values for the resulting thickness are compared with European requirements to check the operational performance. All the data are normalized according to the Reference Energy Surface (RES).

6.1 Geometric parameters for the Building Typologies

The geometric information for the four European Building Typologies (BT) are extracted from the TABULA/Episcope database [42], more precisely in the excel file "tabula calculator.xlsx".

In particular, the data extrapolated from this database that are used in this study to set the dimensions of the configurations for the different BT are:

- RES [m^2],
- Number of conditioned stories (NCF) [-],
- Floor Surface (SSCF) = Roof Surface (SR) = Basement Surface (SB) [m^2/m^2_{RES}],
- Exterior Walls Surface (SW ALL) [m^2/m^2_{RES}],
- Window Surface (SWIND) [m^2/m^2_{RES}],

(see paragraph 1.1 in SI for the extrapolation of data that are taken into account and the simplifications made for defining the final geometric parameters).

Since the variation range of the collected data is quite wide for each of these parameters, we analyze the data statistically by sampling the maximum (upper Whisker), minimum (lower Whisker) and a median values of the data sets. This is done graphically with the aid of Box and Whisker plots. The upper Whisker corresponds to the Maximum Data Point, which is the end of the 4th quartile. The lower Whisker corresponds to the Minimum Data Point, so the 0th quartile. Whereas the median is the 2^{nd} quartile. In Figure S1 in SI, it is possible to see all the representations for the 4 geometrical parameters.

There, the windows' values are assigned in a second moment. For the purpose of this study, final geometrical configurations aim at minimizing, maximizing and having an average value of the building material emissions. Usually the material used for the windows have high environmental impacts. For this reason, we calculate the emissions resulting for finishing and waterproofing membrane (see paragraph 6.3) and the structures (see in paragraph 6.2) for the three diets, and, later, we assign the higher window surfaces to the most polluting geometric configurations for each building typology (see final parameters in Table S1 in SI)

6.2 Structural mass incidence

In order to define the carbon footprint of the different structural systems, a parametric model is set up to quantify the material incidence per gross floor area of a given structure over the total number of stories of the building. Four different structural configurations are defined, two foresee buildings with up to 20 stories, while the other two are designed for a maximum building height of 10 stories. Reinforced concrete as well as timber and engineered laminated bamboo are the materials chosen for the above ground structures, while the foundation is constantly in reinforced concrete, with eventually deep foundation out of steel when needed.

The parametric model is coded in MATLAB [51] (see SI Annex A for the script) and defines the minimal load-bearing areas of columns, beams, walls and slabs, to support the structural loads under two combinations: service state limits and ultimate state limits. The model is based on simplified modular geometries, with a mesh 10x10m and a floor height fixed of 3,2m and variable number of storeys in a range between 1 and 20 (Figure S2 in SI). One of the most important parameters which influence the structural design when biogenic materials are used is the fire resistance. No specific design for fire safety is performed, since all structural elements results protected with fireproof finishing.

Reference numbers of conditioned storeys are the one collected and elaborated in the geometric parameter phase (see Table S1 in SI) and applied to the four schemes. The four different schemes for the three diets are shown in Figure S 3 in SI. Scheme 1 (RC) is designed as in-situ cast concrete columns and walls supporting a reinforced concrete plate. Scheme 2 (PTF) represents a platform timber frame system composed of walls with offsite assembled load-bearing elements (massive sawn timber and OSB panels) and beams in solid wood. Engineered cross-laminated bamboo is used in scheme 3 (CLB), which is modelled as load-bearing walls and floor panels. Finally, scheme 4 (PB) represents a posts and beams frame structure with diagonal bracing and floor panels, which is used for high-rise structure both with timber and cross-laminated bamboo.

RC scheme is computed for tall buildings up to 10 stories as well as the PB scheme, while PTF and CLB are limited to a maximal height of 10 stories. The vertical loads are transferred via the slabs to the vertical supports and down to the bottom of the structure into the foundation. Where the walls and the beams of the bio-based schemes act as linear supports, the columns used in the RC scheme are combined together by using strong bands in the concrete slabs. All slabs are designed as one-directional load bearing elements and act as two-span system for the RC scheme and as single-span systems for the other three schemes in bio-based materials. This choice is due to the offsite assembly of the bio-based slab elements, facilitating the onsite installation. The modular structure of all schemes has a footprint geometry of 10 meters in both directions, with a distance of 5 meters between the columns or the walls. An exception is the PB scheme with its wide spans of 10 meters between the columns. All spans are assumed by the authors, in order to facilitate the assembly of the structure modules into different geometrical combinations and to represent the widest range possible of existing buildings. On top of that, the resulting floor area of 100 m^2 is an easy value for future parameters to be multiplied with or divided for, facilitating so the readability and interpretation of the results. All the values are finally normalized according to the gross floor area of the module to obtain normalized values and are applied to the different building typologies according the diets and building height (see Figures S4 - 8 in SI).

6.3 Construction materials and Net-GWP computation

In this study, we define the materials according to their carbon removal or releasing potentials. More precisely, we divide the materials used into three main categories: i) non-bio-based, ii) slow-growing bio-based, and iii) fast-growing bio-based, according to their resulting Net-GWP (see paragraph 6.3.1).

Non-bio-based are materials not composed by biogenic mass. In this investigation we assume:

- glass for the windows;
- PVC, wood-aluminum and wood window frames;
- polyethylene water proofing membrane;
- steel for the reinforced concrete structure;

- gypsum plasterboard, mineral plaster, ceramic tiles and clay plaster as internal ceiling and wall finishing.

The bio-based ones are divided in slow-growing, or “Woody”, and fast-growing, or “Herbaceous”, which is related to their rotation period. The rotation expresses the time that the plant needs to completely regrow before being clear-cut and harvested again.
Plants, whose time needed to regrowth is larger than 10 years, contribute to provide slow-growing bio-based materials, e.g. timber, wood fibers, cellulose flakes, etc.
In this project, five types of forest products are adopted for different applications:

- solid wood used for structural and finishing applications. It is subdivided in softwood and hardwood;
- glued laminated timber, also known as glulam, is well suited for structural applications;
- oriented strand board (OSB) is used for structural applications;
- cross laminated timber (CLT) is used for structural applications.

All these types differ in the fabrication process, nevertheless, are available worldwide. In this project, the regeneration period of coniferous forests for softwood supply, used in load-bearing elements and finishing, is assumed to be 90 years [52].
Plants with regrowth period lower than 10 years are categorized as fast-growing bio-based materials. The capacity to remove the CO_2 due to the restoration of the carbon in the land under a time horizon of 100 years is much higher than the one in slow-growing materials (e.g. forest products), since their regeneration is much shorter than the expected lifetime of a building, and thus is able to compensate with negative emissions the positive GWP of products manufacturing. Here we assumed:

- bamboo for structural or finishing applications with a regeneration period of 5 years;
- straw, hemp and cotton stalks as insulation materials with a regeneration period of 1 year.

We collected the essential information of the materials used in the project in Table S2 in SI.
The λ-values have been collected only for finishing and the insulation materials (see paragraph 3.1 in SI) since they were useful to evaluate the thermal performance of the external envelope, while the rest of data are used to evaluate the Net-GWP for each material.

6.3.1 Net-GWP Calculation

The calculation of the Net-GWP of construction materials, which measures the consequence on climate change of fossil GHG emissions and biogenic CO_2 emissions/removals during the lifecycle of a product, followed three steps. First, we collected the GWP at 100 years (GWP_{100y})

index of each material expressed, according to the IPCC 2013 assessment method [53], in kg CO_{2eq}/kg. Afterwards, the calculation of the CO_2 removal of bio-based materials has been performed, according to the GWP_{bio} method [35]. And finally, the two obtained values were summed up to obtain the net-value, here called Net-GWP.

Life-Cycle Assessment_ LCA is a method, which measures the environmental impacts a product or a service generates and can cover a lot of stages. In this study, the cradle to gate stages are taken into account as well as the waste disposal, according to EN 15804 standard [54], namely:

- Resource Extraction (A1)
- Transport (A2)
- Production (A3)
- Waste Disposal (C1-4)

All the GWP values for non-bio-based materials are assumed from the KBOB [55]. Regarding bio-based materials, KBOB contains only a few values for common insulation materials as straw or cork. In order to enlarge all targeted materials, we performed a scientific and commercial literature review. For the unconventional insulation materials, we were not able to collect all the necessary data, thus they needed a deeper research into the literature, which we did for each material according to the following steps:

1. GWP values were researched in the KBOB for each material.
2. If the unconventional material is not present in the database, then the research has been extended to Environmental Product declarations (EPDs) in the market.
3. If GWP values cannot be found in any EPD, then the research has been extended to scientific papers.

Carbon Sequestration_ Bio-based materials can help decreasing the GWP by uptaking the CO_2 and keep it stored in a construction product for a long period. More precisely, the biomass is stored in the anthroposphere as a harvested product, e.g. solid wood, while the carbon uptake happens in the biomass that is regrowing through the photosynthesis, reducing the atmospheric carbon dioxide concentration. To account for this biogenic CO_2 storage in the anthroposphere, we use the method proposed by Guest and coauthors [35] and depicted in Figure S9 in SI. It proposes a GWP_{bio} index for considering the consequential GWP of storing 1 kg of biogenic CO_2 for a given storage period in a 100 years' time horizon. Thus, the method combines through a Dynamic LCA (DLCA) the annual CO_2 uptake in the land via biomass growth and the delayed biogenic CO_2 emissions through biomass incineration at end of life of a building, here assumed equal to 60 years [56]. The GWP_{bio} index can assume a positive value if the storage period is short and rotation long, while can reach negative values, up to -1 $kgCO_{2eq}$, for long storage and very short rotation periods. Hence, to remove from the atmosphere the equal amount of carbon that is stored in bio-based products, fast-growing spices need a shorter time than slow-growing ones, resulting in a more advantageous effect in lowering the radiative force remaining in the atmosphere in a short period.

In this work, the storage period in the anthroposphere is assumed to be 60 years (building lifespan[56]), while the rotation depends on the different regeneration periods described above for each material used. Therefore, by using Figure S9 in SI, we extract the GWP_{bio} for every bio-based material by entering in the graph at 60 years and extracting the GWP_{bio} index for the different biomass according their rotation period (e.g. solid wood with a rotation period of 90 years has a GWP_{bio} index equal to -0.10 $kgCO_{2eq}$ per $kgCO_2$ stored).

To calculate the carbon sequestration of bio-based materials, the following Equation (1) is considered, which calculate the mass of CO_2 that can be stored in the final product:

$$\mathrm{CO}_{2,storage} = \rho_0 \cdot CC \cdot BC \cdot 3.67\ [kg \cdot m^{-3}] \qquad (1)$$

Where:

- ρ_0 is the dry density of the material, in kg/m^3;
- CC is the carbon content of the biogenic material;
- BC the biomass content of the finished product;
- 3.67 is the molar weight ratio between CO_2 and C [43].

Since the exact moisture content of biogenic materials is often unknown, we suppose a 20% moisture content for structural materials, 15% for finishing and membrane, and 10% for isolations. Therefore, we calculated the dry volumetric mass according to the CEN/TC 124 [57], as reported in the following Equation (2):

$$\rho_0 = \rho_{\omega<25} \cdot \frac{00+0,45\cdot\omega}{100+\omega}\ [kg \cdot m^{-3}] \qquad (2)$$

where:

- $\rho_{\omega<25}$ is the wood density at moisture content lower than 25%, in kg/m^3;
- ω is the moisture content, in %.

Consequently, as reported in Equation (3), the contribution on GWP from carbon uptake can be calculated by multiplying the CO_2 storage with the GWP_{bio} index, which is a portion of the total carbon storage a material could reabsorb in the land during the storage period in 100 years of time horizon:

$$GWP_{bio} = GWP_{bio}index \cdot CO_{2,storage}\ [kg \cdot m^{-3}] \qquad (3)$$

Finally, summing up the fossil $CO_{2\text{-}eq}$ emissions, which contribute to the GWP as defined by IPCC 2013 method (GWP_{IPCC}), and the CO_2 uptake from biogenic regeneration in the land (GWP_{bio}), we obtain in the final Net-GWP value (GWP_{net}), according to Equation (4):

$$\mathrm{GWP}_{net} = \mathrm{GWP}_{IPCC} + \mathrm{GWP}_{bio} \qquad (4)$$

The Net-GWP, which is the most important output of this materials section, for every single material used in this study has been illustrated in Table S2 in SI both per mass and volumetric values. Non bio-based materials do not contribute to carbon storage or uptake, therefore their Net-GWP values are always positive, as equivalent to GWP_{IPCC} value. Contrary, every bio-based material used in construction can account for a removal potential and, depending on their carbon fossil emissions and their storage and rotation period, their Net-GWP values can be either negative or positive.

6.4 The climate-neutral building assessment

After the computation of total mass of construction product used in the building, we multiply it for each Net-GWP value for the four BT and the three material diets as follows in the climate-neutrality Equation (5):

$$GPW_{net,b}\left[\frac{kg\ CO_{2\,eq}}{m^2{}_{RES}}\right] = \sum_i GWP_{net,i} \cdot m_i \qquad (5)$$

where:

- $GWP_{net,b}$ is the specific Net-GWP value calculated for each diet
- $GWP_{net,i}$ is the Net-GWP value of each material, expressed in $kgCO_{2eq}/kg$
- m_i is the mass of each building material

In this work we consider five construction elements: i) above and underground structure, ii) windows, iii) water proofing membrane and iv) finishing. The total building positive GWP, based on fossil emissions, need to be neutralized by the fast-growing bio-based insulation (see Figure S10 and Table S3 in SI). The mass of insulation to be installed in the envelope that is able to compensate through negative CO_2 emissions the positive GWP of material production and final disposal can be calculated according to the following Equation (6):

$$m_{ins}\left[\frac{kg}{m^2{}_{RES}}\right] = \frac{\sum_i^{n-1} GWP_{net,i}}{\left|GWP_{bio,ins}\right|} \qquad (6)$$

where:

- m_{ins} is the mass of insulation needed to achieve the climate neutrality in 100 years

- $GWP_{net,i}$ is the net-GWP value of a generic non-insulating material, expressed in $kgCO_{2eq}/m_2RES$
- $GWP_{bio,ins}$ is the GWP_{bio} value of the selected insulation material, expressed in $kgCO_{2eq}/kg$

We perform this calibration with three herbaceous bio-based insulation materials. From Table S2 in SI we choose the cotton stalks, which exhibits the highest carbon storage value, straw, which is the closest value to the median one calculated for only the negative values, and hemp fibers, which exhibited the lowest value.

6.5 Architectural feasibility assessment

To obtain the ratio among the positive and negative materials (showed in Figure 4), we summed the materials that exhibit a positive Net-GWP and the ones with a negative Net-GWP (see Table 2 in SI).

As a conclusion, we evaluated the architectural and thermal feasibility of the quantity of insulation obtained. First, we calculate the wall thickness according to the following Equation (7):

$$t_w\ [m] = \frac{m_{ins}}{\rho_{ins}} \cdot S_e \qquad (7)$$

where:

- t_w is the mean thickness of the envelope
- m_{ins} is the mass of insulation, in kg
- ρ_{ins} is the volumetric mass of the insulation, in kg/m^3
- S_e is the total surface of the envelope, in m^2

The total surface of the envelope is the sum of the exterior wall, roof and basement area, since we made the assumption of filling each envelope element with a constant insulation level.

The U-value of the resulting elements is calculated (See paragraph 1.4 in SI) and compared with the European energy requirements to check whether these buildings fulfil the energy requirements, or we need to increase the insulation level providing extra material. The U-values across European Countries vary County by Country as depends on climatic conditions [44]. We statistically calculated the median European energy requirement for low-energy building, which is equal to 0,35 W/m^2K, and highlight the cases where the U-values excess the limit and don't' guarantee a minimal energy performance. The essential data for these calculations can be found in Table S 5 in SI (mass element and envelope surface – sum of the roof and exterior wall area) and in Table S 2 SI (material density).

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Additional information

Extended data is available for this paper.

Supplementary information is available for this paper: Supplementary Methods and Results, Figs. S1–10 and Tables S1 and 5.

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