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How Can a Climate-Neutral Building Look Like?

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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. Considering that a complete material substitution is not possible, we explore in this paper a material GHG compensation where fast-growing bio-based insulation materials are used to compensate building elements that necessarily release GHG. Looking for analogies with other human activities, 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. The material diets are defined according to the gradual use of herbaceous materials, from the insulation up to the structural level: omnivorous, vegetarian and vegan. Our results show the relationship in terms of volume between the climate intensive materials and the climate-negative ones needed to neutralize the overall building GHG emissions. Moreover, they suggest how climate-neutral building can look like and that it is possible to have climate-neutral buildings with wall thickness within the range of current construction practices.

1 Introduction

Considering the greenhouse gas budget left (Habert et al., 2020) that can be emitted before reaching the tipping point, we need to reach the climate-neutrality by reducing to net-zero the GHG emissions in every sector of the economy within 50 years. Buildings are a key leverage point to reduce greenhouse gas (GHG) emission, but the embodied emissions, related to their material manufacture, transportation, construction and end-of life disposal, remain often the hidden challenge of any ambitious policy. In fact, conventional building materials, such as concrete, steel, or mineral insulations, represent a massive source of GHG emissions due to both their manufacturing energy intensive processes (De Wolf et al., 2020) and releasing of chemical reactions (Davis et al., 2018). Here, we referred to them as climate-positive materials and they were divided according to their GWP_{net} values in high and low climate intensive materials. To mitigate the embodied emissions, recent studies demonstrated the efficiency of substituting climate-positive materials with bio-based ones, e.g. wood and straw, due to their carbon storage potential and reduced life-cycle emissions (Churkina et al., 2020; Pittau et al., 2018). However, Pomponi and coauthors (Pomponi et al., 2020) demonstrated that the related increase of wood in the construction industry could intensify the deforestation and illegal logging, whereas they suggest the use of fast-growing (or herbaceous) bio-based materials, such as hemp and straw, that have greater yield. Moreover, inside the controversy either to consider or not the biogenic carbon in the different bio-based product life-cycle stages (Hoxha et al., 2020), Guest et al (Guest et al., 2013) showed that by adding the time factor with the regrow of plants and considering the carbon storing within the building boundaries in the life cycle assessment (LCA) methodology, the herbaceous biomass are the most promising to regenerate the climate. To calculate this potential, they defined an index, the biogenic global warming potential (GWP_{bio}), to consider the storage period of harvested biomass with different rotation periods in the anthroposphere as a negative value to be considered at the beginning of a classical LCA. Hence herbaceous biomass can be considered as climate-negative in virtue of the carbon uptake through photosynthesis and they exhibit a great potentials as insulation material (Schiavoni et al., 2016). Unfortunately, not all the construction materials can be substituted with the herbaceous ones. Consequently, we aimed to 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 neutralize the emissions resulting from the climate-positive ones. To this end, different material "diets" were designed according to the gradual use of herbaceous materials, from the insulation up to the structural level: omnivorous, vegetarian and vegan (*Fig. 1*). For all the diets, the insulation materials are the herbaceous ones, in particular we used three different biomasses, namely cotton stalks, straw and hemp fiber. By leveraging their negative GWP_{bio}, this research quantified the herbaceous biomass needed to bring to net-zero the total embodied emissions of buildings. In literature, there is no similar approach to design the insulation finalized to reach the building climate-neutrality instead of the energetic performance.

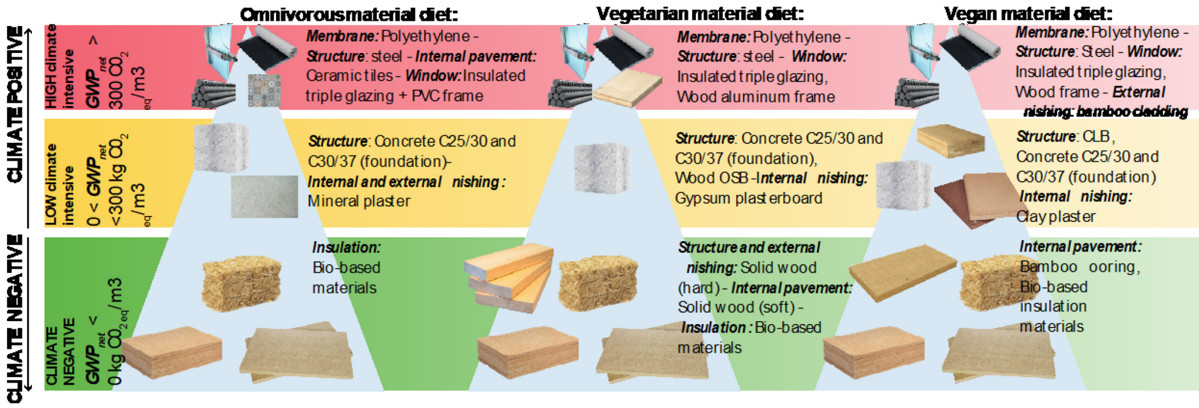

Fig. 1: From the left: omnivorous, vegetarian and vegan material diets. Materials' classification according the Net-GWP value, that divides them to Climate Positive or Climate Negative materials

2 Method

2.1 Building models

We tested the climate-neutrality of the three material diets on new residential buildings in the European context. Therefore, the four typical European Building Typologies (BT), namely single-family house (SFH), terraced house (TH), multi-family house (MFH) and apartment block (AB), were used to create the geometrical reference buildings form the Tabula/Episcope database (Intelligent Energy Europe, 2016). The data extrapolated from this database used to set the dimensions of the building models for the different BT are: Reference Energy Surface (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}]. Moreover, the single area for every floor was kept the same for each storey. All these geometrical data collected from Tabula/Episcope database were normalized according to the RES, except for the NCF. RES is the total surface of the conditioned building, which in this case is the single conditioned storey surface multiplied by the number of conditioned storeys. Usually, the materials used for the windows have high environmental impacts. Hence, first the emissions resulting for finishing, waterproofing membrane and the structures for the three diets were calculated, and, later we assigned the higher window surfaces to the most polluting geometric configurations for each building typology. In this study, only the MEDIAN geometrical configuration for the 4 BT were reported as the statistically significant values of data sets, for a total of four building models (*Tab. 1*).

Tab. 1: Geometrical parameters of the four building models

MEDIAN	SFH			MFH			AB			TH		
	OMN	VEGT	VEGA	OMN	VEGE	VEGA	OMN	VEGE	VEGA	OMN	VEGE	VEGA
RES [m²]	145			842			1702			137		
NCF	2			4			5			2		
SSCF = SR = SB [m²/ m²RES]	0.50			0.25			0.20			0.50		
SW ALL [m²/ m² RES]	1.13			0.68			0.65			0.72		
SWIND [m²/ m² RES]	0.15	0.16	0.15	0.16	0.17	0.16	0.17	0.17	0.17	0.15	0.15	0.15

2.2 Structural volume incidence

To define the carbon footprint of the different structural systems of the three material diets, a parametric model was set up in MATLAB. The omnivorous diet was designed as in-situ cast concrete columns and walls supporting a reinforced concrete plate; the vegetarian one, as a platform timber frame system composed of walls with offsite assembled load-bearing elements (massive solid wood and OSB panels) and beams in solid wood; the vegan one, with the engineered cross-laminated bamboo (CLB) modelled as load-bearing walls and floor panels. The foundation was constantly in reinforced concrete. The parametric model defined 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 was based on simplified modular geometries, with a mesh 10x10m and a floor height fixed of 3,2m and variable number of storeys according the ones collected in in TABULA for the MEDIAN geometrical configurations. All the values were finally normalized according to the gross floor area of the module to obtain normalized values and were applied to the different BT. Since for the rest of the materials were normalized according to the RES, we assumed that the structural normalization is equal to the normalization to the RES. Therefore, the structural incidence was expressed in m^3/m^2_{RES}. In addition, no specific design for fire safety was performed, since all structural elements were protected with fireproof finishing.

2.3 GWP_{net} computation of construction materials

For the representative MEDIAN geometrical configurations of the four BT, the non-structural material volume was computed. After that, the structural and non-structural GHG emissions (kg CO_{2e} /m^3) were determined. The latter are depending on the potential carbon uptake of materials used, which have been here classified into three main categories: i) high climate-intensive, ii) low climate-intensive and iii) climate-negative according to their resulting GWP_{net} (*Fig. 1*).

GWP_{net} Calculation

The GWP_{net} of construction materials measures the consequence on climate change of fossil GHG emissions and biogenic CO_2 emissions/removals during the lifecycle of a product. To calculate it, three steps were followed. First, we collected the GWP at 100 years (GWP_{100y}) index of each material, according to the IPCC 2013 assessment method (Joos et al., 2013). Afterwards, we computed the CO_2 removal of bio-based materials according to the GWP_{bio} method (Guest et al., 2013). And finally, the two obtained values were summed up and multiply for the material density to obtain the net-value, here called GWP_{net} in $kgCO_{2eq}/m^3$.

Life-Cycle Assessment (LCA)

In this study, the cradle to gate stages (A1-3) were taken into account as well as the waste disposal (C1-4) to perform the LCA. The GWP values for non-bio-based materials have been assumed from the "*Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren*" (KBOB) (Eidgenossenschaft, 2016), which is the "Coordination Conference of Building and Real Estate Bodies of Public Builders" in Switzerland. Unfortunately, the KBOB does not contains neither a huge selection of bio-based insulation materials nor the bamboo ones. Therefore, the research was also extended to Environmental Product declarations (EPDs) (Cavac Biomatériaux, 2018) in the market, and to the scientific papers (Schiavoni et al., 2016; Vogtländer and van der Lugt, 2015). As a conclusion, three bio-based insulations with different negative GWP_{net} values were chosen to cover the material variability, namely the cotton stalks, which exhibits the highest GWP_{net}, hemp fibers, which exhibited the lowest value, and straw, with a value in between the two others.

Carbon Sequestration

Guest and coauthors (Guest et al., 2013), with the GWP_{bio} index, prosed a method that combines, by means of a Dynamic LCA (DLCA) (Levasseur et al., 2010), the annual CO_2 uptake in the land due to the biomass regrowth and the delayed biogenic CO_2 emissions through biomass incineration at end of life of a building. The storage period in the anthroposphere was here assumed to be 60 years while the rotation depends on the different regeneration periods for each material used, namely 90 years for the wood, 5 for the bamboo and 1 for the fast-growing or herbaceous species. The herbaceous spices, e.g. hemp and straw, need a shorter time than slow-growing ones (wood), resulting in a more advantageous effect in lowering the radiative force remaining in the atmosphere in a limited period. Therefore, the GWP_{bio} was extracted for every bio-based material by entering in the graph at 60 years, i.e. the chosen building lifespan and extracting the GWP_{bio} index for the different biomass according their rotation period. To calculate the carbon sequestration of bio-based materials, the following Equation (1) was considered, which calculate the mass of CO_2 that can be stored in the final product:

$$\mathrm{CO}_{2,storage} = CC \cdot BC \cdot 3.67\ [kgCO_2 \cdot kg^{-1}] \tag{1}$$

Where:

- 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 (Vogtländer and van der Lugt, 2015)

Consequently, as reported in Equation (2), the share of GWP from carbon uptake can be calculated by multiplying the CO_2 storage with the GWP_{bio} index, which is a part of the total carbon storage a material reabsorbed in the land during the storage period in a time horizon of 100 years:

$$GWP_{bio} = GWP_{bio} index \cdot CO_{2,storage}\ [kg\ CO_2 \cdot kg^{-1}] \tag{2}$$

Finally, summing up the fossil $CO_{2\text{-}eq}$ emissions, which contribute to the GWP_{100y}, and the CO_2 uptake from biogenic regeneration in the land (GWP_{bio}), the final GWP value (GWP_{net}) was obtained according to Equation (3):

$$\mathrm{GWP}_{net} = (\mathrm{GWP}_{IPCC} + \mathrm{GWP}_{bio}) \cdot \rho_0 \quad [kgCO_{2eq} \cdot m^{-3}] \tag{3}$$

Where:

- ρ_0 is the density of the material, in kg/m^3.

Tab. 2 shows the data to compute the GWP_{net} values for the construction materials chosen.

2.4 The climate-neutral building assessment

The total volume of construction products used in the building was multiplied for each GWP_{net} value for the four BT and the three material diets as showed in the climate-neutrality Equation (4):

$$GWP_{net,b} \left[\frac{kg\ CO_{2\,eq}}{m^2{}_{RES}}\right] = \textstyle\sum_i GWP_{net,i} \cdot v_i \tag{4}$$

where:

- $GWP_{net,b}$ is the specific GWP_{net} value calculated for each diet
- $GWP_{net,i}$ is the GWP_{net} value of each material, expressed in $kgCO_{2eq}/m^3$
- v_i is the volume of each building material, expressed in $m^3/m^2{}_{RES}$

The total building positive GWP, based on the high and low climate intensive material emissions, has to be neutralized by the three herbaceous insulation chosen. The volume of insulation to be installed in the envelope was calculated according to the following Equation (5):

$$v_{ins} \left[\frac{m^3}{m^2{}_{RES}}\right] = \frac{\sum_i^{n-1} GWP_{net,b}}{|GWP_{bio,ins}|} \cdot \rho_0{}^{-1} \tag{5}$$

where:

- v_{ins} is the volume of insulation needed to achieve the climate neutrality in 100 years
- $GWP_{net,i}$ is the GWP_{net} value of a generic non-insulating material, expressed in $kgCO_{2eq}/m^2_{RES}$
- $GWP_{bio,ins}$ is the GWP_{bio} value of the selected insulation material, expressed in $kgCO_{2eq}/kg$

Tab. 2: Properties of construction materials used

Materials	ρ_0 [kg/m^3]	**CC** [%]	**BC** [%]	GWP_{IPCC} [kg CO_{2eq}/kg]	GWP_{bio} [kg CO_{2eq}/kg]	GWP_{net} [kg CO_{2eq}/m^3]
Steel (reinforcement)	7850	0%	0%	0.68	0.00	5353.70
PVC Window Frame, thickness 80mm	1181.25	0%	0%		0.00	3562.50
Wood-Aluminum Window Frame, thickness 80 mm	1042.5	0%	0%		0.00	2712.50
Waterproof membrane (polyethylene)	1000	0%	0%	2.52	0.00	2520.00
Insulated Triple Glazing, thickness 40 mm	30	0%	0%		0.00	1670.00
Wood Window Frame, thickness 80mm	1002.5	0%	0%		0.00	1600.00
Ceramic tiles, thickness 0,009 m	2000	0%	0%	0.78	0.00	1555.56
Bamboo Cladding	1150	54%	93%	1.20	-0.48	364.92
OSB	605	50%	98%	0.61	-0.10	262.67
Gypsum plasterboard	850	0%	0%	0.29	0.00	249.05
Concrete C30/37	2300	0%	0%	0.10	0.00	227.70
Concrete C25/30	2300	0%	0%	0.07	0.00	170.20
Mineral plaster	1100	0%	0%	0.15	0.00	161.70
Cross Laminated Bamboo (CLB)	700	54%	98%	1.08	-0.48	100.63
Clay plaster	1800	0%	0%	0.02	0.00	41.40
Bamboo Flooring	700	54%	100%	0.92	-0.48	-21.88
Hemp fiber	82	45%	64%	0.14	-0.50	-32.11
Solid wood (softwood)	485	50%	100%	0.09	-0.10	-46.80
Straw	100	40%	100%	0.09	-0.50	-64.40
Solid wood (hardwood)	705	50%	100%	0.07	-0.10	-81.43
Cotton (stalks)	450	40%	90%	0.34	-0.50	-144.27

2.5 The architectural feasibility assessment

With the bio-based insulation volumes, the resulting envelope thicknesses were calculated by inserting the insulation materials in the building envelopes, namely façade (SW ALL), roof (SR) and basements (SB), with a constant insulation level. In this way it is possible to 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.

3 Results

Tab. 1 and Tab. 3 contain all the parameters of the MEDIAM geometrical configurations statically sampled from the TABULA/EPISCOPE database and the structural incidences. With these values and the Tab. 2 ones, it is possible to perform the climate-neutral building assessment and obtain the volume of the three bio-based materials, namely cotton stalks, straw and hemp fiber that are reported at the end of Tab. 3.

Tab. 3: Structural volume incidence resulting from the MATLAB code and the bio-based insulations resulting from the climate-neutral building assessment.

MEDIAN	SFH			MFH			AB			TH		
	OMN	VEGT	VEGA	OMN	VEGE	VEGA	OMN	VEGE	VEGA	OMN	VEGE	VEGA
Structural material volume incidence												
Steel	0.005	0.002	0.002	0.004	0.001	0.001	0.009	0.001	0.001	0.005	0.002	0.002
C25/30	0.306	0.052	0.052	0.290	0.026	0.030	0.303	0.023	0.028	0.306	0.052	0.052
C30/37	0.025	/	/	0.040	/	/	0.046	/	/	0.025	/	/
Wood OSB	/	0.074	/	/	0.047	/	/	0.047	/	/	0.047	/
CLB	/	/	0.258	/	/	0.258	/	/	0.258	/	/	0.258
Solid wood	/	0.110	/	/	0.115	/	/	0.121	/	/	0.102	/
Bio-based insulations resulting from the climate-neutral building assessment												
Cotton stalks	0.861	0.308	0.468	0.826	0.230	0.384	1.04	0.216	0.381	0.843	0.298	0.445
Hemp fiber	3.87	1.38	2.10	3.71	1.03	1.72	4.66	0.971	1.71	3.78	1.34	2.00
Straw	1.93	0.690	1.05	1.85	0.51	0.860	2.32	0.484	0.854	1.89	0.668	0.998

In particular, Fig. 2 summarizes the climate-neutrality assessment results in terms of the climate negative materials needed (three shades of green) to neutralize the emissions resulting from the high (red) and low (yellow) climate intensive materials. The Omnivorous diets are the most volumetric-intensive ones for all the building typologies, followed by the Vegan and concluding with the Vegetarian ones. In fact, the Vegan ones, that should be the more stringent due to the vast use of herbaceous materials also in the structure, still exhibit high GWP_{net} due to the material transportation of bamboo from the Asiatic countries (Vogtländer and van der Lugt, 2015).

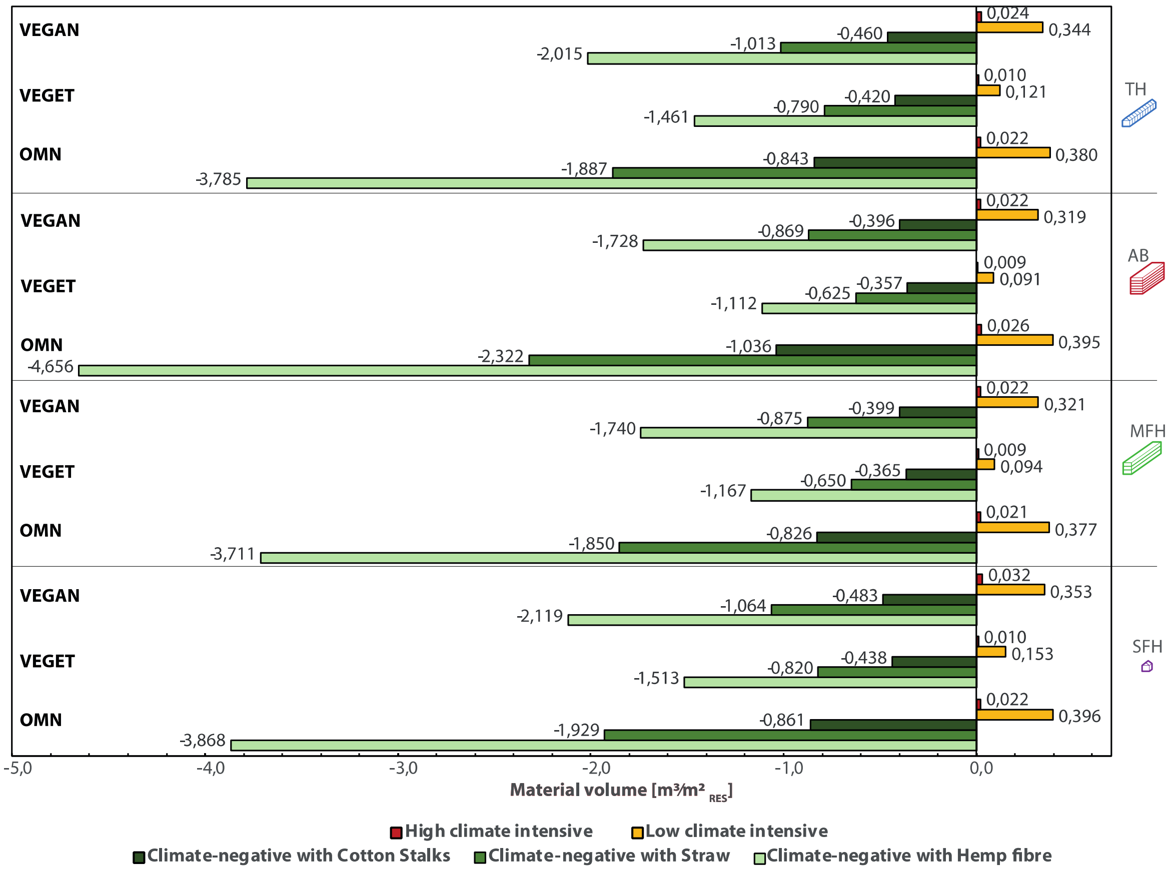

Fig. 2: Material diets showed in a positive and negative logic to reach the climate-neutrality. The quantity of materials is expressed for the 4 BT for the three diets, namely: OMN= omnivorous diet; VEGET = vegetarian diet; VEGAN = vegan diet

However, the material quantities resulting in each material diet are similar for the high, low climate intensive and negative materials no matter the BT. The high climate intensive values range between 0,026 and 0,021 m^3/m^2_{RES} for the omnivorous diets, 0,01 and 0,009 m^3/m^2_{RES} for the vegetarian ones and 0,032 and 0,22 m^3/m^2_{RES} for the vegan ones; while the low climate intensive values range between 0,396 and 0,377 m^3/m^2_{RES} for the omnivorous diets, 0,153 and 0,091 m^3/m^2_{RES} for the vegetarian ones and 0,353 and 0,438 m^3/m^2_{RES} for the vegan ones. The climate-negative insulation volumes follow a similar correspondence. Especially, the hemp fiber required are 4,656 and 3,711 m^3/m^2_{RES} in the omnivorous diets, 1,513 and 1,112 m^3/m^2_{RES} for the vegetarian ones and 2,119 and 1,728 m^3/m^2_{RES} for the vegan ones; the straw variates among 2,322 and 1,85 m^3/m^2_{RES} in the omnivorous diets, 0,82 and 0,625 m^3/m^2_{RES} for the vegetarian ones and 1,064 and 0,869 m^3/m^2_{RES} for the vegan ones; while for the cotton stalks coincide to1,036 and 0,826 m^3/m^2_{RES} in the omnivorous diets, 0,438 and 0,357m^3/m^2_{RES} for the vegetarian ones and 0,483 and 0,396 m^3/m^2_{RES} for the vegan ones. Furthermore, Fig. 2 highlights how the bio-based insulating material choice can influence the volume necessary to obtain the climate-neutrality. By selecting an insulation with the GWP_{net} value analogous to the hemp fiber, i.e. the worse one, a greater quantity of material is needed, whilst preferring a solution with a GWP_{net} value closer to the cotton stalks one can ensure a lower quantity of insulation. For the architectural feasibility assessment, our results (*Tab. 4*) demonstrate how the wall thickness vary according to the herbaceous insulation material used. In the hemp fiber insulation cases, the thickness is the most impacting since can reach the 4,43 m in case of the AB omnivorous diet, whereas by using the cotton stalks the wall would be only 0,99 m wide and 2,21 m by choosing the straw. The straw values stay for most of the construction solutions within an acceptable range for the wall thickness, smaller than 1 m. The use of cotton stalk always produces wall thicknesses smaller than 1 m.

Tab. 4: Wall thickness for the 3 material diets for the four building typologies expressed in m^3/m^2_{RES}

	SFH			MFH			AB			TH		
MEDIAN	**OMN**	**VEGT**	**VEGA**	**OMN**	**VEGE**	**VEGA**	**OMN**	**VEGE**	**VEGA**	**OMN**	**VEGE**	**VEGA**
Cotton stalks	0.861	0.308	0.468	0.826	0.230	0.384	1.04	0.216	0.381	0.843	0.298	0.445
Straw	1.93	0.690	1.05	1.85	0.515	0.860	2.32	0.484	0.854	1.89	0.668	0.998
Hemp fibre	3.86	1.38	2.10	3.71	1.03	1.72	4.66	0.971	1.71	3.78	1.34	2.00

4 Conclusion

This research shows how the material choices have a great influence on the building embodied emissions by providing a practical approach. The use of herbaceous insulation materials that are able to neutralize the GHG burden on the climate, shows that is possible to build climate-neutral buildings with contemporary construction practices. In fact, current European constructions usually account for a wall thickness of 40÷50 cm in concrete or brick buildings and even 80 cm for the strawbale buildings. At the same time, we only focused on three bio-based insulation materials, but it could be enlarged to others according to a growing data availability on their performances and embodied emissions. 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.

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