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A Life-Cycle Approach to Building Energy Retrofitting: Bio-Based Technologies for Sustainable Urban Regeneration

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Abstract. The construction sector and, more specifically, the building renovation sector plays a decisive role in the achievement of the EU targets for the reduction of energy consumption and CO₂ emissions. The main strategies implemented by the EU are aimed, on one side, at increasing the number of buildings to be renovated and, on the other, at promoting deep renovation on the existing stock. The main objective is to drastically reduce the CO₂ emissions associated with the energy consumption of buildings during their operation in consideration of the decarbonization targets by 2050. Several studies have shown that around 75% of the EU building stock needs energy retrofitting, and a significant amount of thermal insulation is expected to be installed on the building envelopes in order to decrease the energy losses. The carbon emission for the production of materials and construction might slow down the transition to a low carbon society and significantly reduce the carbon budget available by 2050. In this perspective, the paper shows the results of some recent research activities aimed at identifying alternative approaches based on the use of biogenic materials applied to the building envelope retrofitting. On one side, they meet the energy and CO₂ targets established by the EU while promoting, on the other one, sustainable regeneration processes that include, among the others, the storage of CO₂ in building elements and the efficient land use. A specific calculation tool, based on a dynamic LCA method, is introduced to holistically quantify the environmental benefits expected over time.

1. Introduction: decarbonisation of the existing building stock and deep renovation measures

It is a well-established awareness that the construction sector and, more specifically, the building renovation sector plays a decisive role in the achievement of the European targets for the reduction of energy consumption and CO₂ emissions. The main strategies implemented by the European Union are aimed, on one side, at increasing the number of buildings to be yearly renovated and, on the other side, at promoting deep renovation measures on the existing building stock [1]. The main objective is to decarbonise the building stock by 2050 by seeking a cost-efficient equilibrium between decarbonising energy supplies and reducing final energy consumption. A recent study confirmed that high energy efficient buildings after deep retrofit show multiple benefits at different scales: a considerable reduction in the overall energy demand and, consequently, a reduction of grid infrastructure and power system operational costs [2].



More than the 75% of the European building stock has been built before 1980, i.e. before the introduction of the first energy performance regulations in several EU countries [3]. Residential buildings account for the biggest segment of this stock and are responsible for the majority of the sector's energy consumption. Within the existing European stock, a large share (more than 40%) – widespread in urban areas – is built before 1960s with low insulation levels and old and inefficient systems [4]. A wide range of retrofit technologies are available and several studies have been carried out in order to identify optimized solutions in consideration of the cost-effectiveness, the improvement of energy performances and indoor comfort [5]. Because of the age of the European building stock and the new European regulations for improving the energy performance of existing buildings, there is a need of extensive solutions for the renovation of exterior walls as they offer a great potential of energy saving due to the decrease of energy losses on a greater surface, both in single housing and apartment blocks. On one hand, the renovation of residential building stock to reduce the primary energy demand represents a priority in EU-28, not only to address the carbon mitigation, but also to mobilize investments in construction [6,7]. On the other hand, when the primary energy demand of a building is reduced due to retrofitting, the contribution on carbon emissions due to insulating materials processing increases [8]. At European scale, an increased inflow of materials is expected for deep renovation scenarios in the coming years and the fossil carbon emitted by manufacturing of materials and construction might significantly affect the carbon saving from operational energy [9]. Thus, the carbon emission for the production of materials and construction is expected to slow down the transition to a low carbon society and significantly reduce the carbon budget available by 2050, i.e. the finite amount of greenhouse gases we can emit to limit global warming to 2°C [10], ratified by the Paris Agreement as the maximum possible increase without drastic consequences for human life on the planet. In this scenario, the adoption of low carbon materials able to store carbon for a long time horizon is an opportunity that should be taken urgently in order to comply with climate change target [11].

The objective of this paper is to evaluate the global warming potential of different bio-based insulation alternatives when used for the retrofitting of existing facades compared to standard synthetic insulations. More specifically, in order to properly consider the biogenic carbon, a dynamic time-dependent life cycle assessment has been introduced in order to verify the contribution of the different bio-based materials in affecting the radiative forcing over time.

2. Methodology

In this study, five envelope retrofitting solutions have been identified considering their potential for application to the external walls of typical European residential buildings, in order to improve their thermal resistance. In particular, as illustrated in Figure 1, the selected alternatives include both systems with lightweight elements that can be installed on-site and large prefabricated modules, in order to take into account also high-quality renovation options [12].

The Functional Unit (FU) assumed for materials and life cycle impacts assessment (LCIA) is the same for all the investigated alternatives and is defined as follows:

- 1 m² of wall;
- U-value = 0.125 W/m²K;
- non load-bearing structure;
- identical fire safety;
- 60 years lifespan assumed as the same of the reference service life (RSL) of residential buildings.

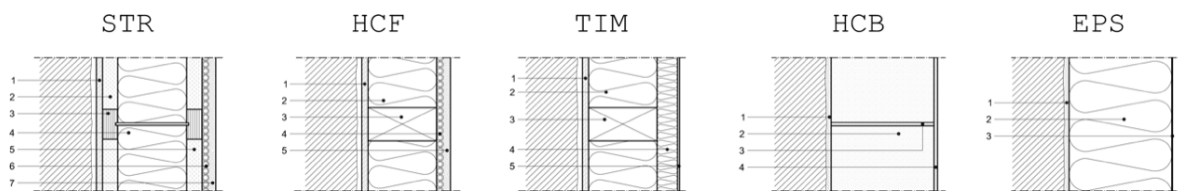


Figure 1. The five alternatives for the external insulation systems investigated in the study: STR (bio-based, prefabricated), HCF (bio-based, prefabricated), TIM (mixed mineral+wood, prefabricated), HCB (bio-based, on-site), EPS (synthetic, on-site). Description of materials are listed in Table 1.

2.1. External insulation system for envelope retrofitting: description of the 5 alternatives

In the first four alternatives, different biogenic products are used for the thermal insulation and, in the case of prefabricated modules, for the structural elements as well. The thickness of the insulation for each alternative is a variable and has been chosen considering the required U-value of the walls in the different European Member State after renovation. In particular, for the identification of prevailing wall assemblies of existing building stock in EU, data from relevant databases have been considered, specifically the databases developed in the TABULA and EPISCOPE projects [13], and the information for the different States grouped according to the seven prevailing climatic conditions – as shown in Figure 2 – in the framework of a geo-clustering approach [14].

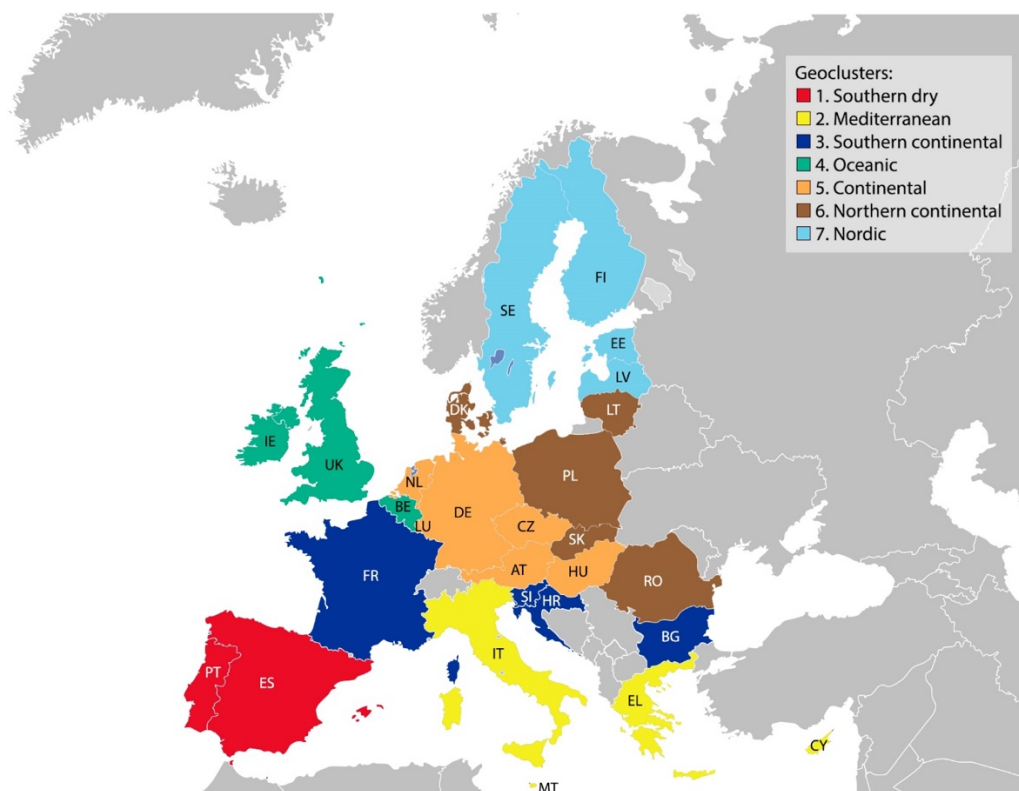


Figure 2. The European states grouped in seven geoclusters per similar climate conditions.

2.1.1. STR – I-joist frame with pressed straw. An engineered I-joist frame is filled with straw which is pressed to a density of 100 kg/m^3 to support a thick clay plaster layer mixed with straw on both sides. The structure is finished internally with an oriented strand board (OSB) to create a regular surface on the existing wall. After the assembly, the module is transported on the construction site and, once installed, is finished with a lime plaster on a reed mat.

2.1.2. HCF – Timber frame with injected hempcrete. A timber frame is filled with an insulation mortar of hemp shives bound with lime-based binder. The mass ratio of shives to binder is 1:1. Assembly and drying process is carried out off-site. Anchoring and plastering are executed on site.

2.1.3. TIM – Timber frame with mineral insulation. A timber frame is filled with a layer of glass wool. An additional wood fibreboard insulation is connected to the frame to increase the thermal performance of the wall and create a regular support for the external finishing.

2.1.4. HCB – Hempcrete blocks. After a preliminary preparation of the external surface of the existing wall, precast pre-dried hemp-lime concrete blocks are laid in order to wall up an insulation layer. A lime based plaster and render is applied as finishing.

2.1.5. EPS – Expanded polystyrene for external thermal insulation composite system (ETICS). An ETICS with polystyrene boards has been assumed as a reference system with an amount of bio-genic material equal to zero. EPS panels are applied on the existing wall, after the preparatory works on the existing wall surface, with an external render.

Table 1. Materials inventory for the five alternatives for exterior walls retrofitting.

Cod.	Material	Thickness mm	Density kg·m ⁻³	Thermal conductivity W·m ⁻¹ ·K ⁻¹	Mass kg·m ⁻²	Life span yr	Waste treatment category
01. STR – I-joist frame with pressed straw							
1	OSB	18	650	0.13	12	60	Wood
2	Light clay straw	45	600	0.16	27	60	Recycling potential
3	Timber I-joist	var*	500	0.12	var*	60	Wood
4	Straw chips	var*	100	0.051	var*	60	Fast decomposing
5	Light clay straw	45	600	0.16	27	60	Recycling potential
6	Reed mat	20	145	0.06	3	30	Fast decomposing
7	Lime plaster	20	1800	0.67	36	30	No potential
02. HCF – Preassembled frame with injected hempcrete							
1	OSB	18	650	0.13	12	60	Wood
2	Injected hempcrete	var*	200	0.054	var*	60	Recycling potential
3	Timber frame	var*	500	0.12	var*	60	Wood
4	Reed mat	20	145	0.06	3	30	Fast decomposing
5	Lime plaster	20	1800	0.67	36	30	No potential
03. TIM – Timber frame							
1	OSB	18	650	0.13	12	60	Wood
2	Glass wool	var*	18	0.038	var*	40	No potential
3	Timber frame	var*	500	0.12	var*	60	Wood
4	Wood fibreboard soft	60	130	0.05	8	40	Wood
5	Cover plaster	6	1800	0.8	11	40	No potential
04. HCB – Hempcrete blocks							
1	Cement mortar	10	1800	0.80	18	60	No potential
2	Hempcrete blocks	var*	330	0.07	var*	60	Recycling potential
3	Light lime mortar	-	500	0.1607143	6	60	Recycling potential
4	Lime plaster	20	1800	0.67	36	40	No potential
05. EPS – Expended polystyrene for external thermal insulation composite system (ETICS)							
1	Cement mortar	1	1800	0.80	2	60	No potential
2	EPS	var*	16	0.04	var*	40	Combustible
3	Base plaster	2	1800	0.80	4	40	No potential

2.2. Dynamic Life Cycle Assessment

In order to analyse and compare the environmental impact of the different alternatives, a time-dependant life cycle assessment has been performed in order to properly account the biogenic CO₂. Normally, impacts of biogenic CO₂ are neglected in a traditional LCA since the same amount of CO₂ released from biogenic sources is assumed to be absorbed during the regrowth of the biomass, and the net emissions are therefore zero [15]. This widely used assumption about biomass carbon neutrality and climate neutrality has been increasingly criticized [16]. For this reason, a dynamic life-cycle assessment (DLCA) approach has been adopted for taking into account the timing of carbon uptake and GHG emissions, which is particularly relevant for bio-based products that temporarily store carbon and delay emissions [17]. The method was implemented taking into account only the GHG effect of CO₂ and methane (CH₄), since it was observed they contribute for the largest share of the radiative forcing impact due to the high amounts released in the process. A Time horizon (TH) of 200 years was assumed, in order to include into the calculation both short-term (2050) and long-term (2100) effects.

2.2.1. System boundaries. The LCA model was developed according to the standard EN 15804:2012 (CEN/TC350, 2012), and includes the following:

- *product stage* (modules A1-5) – extraction, transportation, production supply to the building site, and construction;
- *usage stage* (modules B1 and B4) – emissions by replacement of exhausted elements and uptake by the use of biomass and lime-based products;
- *end of life* (EoL) stage (modules C1-4) – wall demolition, transportation to waste treatment, sorting, waste processing, and final disposal.

Additional benefits, such as avoided virgin materials due to recycling or avoided emissions through energy recovery, are accounted for separately as additional loads and benefits beyond the system boundaries (module D).

2.2.2. Calculation model. The ΔR_T needed to meet the expected U-value limits in the future was evaluated for each European Member State, as well as the surface of the external walls that is expected to be yearly renovated. The two values were aggregated together according to the clustering process for each Geocluster, and then correlated to the materials inventory for the five alternatives in order to define the annual material intensity. A life cycle inventory (LCI) from modules A1 to C4 was performed to calculate the impact inventory, measured in terms of kg of GHG emitted per year. In parallel, three different carbon sinks were modelled and included into the analysis in module B1: two sinks from biosphere (forest and crops) and one from technosphere (lime), to take into account carbonation of lime-based products. On the base of the materials required, the annual carbon uptake, typically time depending, was measured and the resulting carbon removal were correlated to the GHG emitted by renovation of the stock to define a time depending matrix which was used as input to address the dynamic impact assessment. Finally, the results, expressed in instantaneous and cumulative radiative forcing, were converted into kgCO_{2-eq} according to the IPCC method in order to measure the global warming potential (GWP).

2.2.3. End of life (EoL). Typically, the GWP calculation through a DLCA is particularly sensitive to the assumption concerning EoL treatment. A full understanding of the sensitivity of the results to the disposal scenarios (DS) is needed to succeed a careful interpretation [18]. At the EoL, the following five different waste treatments (WT) were assumed:

- WT1 – inert landfill: considered for materials that do not release hazardous substances after building deconstruction;

- WT2 – sanitary landfill: considered as temporary storage for reactive materials as biogenic products;
- WT3 – composting facility: considered as alternative to WT2, where the full amount of methane produced during biological decay is captured and reused as bio-methane as substitution of natural gas;
- WT4 – municipal incineration: consists of incineration of waste with thermal energy recovery;
- WT5 – recycling: consists of generating new products from waste materials.

From the combinations of different waste treatments illustrated in Figure 3, the following three alternative disposal scenarios (DS) were defined:

- DS1: landfill;
- DS2: energy recovery;
- DS3: material recycling.

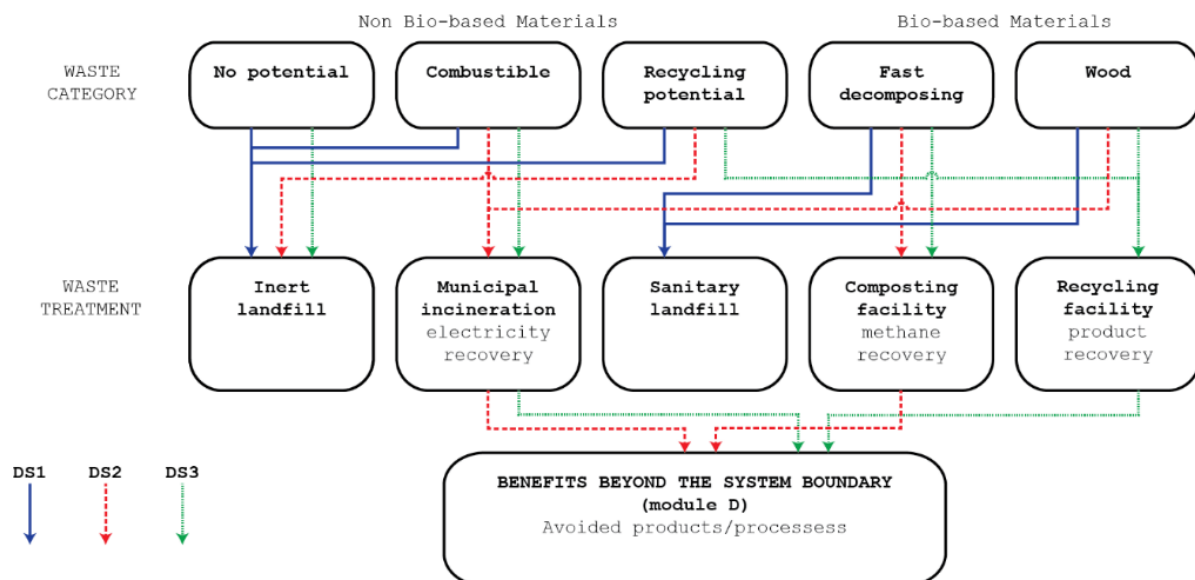


Figure 3. Waste treatments and disposal alternatives for each end of life disposal scenario [19].

3. Results

The instantaneous radiative forcing – which contributes to alter the Earth’s radiative equilibrium, forcing temperatures to rise or fall – was calculated for each wall alternative and for the three DSs through the DLCA calculation model. The values of instantaneous radiative forcing calculated per year are summed to show the cumulative effect of the released emissions during the life cycles of the five construction alternatives. Finally, the results are converted into GWP according to the IPCC method in order to quantify dynamically the carbon emissions/removals.

The dynamic values of the GWP for each alternative and each DS are shown in Figure 4.

After an initial positive emission in 2018 of 7.64 Mt of CO_{2,eq}, the GWP impact of straw-based alternative (STR) rapidly decreases, with a carbon neutrality which is achieved after just 4 years. Then, the effect of removing carbon from the atmosphere continues with the same positive trend. It is expected that by 2050, almost 100 Mt of CO_{2,eq} are removed from the air due to the massive use of straw. It is roughly equivalent to a reduction by 27% of carbon emissions from industrial processes and product use in 2015 in EU-28, or 23% of emissions from agriculture in the same year, which is equal to 3% of total carbon emissions from all sectors. In 2050, the materials required to renovate the

residential building stock with HCF still lead to a positive emission, with a GWP of 3.55 Mt of CO_{2,eq} that are expected to be cumulatively emitted since 2018. In 2100, the GWP registers a negative value, with a mean removal potential of almost 54 Mt of CO_{2,eq}, which is equal to a reduction by 17% of carbon emissions from industrial processes and product use, or 15% of emissions from agriculture in the same year or 2% of total carbon emissions from all sectors in EU-28 in 2015. A similar trend is observed for HCB, even if a negative GWP is achieved in 2050 due to the higher amount of carbon sequestered by hempcrete blocks. For the last two alternatives, no carbon removal is expected by 2100. Even if in TIM a large amount of bio-based material is used, the long time required to reabsorb the carbon in the forest by tree regrowth (a rotation period of 45-120 years was assumed in this calculation) drops down the positive effect of storing carbon in products.

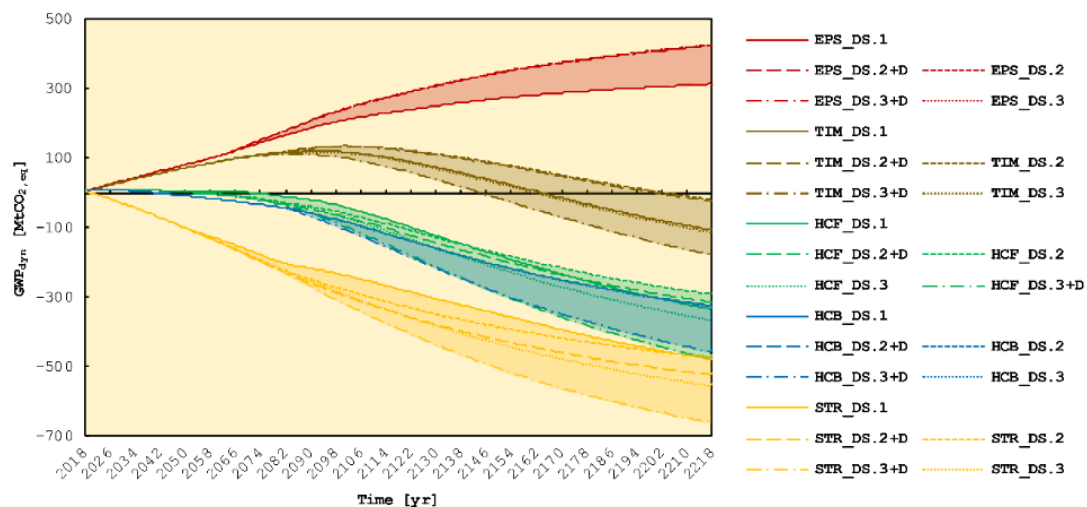


Figure 4. Dynamic GWP for all scenarios. DS1, 2, 3 stand for disposal scenario with landfill, energy recovery and material recycling respectively. DS +D stand for disposal scenario with module D and DS for disposal scenario without module D.

4. Conclusions

Fast-growing bio-based materials, such as hemp and straw, have a considerable potential of capturing and storing carbon when used as thermal insulation for renovating existing facades in Europe. Unlike forest products, they do not require long rotation periods, and the capacity for storing carbon increases when they are used as thick insulation for exterior walls due to the rapid CO₂ uptake in the crop fields. Among the five alternatives selected, STR showed the most promising potential, being the only one able to remove by 2050 3% of the CO_{2,eq} emitted from all sector in 2015. The other two bio-based alternatives based on hemp start to be carbon negative slightly after 2050, with a carbon storage potential in 2100 of roughly 2% of the emissions from all sectors in EU-28 in 2015. Contrarily, timber-based construction always contributes to increase the emissions from renovation in a short and mid-term prospective, and the carbon capture and storage capacity of wood, if only timber is used in the structure, seems cannot be proposed as a valid strategy in Europe to contribute achieving the Paris Agreement targets. Clearly, EPS, which is nowadays the most used renovation system widely spread in Europe for energy retrofit, reduces the extra loads that the existing facades should support, but cannot contribute to actively remove CO₂ from the air.

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