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Retrofit as a carbon sink: the carbon storage potentials of the EU housing stock

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Abstract

In the next decades, a large share of residential buildings in EU-28 is expected to be renovated to achieve the 2 °C target requested by the Paris Agreement by 2050. Bio-based materials used for increasing the thermal insulation and temporary store carbon in construction elements might be a valuable opportunity that can contribute to accelerate the transition to a zero-carbon society. This article investigates the effect of massively storing carbon in bio-based construction products when used for the renovation of existing facades. Five alternative construction solutions were compared, three with a large amount of fast-growing biogenic material used as insulation, one with timber used for the frame and additional fibrewood as insulation, and the last one with synthetic insulation. A statistic-based Geocluster model was developed to predict the future material flow for building renovation in EU-28 and a dynamic life cycle assessment performed in order to verify the contribution of construction materials in reducing/increasing the carbon emissions over time. The results show that fast-growing biogenic materials have an increased potential to act as a carbon sink compared to timber. In particular, if straw is used as an insulation material, the capacity to store

carbon from the atmosphere is effective in the short-term, which represents an important strategy towards the Paris climate Agreement goals.

Keywords: Building renovation; Europe; Biogenic materials; Carbon capture and storage; Dynamic LCA; Geocluster.

Nomenclature

ΔR_T - Additional mean thermal resistance
λ – Thermal conductivity
CCS - Carbon Capture and Storage
CH_4 - Methane
EoL - End of Life
DLCA - Dynamic Life Cycle Assessment
DS - Disposal Scenario
EPS - Expended Polystyrene
ESL - Expected Service Life
ETICS - External Thermal Insulation Composite System
EU-28 - European Union Member States
FU - Functional Unit
GHG - Greenhouse Gas
GWI - Global Warming Impact
GWP - Global Worming Potential
HCB - Hempcrete blocks
HCF - Preassembled frame with injected hempcrete
LCI - Life Cycle Inventory
LCIA - Life Cycle Impact Assessment
MF - Multi-Family House
nZEB - Nearly-Zero Energy Building
RBS - Residential Building Stock

RR - Renovation Rate

R_T - Thermal Resistance

SF - Single-Family House

SL – Service Life

STR - I-joist frame with preassembled straw

TH - Time Horizon

TIM - Timber frame

WT - Waste Treatments

1. Introduction

In the European Union Member States (EU-28), the construction and building sector is of strategic importance for reducing the anthropogenic carbon footprint, since it contributes to approximately 36% of global carbon emissions (Eurostat, 2017a). Approximately, 75% of the 25 billion m^2 of building stock is represented by housing, which contributes for about 22% of total energy consumption (Gynther et al., 2015; Loga et al., 2016a).

A large share of the residential building stock (RBS) is characterized by a low thermal performance of the building envelope, which negatively affects the space heating demand. In Europe, space heating is the most energy consuming end use, representing 71% of the total consumption of households (Eurostat, 2016). The renovation of dwellings to reduce the primary energy consumption is a key strategy for the EU-28 member states to reduce carbon emissions (Ballarini et al., 2014; Passer et al., 2016). However, studies, such as Rovers et al. (Rovers et al., 2017) and Pauliuk et al. (Pauliuk et al., 2013) show, that even the most optimistic building energy reduction scenarios are not sufficient to meet the 2°C target of the Paris climate Agreement. In that context Carbon Capture and Storage (CCS) technologies appear as an important strategy to transition towards a zero-carbon society (Rockström et al., 2017). Nevertheless, most of the existing CCS technologies, such as use of biochar for storing carbon in soils or products, direct air capture, etc., are still highly expensive, and a large-scale market adoption does not seem realistic in the short term (Williamson, 2016). The RBS in EU-28 has a large potential for temporary storing carbon, since technologies for carbon removal can be developed for a rapid market penetration and costs are much lower than alternatives in other sectors. Almost 80 million dwellings are expected to be renovated in Europe by 2050 and a large amount of additional insulation will be installed on facades to improve the thermal resistance (Wiedenhofer et al., 2015). The use of wood-based components and bio-based elements in general can be a valid solution to improve the building energy performance, the aesthetic of the facades and, especially, for massively storing carbon (Gustavsson et al., 2017). Forest ecosystems play a significant role for carbon sequestration. It is estimated that forest biomass in EU-28 contains more than 10 Gt of carbon, which is equal to nearly seven-folds the annual carbon emissions of Europe (Vallejo, 2015). Skog (Skog, 2008) estimated that in 2005, in the United States, harvested bio-based products stored 110 Mt of CO_2, which corresponds to approximately 2% of the national emissions. Similarly, Pilli et al. (Pilli et al., 2015) assessed that the carbon dioxide sequestrated by wood products in Europe in 2015 was 44 Mt per year, corresponding to about 10% of the carbon dioxide sequestrated by forests each year. When wood is harvested from the forest and used as timber or insulation material, the biogenic carbon embedded in the mass is fixated for as long as the product, e.g. a building, is in use. During that time, the same amount of carbon is taken up in the forest due to the regrowth of trees. However, the carbon uptake process in the forest typically requires long cycles, around 45-120 years (Lippke et al., 2011; Masera et al., 2003), because of the slow growth rate of trees. Brunet-Navarro et al. (Brunet-Navarro et al., 2016) calculated a yearly emissions savings under the current use of wood products in Europe to be of 58 Mt CO_2 per year. The potential saving could be improved by 5 Mt CO_2 by 2030 if the average lifespan of wooden products and the recycling rate are increased by roughly 20%. Similarly, Hildebrandt et al. (Hildebrandt et al., 2017) estimated for the European building sector an achievable potential for net carbon storage of about 46 million tonnes CO_2-eq. per year.

In contrast to woody biomass, agricultural crops require short periods to regrow, typically less than one year, and can be used as a building material, for instance as insulation material. In Europe, crops, such as wheat, rice, corn, etc., are largely used for cereal production in the food market. During harvesting and production, a significant amount of the plants' biomass is discarded and, thus, is available as a bio-product creating an added value. In the EU-28, cereal crops cover more than 58 million hectares, and 116 million tonnes of straw are produced each year (Eurostat, 2017b). If properly processed, the thermal conductivity (λ) of straw is around 0.04 W/mK and therefore in the order of magnitude of conventional insulation materials (Costes et al., 2017; Dessuky, 2009). Another multi-purpose crop is cannabis sativa, which can be processed to produce fibrous material hemp and woody shives. It is mostly available in Europe, and its application in construction might be highly beneficial for implementing the carbon storage in the built environment. The yearly hemp straw production is about 85'000 tons (Carus and Sarmento, 2016). Fibres account for 31% of the production, and are mainly used for lightweight papers, insulation material and bio-composites. Shives, the woody inner core of the stem, are a by-product of fibre production, and represent 53% of the production. They are sometimes used for animal bedding and construction blocks, mixed with mineral binders (Arrigoni et al., 2017; Martinez, 2017). The remaining 16% is dust, which is mainly used for incineration and compost (Carus and Sarmento, 2016).

Pittau et al. (Pittau et al., 2018) evaluated the benefit of using fast-growing biogenic materials, such as straw and hemp, for storing carbon in new construction elements. A functional unit (FU) of 1 m^2 of wall was considered and a dynamic LCA (DLCA) method adopted in order to take into account the timing of the emissions. In contrast to traditional construction systems (i.e. masonry or concrete walls with synthetic insulation), walls insulated with fast-growing biogenic material exhibited a net negative radiative forcing. However, wood-based elements resulted in an increased global worming impact (GWI) for the building life cycle. In the next decades, the total population in Europe is expected to stabilize at a number around 515 million capita (Statista, 2016). Consequently, the demand for new residential buildings is expected to be drastically reduced, while housing renovation will become the main driver that influences the dynamic transformation of the building stock (Heeren and Hellweg, 2018). In order to evaluate the consequences of such a shift in focus, it is necessary to perform an LCA-based assessment of the housing sector. In the following, we investigate the potentials of bio-based products to reduce the carbon footprint of the European building sector.

2. Objectives and scope

The purpose of the work is to investigate the potential of storing biogenic carbon in walls. We consider the material demand in the EU-28 building due to renovations over period of 2018 until 2218. We compared five different alternatives for retrofitting building facades including bio-based insulation materials relying on a dynamic LCA approach. The main objective is to demonstrate the building sector's future potential to climate change mitigation.

A Supplementary Information (SI) document provides details about the calculation model. It is structured in two parts: Appendix A, which includes supplementary data about the material flow analysis, and Appendix B, which includes data about LCA processes.

3. Method

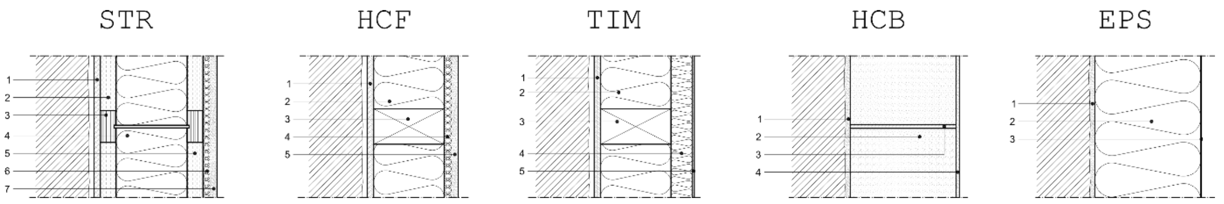
3.1 Reference construction alternatives for the renovation of exterior walls

Five alternative construction solutions for the renovation of exterior walls were considered as references in this study. The proposed strategy is a recladding with additional insulation, which can be applied to the exterior of outside walls, in order to improve their thermal resistance. The FU assumed for materials and life cycle impacts assessment (LCIA) is identical for all investigated alternatives and is defined as follows:

- 1 m^2 of retrofitted wall;
- identical thermal resistance (R_T);
- non load-bearing structure;
- identical fire safety;
- 60 years lifespan.

As illustrated in Table 1, three wall elements are typically prefabricated offsite, while the latter two are installed onsite. In the first four alternatives, a varying amount of biogenic products is used for the structural elements and thermal insulation. The thickness of the insulation for each alternative is a variable and depends on the additional thermal resistance required for the application on different European Member State (see 3.2.3). Specifically, in the I-joist frame with preassembled straw (STR), preassembled frame with injected hempcrete (HCF), and hempcrete blocks (HCB), a substantial amount of fast-growing biogenic materials is used. In STR, the cavity created by a thin sub-structural frame of I-joist elements 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, while externally, a lime plaster is applied on a reed mat.

Table 1. Materials inventory for the five alternatives for exterior walls renovation. The waste treatment categories are described in section 3.4.5.



Cod.	Material	Thickness	Density	Thermal conductivity (λ)	Mass	Life span	Waste treatment category
		mm	kg·m^{-3}	W·m^{-1}·K^{-1}	kg·m^{-2}	yr	
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 – Expensed 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

* "var" means that this layer thickness or quantity changes depending on the insulation requirement, as described in 3.2.3.

Similarly, in HCF, the cavity of the massive timber frame is filled with an injection of insulation mortar of hemp shives bound with lime-based binder. The mass ratio of shives to binder is 1:1. Similarly to STR, the panel is finished internally with an OSB and externally with a lime plaster supported by a reed mat. In timber frame (TIM), a glass wool filling is used. 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 cover plaster. In HCB, hempcrete blocks are used as insulation and finished with an exterior lime plaster. The composition of the blocks is the same as that described by Arrigoni et al. (Arrigoni et al., 2017). The ESL of hempcrete blocks and mortars is assumed 60 years, while the plaster is supposed to be replaced after 40 years. The same renovation concept is assumed in the expanded polystyrene ETICS (EPS), but, in contrast to HCB, the amount of biogenic material is equal to zero. In EPS, the synthetic ETICS is directly applied on the existing façade with 2 mm of render. The existing finishing of the facade might be used as direct support of the ETICS but their conditions are often not suitable for a direct application. Thus, an additional 10 mm cement mortar is assumed to be applied on the existing facades, in order to guarantee a regular and durable support for the ETICS.

3.2 Building stock model for material flow analyses

3.2.1 European Geocluster aggregation

The RBS in Europe is largely heterogeneous and a characterization method has to be adopted to assess the thermal characteristics and geometrical features to simulate large-scale renovation scenarios. Using a simplified bottom-up approach, mainly supported by statistical data, we approximated annual material inflow. The spatial extension is limited to the European Member States of the European Union (EU-28) and we consider only residential buildings, which represent around 76% of the European building stock and are responsible for 67% of the total primary energy demand (Eurostat, 2016). The Geocluster-based logic was introduced in order to aggregate data and fit the gap in case of lack of information at national level. As defined by Sesana et al. (Sesana et al., 2015), a Geocluster is a virtual trans-national area that can be identified by similar conditions such as climate, cultural heritage, energy price, gross domestic product, etc. Specifically, in this work the methodology suggested by Birchall et al. (Birchall et al., 2014) was adopted, which is based on the aggregation by similar climate conditions. As shown in Figure 1, the following seven different climate-based macro-areas where identified:

1. *Southern Dry* (Spain and Portugal);
2. *Mediterranean* (Italy, Greece, Cyprus and Malta);
3. *Southern continental* (France, Bulgaria, Croatia and Slovenia);
4. *Oceanic* (United Kingdom, Ireland and Belgium);
5. *Continental* (Germany, Netherland, Austria, Hungary, Czech Republic and Luxemburg);
6. *Northern continental* (Poland, Denmark, Romania, Slovakia, Lithuania);
7. *Nordic* (Sweden, Finland, Latvia and Estonia).

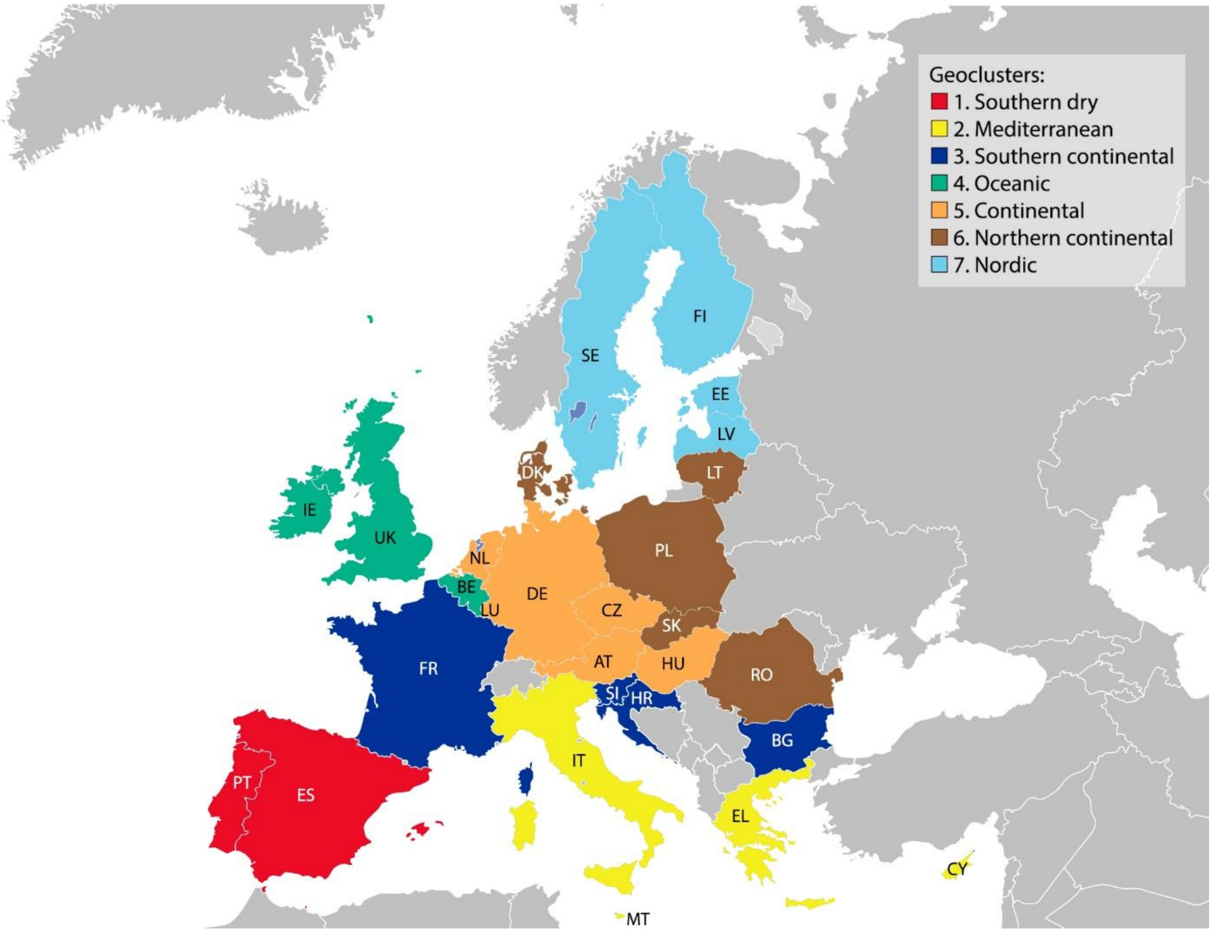


Figure 1. Geo-mapping of the Geoclusters of EU-28. Seven macro-areas identified per similar climate conditions.

3.2.2 Age distribution of the residential building stock

The RBS in EU-28 accounts for 250 million dwellings in total, which are represented by 22.6 billion m^2 of floor area (Eurostat, 2016). As shown in Figure 2, buildings built before 1945 account for roughly 23% of the total share. Within this category, three typologies can be distinguished all over Europe: (a) buildings with historical value, where generally every single part need to be preserved and special severe restrictions are often imposed to ensure the conservation; (b) ancient buildings, where ordinary facade retrofit might be complex to be applied; (c) abandoned buildings, which can be rehabilitated in the next decades to meet the rising demand of houses in Countries where population is still expected to grow (Diefenbach et al., 2016).

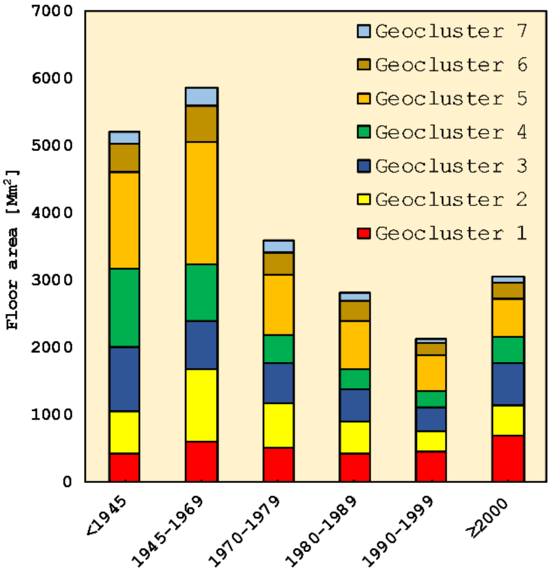


Figure 2. Age distribution of floor area among the 7 EU Geoclusters (Eurostat, 2016).

Post-war buildings built between 1945 and 1969 account for the highest total fraction, with a peak in Geocluster 5 where they represent 30% of the total RBS. No energy saving regulations were introduced in that period, thus buildings from 1945-1969 are largely characterized by non-insulated envelopes or with very low insulation content (Mazzarella, 2015). The first energy policy in an EU State Member was introduced in late ‘70, and implemented in other Countries the next decades with gradually restricted requirements (Langsdorf, 2011). 64% of the residential building stock was built between 1945 and 1999 with thermal resistance of the envelope which does not meet the limits required by today’s standards. Thus, the renovation of this category of buildings is a priority since at least 70% of them are expected to be still preserved in the RBS in 2050 (Visscher et al., 2016). The envelope of buildings built after 1999 is supposed to be mostly well insulated and no major renovations are expected by 2050 (Entranze, 2016). For this reason, this building category was excluded from the calculation model, as well as new buildings that are expected to be low or zero-carbon in the near future. Demolitions do not have material input and are therefore outside the system boundary. The total share of dwellings expected to be potentially renovated represents around 87% of the total current RBS.

3.2.3 Composition of the RBS and thermal performance

In order to define the characteristic of the RBS, the geometry of the prevalent building typologies should be defined. Unfortunately, this information is generally highly difficult to be gathered since complete representative statistical data are missing in the scientific literature and complex GIS-based models, occasionally available at urban level (Heeren and Hellweg, 2018), cannot be extended to the entire European stock. Thus, in this work, statistical archetype-based data collected within the European project TABULA (Loga et al., 2016b) was used. Per each Geocluster, different building typologies identified in the TABULA catalogue were aggregated and split in two categories: (a) single-family houses (SF) and (b) multi-family houses (MF).

A mean ratio value between the external wall area (S_w) and the building floor area (S_f) was evaluated per each building typology and results were aggregated on the base of the two selected categories, as shown in Table 2. In case explicit national data were missing, data from other countries inside the same Geocluster were considered as representative.

Table 2. Characterization of the residential building stock per each Geocluster. For complete calculation, aggregation and data source see SI Appendix A.1-5.

		Geocluster						
	Unit	1	2	3	4	5	6	7
Floor area	10^6 m^2	2'406	3'203	3'059	2'979	5'398	1'775	781
Multifamily (MF)	%	58%	69%	33%	15%	35%	40%	40%
	$S_w \cdot S_f^{-1}$	1.00	0.98	0.85	0.60	0.64	0.49	0.62
Single family (SF)	%	42%	31%	67%	85%	65%	60%	60%
	$S_w \cdot S_f^{-1}$	1.34	1.34	1.38	0.76	1.03	1.00	1.13
Renovation Rate (RR)	%	0.1%	0.8%	2.0%	0.3%	1.4%	0.5%	0.9%
Walls yearly renovated	10^6 m$^2 \cdot$yr^{-1}	2.05	25.57	68.55	6.81	65.21	6.47	5.53
Current U-value of ext. walls	W$\cdot$m$^{-2}\cdot$K^{-1}	1.90	1.42	1.36	1.60	1.14	1.07	0.44
Min U-value from legislation	W$\cdot$m$^{-2}\cdot$K^{-1}	0.54	0.33	0.35	0.29	0.27	0.29	0.18
U-value target after retrofit	W$\cdot$m$^{-2}\cdot$K^{-1}	0.38	0.22	0.24	0.18	0.17	0.16	0.15

A mean renovation rate (RR) coefficient was defined for each Geocluster, with a mean European value which is nearly 1.0% (Zebra2020, 2014). In this model, the RR is considered as a constant parameter. Through the correlation between RR and S_w/S_f, the yearly amount of walls that require renovation was quantified. As reported in Table 2, in Geoclusters 3 and 5 the amount of exterior walls expected to be renovated is thirty-fold higher than the one expected for Geocluster 1, while results in roughly ten-folds higher than Geocluster 4,6 and 7. Finally, in order to define the quantity of insulation material required per each Geocluster to renovate the exterior walls, the gap between the current thermal insulation and the target insulation needed after the renovation was evaluated. The mean current thermal resistance values (R_T) of exterior walls for each Geocluster were assumed through the aggregation of statistical national data (Entranze, 2016). The optimum amount of insulation needed for a major renovation is a parameter difficult to be defined (Dombayci et al., 2006; Kaynakli, 2008). Nevertheless, many recent national building codes have introduced a minimum U-value for walls that needs to be respected during the design, assuming different limits in case of new construction or renovation (Mazzarella, 2015). In many Countries, the U-value limits have been gradually decreasing year by year, and a nearly-zero energy building (nZEB) standard has been decided to be fully adopted in Europe by 2020 (Hermelink et al., 2013). Current national thermal resistance limits for walls renovation were considered in this model, but stricter values were calculated to take into account a reasonable expected future reduction of U-value limits (Atanasiu et al., 2013). An amplification factor 2 was assumed, which correspond to an incremental mean thermal resistance (ΔR_T) of roughly 5.0 m^2K/W.

3.3 Dynamic LCA model

The lack of time dependence and the treatment of biogenic CO_2 are critical issues in LCA and carbon footprint calculations. Normally, impacts of biogenic CO_2 are neglected in a traditional LCA since the same amount of CO_2 released from biogenic sources is assumed to be absorbed during the regrowth of the biomass, and the net emissions are therefore zero (Berndes et al., 2016). However, this has recently been shown to be an over-simplification, because the time needed by the trees to uptake the carbon sequestered in products affects negatively the radiative forcing (Cherubini, 2015).

Levasseur et al. proposed a DLCA model (Levasseur et al., 2012, 2010) that allows taking into account the timing of carbon uptake and GHG emissions into account. This is particularly relevant for bio-based products because of the temporary carbon release. The model was adopted for this work and implemented taking into account only the effect on the greenhouse gases of CO_2 and methane (CH_4), since it was observed they contribute for the largest share of the radiative forcing impact due to the high amounts released in the process. In accordance with IPCC AR5 (Intergovernmental Panel for Climate Change [IPCC], 2014), , the Bern model was used for CO_2, while for CH_4, the first order exponential decay with $\tau = 12$ years was considered. A Time horizon (TH) of 200 years was assumed, in order to include into the calculation the short-term (2050) and long-term (2100) effects.

3.4 Life cycle assessment

3.4.1 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, material separation and waste processing, and final disposal.

Additional benefit, 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). As discussed in Paragraph 3.4.5, three different disposal scenarios (DS) are considered in module C4. Contributions from natural systems e.g. forest and crop fields, which remove carbon from the atmosphere during plants growing, are taken into account in sub-module B1.

3.4.2 Calculation model

The model developed for the LCA is schematically shown in Figure 3. The ΔR_T needed to meet the expected U-value limits in the future (see 3.2.3) was evaluated for each European Member State, as well as the yearly surface of walls that is expected to be 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 alternative construction solutions in order to define the annual material inflow. A life cycle inventory (LCI) from modules A1 to C4 was performed to calculate the impact inventory, measured in terms of kg of greenhouse gases (GHG), emitted per year.

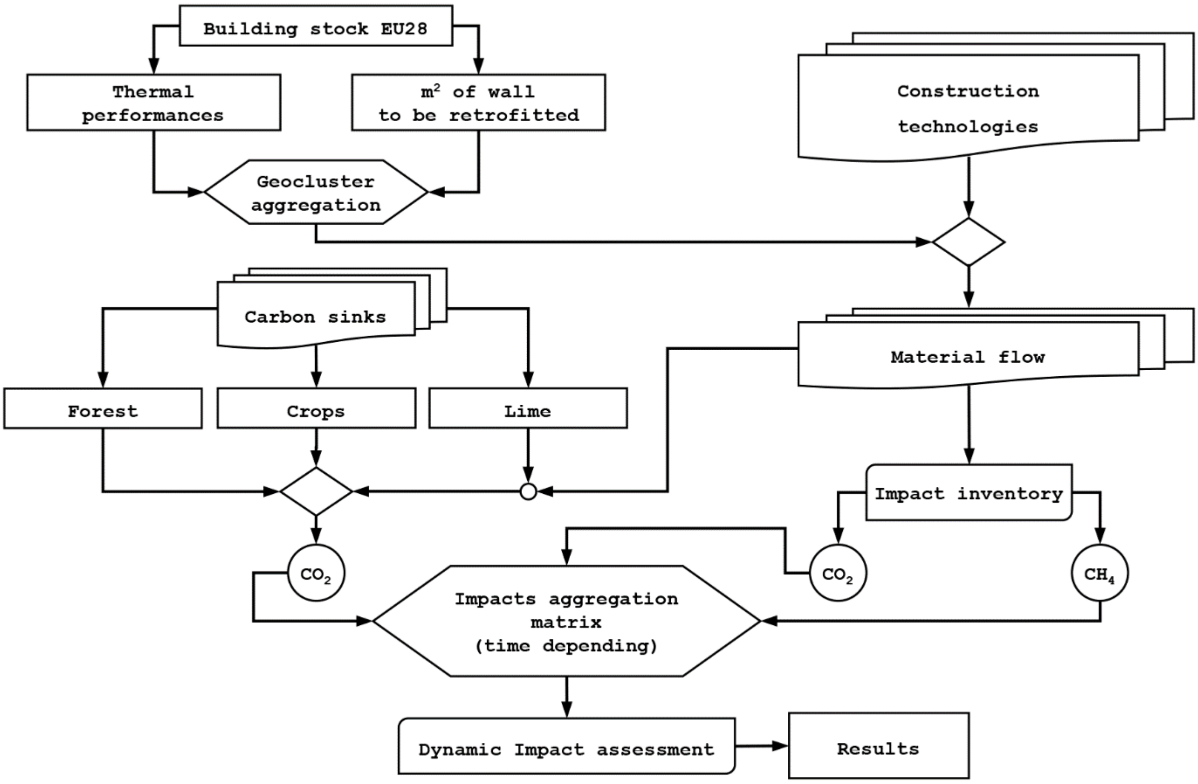


Figure 3. Schematic diagram of the adopted methodology.

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, were measured and the resulting carbon removals 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 according to Levasseur et al. (Levasseur et al., 2012). Finally, the results, expressed in instantaneous and cumulative radiative forcing, were converted to kg CO_2-eq. according to the IPCC method in order to measure the global warming potential (GWP).

3.4.3 Product and construction stage

Products and processes are modelled with SimaPro 8.3 (PRé Consultants, 2016) using the Ecoinvent 3.2 database, allocation cut-off, for primary LCA data (Wernet et al., 2016). Injected hempcrete in HCF, hempcrete blocks and light lime mortar used in HCB, are modelled according to the inventory defined by Arrigoni et al. (Arrigoni et al., 2017). Other non-conventional materials, e.g., light clay straw and reed mats used in STR and HCF, are created from ecoinvent primary data by adopting a mass allocation. All information about processes from production are reported in SI Appendix B.1, while the inventory of off-site assembly, construction and replacement processes are reported in SI Appendix B.2. The energy mix from EU and a mean distance value of 50 km for transportation were assumed (UST, 2012).

3.4.4 Use stage

During the use stage, CO_2 reacts with slaked lime content in lime-based products, such as concrete, plasters and mortars, due to the penetration of humid air though the material pores. Typically, this chemical reaction, commonly called carbonation, is not constant in time, and depends on many factors, such as lime-content, CO_2 and moisture content in the air, thickness of the material, material porosity, etc.

Fick's first law of mono-directional diffusion of carbonation was adopted in order to quantify the amount of CO_2 that can be stored in products during their ESL (Van Balen and Van Gemert, 1994). For an air-exposed thin layer, e.g., plasters and renders, the carbonation process is assumed to be completed within 1 year. For all other lime-based materials, three values of speed factor were assumed according to the material characteristics and exposition: 19.6 $mm \cdot yr^{-0.5}$ for mortars (Xi et al., 2016), 6.2 $mm \cdot yr^{-0.5}$ for hempcrete products (Arrigoni et al., 2017), and 4.0 $mm \cdot yr^{-0.5}$ for concrete based-materials (Xi et al., 2016). Moreover, if the carbonation of a lime-based product is not completed by the ESL, the carbonation process is considered to continue after the EoL in case of landfill.

A significant amount of carbon, roughly 50% of the dry mass, is stored in biomass (Thomas and Martin, 2012). In this work, an equal amount of biomass harvested from the two biomass sinks (forests and crops) for product manufacturing is considered to regrow after a rotation period (Peñaloza et al., 2016). The mass of fast-growing biogenic materials harvested from the crops, e.g., straw and hemp shives, is assumed to be fully regenerated within one year from harvesting. Differently, for timber and wood-based insulation materials a longer period is normally needed to be regenerated in the forest. A traditional management regime for the production of round wood from Norway spruce stand with a rotation period of 90 years was assumed as reference (Eriksson et al., 2007). Data from Masera et al. (Masera et al., 2003) were elaborated for the calculation of the forest regeneration capacity, based on a Norway spruce forest in Central Europe. In this calculation, only the actual amount of biomass allocated to the products was considered. All the forest residues, e.g., leaves, branches, and roots, as well as sawn residues produced during manufacturing and construction phase were excluded. Carbon removed by uptake are accounted for in module B1, while burdens from replacement of products with an ESL shorter than the wall service life, are accounted for in module B4.

3.4.5 End of Life stage

Typically, the GWI 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 (Levasseur et al., 2013).

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. Often impacts from this waste treatment is significantly high since organic materials normally release a large amount of CH_4 during their decay (Møller et al., 2004);
- *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. The thermal energy recovered from bio-based material depends on its energy content (Arfvidsson et al., 2013);
- *WT5 - recycling*: consists of generating new products from waste materials. The recycling of most construction products is limited to a down-cycle process, which leads to by-products with a lower value than the one of the original product.

All processes for waste treatments are reported in SI Appendix B.3. From the combinations of different waste treatments illustrated in Figure 4, the following three alternative disposal scenarios (DS) were defined:

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

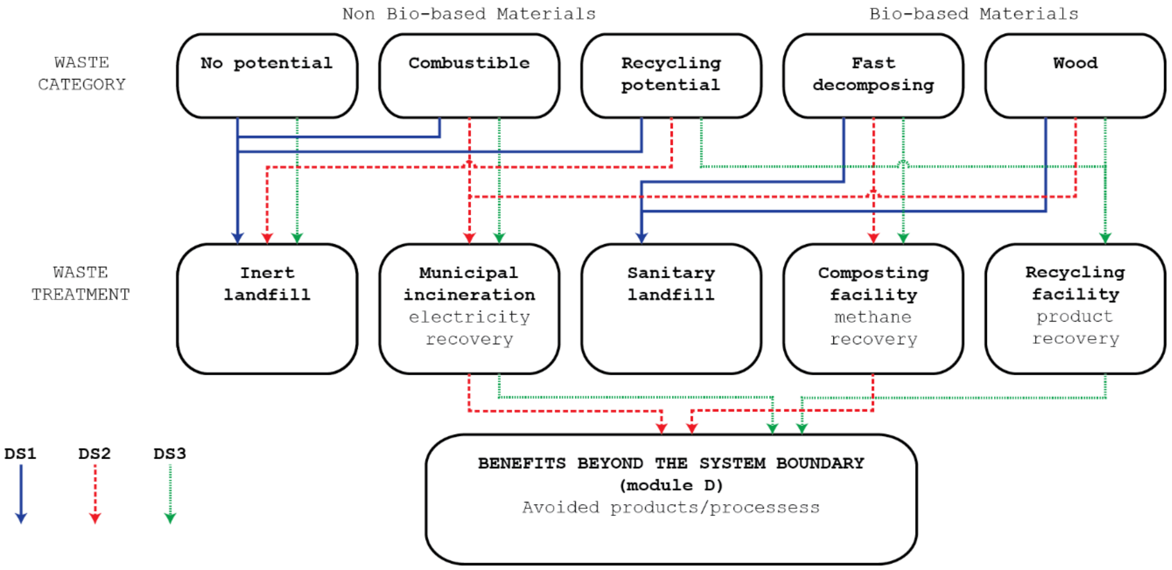


Figure 4. Waste treatments and disposal alternatives for each end of life disposal scenario (Pittau et al., 2018).

In DS1, all non-biogenic materials were assumed to be landfilled, while bio-based products transferred to sanitary landfill. The same specific methane emission from rotting process in landfill was assumed for straw and reeds (Møller et al., 2004; Rasi et al., 2007). Hempcrete-based products are the only exception, since they can be considered as inert material due to the mineralization of the hemp shives by lime (Arrigoni et al., 2017; Courard et al., 2011). In DS2, waste wood and combustible materials were assumed to be burnt in municipal incineration facilities, and the energy recovered to produce electricity. The energy mix from EU was assumed and the avoided emissions from energy production accounted for in module D. Fast-decomposing biogenic materials are supposed to be treated in composting facilities where the methane is captured and stored, while the other non-biogenic materials are assumed to be landfilled.

Finally, in DS3, waste materials from wood and potential recycling category are recycled. Timber was assumed to be recycled in a down-cycling process to produce wood chips, a co-product from sawn products with generally a relatively low impact (Rivela et al., 2006). In addition, hempcrete-based materials as well as light clay straw were considered to have recycling potential since the material can be easily crushed after the EoL and remixed with new binder to regenerate the same product. Waste materials that cannot be recycled were treated as described in DS2. For each scenario, a perfect material separation and recovery was assumed from each element, while material losses due to residual waste was not taken into account.

3.4.6 Loads and benefits beyond the boundaries

All the loads and benefits from avoided processes and avoided materials that are beyond the boundaries were allocated to the products according to the mass allocation method and separately accounted for in module D. In DS2, the benefit of producing electricity from waste incineration was considered as avoided process, while in DS3, benefit from material recycling was considered as avoided virgin material.

4. Results

4.1 Dynamic life cycle assessment

4.1.1 Instantaneous radiative forcing

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 developed by Levasseur et al. (Levasseur et al., 2010), based on the LCI reported in Appendix A.4. The results were divided in two categories: those including module D (DS+D) and those excluding module D (DS), as shown in Figure 5. In DS1, module D was not taken into account since landfilling causes no materials to leave the system boundary and no additional benefits were expected at the EoL. The calculation starts for each Geocluster at year 0 (2018) according to the specific yearly amount of wall that is expected to be renovated per year, as reported in Table 2.

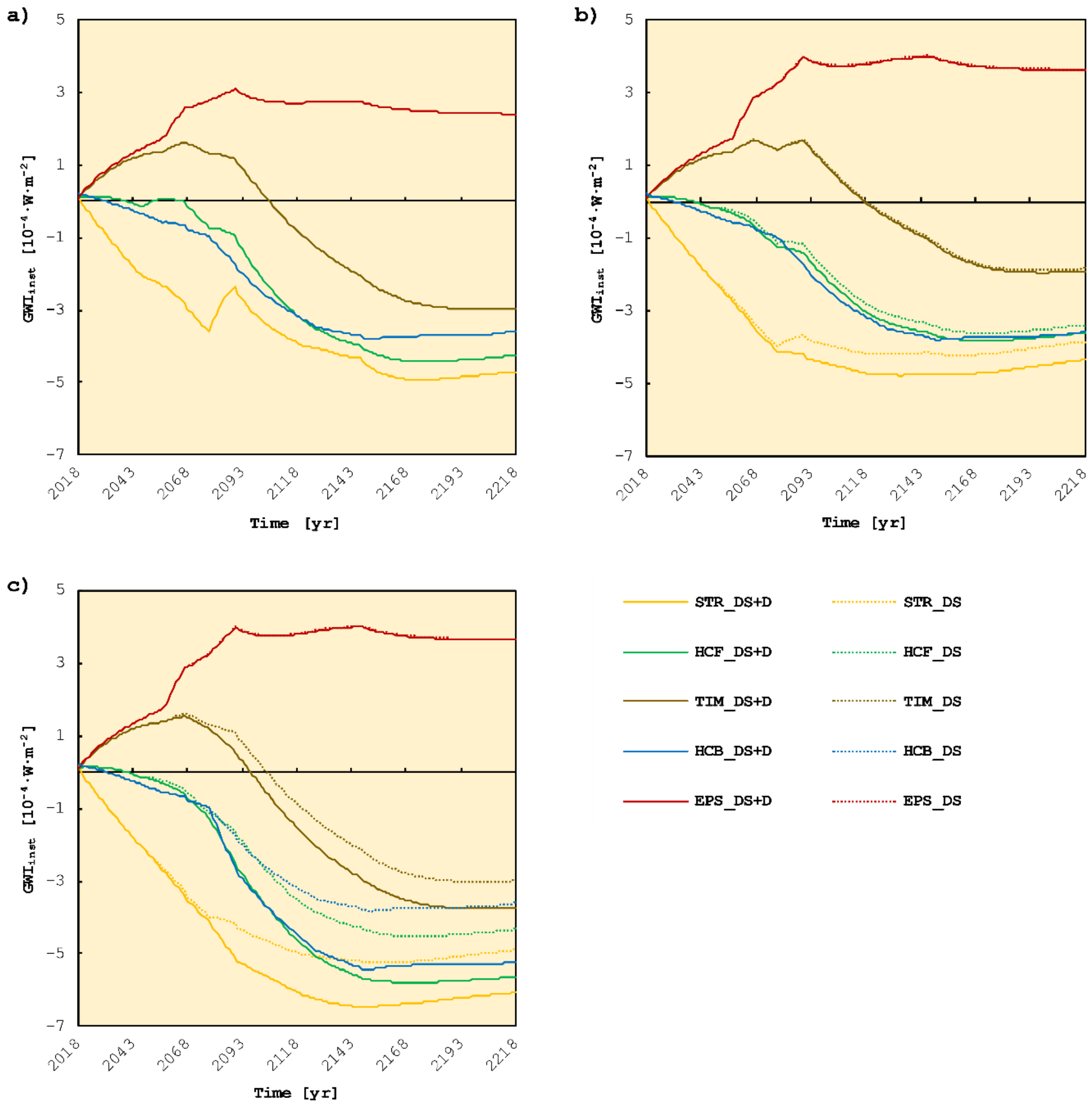


Figure 5. a) Instantaneous radiative forcing for DS.1 scenario; b) Instantaneous radiative forcing for DS.2 scenario; c) Instantaneous radiative forcing for DS.3 scenario. For all graphs, DS+D stands for disposal scenario with module D and DS for disposal scenario without module D.

In 2018, HCB accounts for the highest initial impact, 2.1E-5 W/m^2, due to the high amount of material that requires manufacturing and construction. HCF and STR account for the second highest instantaneous radiative forcing value, 1.30E-5 and 1.38E-5 W/m^2 respectively. Finally, EPS and TIM account for a lower initial impact, 8.72E-6 and 7.75E-6 W/m^2, due to a largely reduced mass of material needed. Alternatives such as STR, HCF and HCB have a high content of fast-growing material inside their structures, and the same amount of carbon stored in the products is supposed to be taken up after 1 year by the crop. The carbon temporarily stored in the products and removed by the crops is largely higher than the carbon yearly emitted for production and construction of products (module A1-5), and it leads to a rapid turn into negative radiative forcing values. Specifically, HCF begins to account for negative values from 2040 (i.e. 22 years after production and construction), while for HCB it is 2031. Similarly, the large amount of carbon stored in STR is able to quickly turn the initial impact to negative values in just 2 years after the first renovation in 2018. Contrary to that, a longer time is required for wood regeneration (i.e. carbon uptake) in the forests, and thus the effectiveness of carbon storage in timber and other wood-based products used in TIM is largely reduced. This aspect is reflected in all DSs, where TIM requires 88 years, 100÷101 years and 79÷87 years, respectively in DS1, DS2 and DS3, to show a negative net forcing effect. In comparison to the others, STR contributes to the fastest reduction of the radiative forcing for each DS considered, with a small deflection of the values in DS1 after 40 years (from 2058). Here the external finishing applied on existing facades in 2018 starts to be replaced, and the reed mat disposed in the sanitary landfill starts to freely emit CO_2 and especially CH_4 into the atmosphere. This undesired impact is avoided in DS2 and DS3, where biogas capturing system in the composting facility avoids the direct emission into the air. By 2068 Geocluster 3, which accounts for 74 Mm^2 of renovated walls per year, is expected to renovate all its RBS, and the global EU-28 material flow is henceforth slightly reduced. In straw, this reduction of material requirement leads to another positive deflection of the values, with a negative pick in 2078. Henceforth, all the alternatives installed from 2018 start to be gradually dismissed since 60 years of SL was assumed. Thus, in STR an inversion of the trend is observed after 2078 in DS1 due to the high amount of GHG released into the atmosphere mainly by straw biological decay. A maximum positive peak is reached in 2091, when the second largest Geocluster, Geocluster 5, with 70 Mm^2 of wall renovated per year, has renovated all of its RBS.

Contrarily to STR, for HCF and HCB the EoL of hempcrete-based products in DS1 does not affect negatively the GWI since the material is considered as inert and no biological decay is expected.

Within the selected time horizon, also Geocluster 7 and Geocluster 2 complete the renovation of their RBS, in 2132 and 2148 respectively, which lead to an additional significant reduction of material inflow and a stabilization of the GWI for each alternative.

TIM for every DS reaches about 1.6-1.7E-4 W/m^2 as maximum positive peak in 2068. Then, the reduced request of material due to the stop of renovation in Geocluster 3 and, later, in Geocluster 5, as well as the regrowth of the forest that, after the first stage when is too young, begins to uptake a larger yearly amount of carbon, start to invert the trend towards negative values. In DS2, the effect of the energy recovery with electricity production from incineration of wood and combustible materials do not significantly affect the GWI. Only in STR, the benefit from biogas capturing in sanitary landfill and energy recovery from timber incineration at EoL after 60 years leads to a notable difference, with a long term reduction of the GWI by roughly 12% in case module D is taken into account. In general, the incineration of waste materials in DS2 increases the negative effect of the carbon emissions compared to DS1. Especially for TIM and EPS, on which the GWI in a long term prospective is increased by 36% and 34% respectively. Except for EPS, where no recyclable material is installed and the EPS incineration lead to a higher GHG emission compared to landfill, DS3 is the most beneficial scenario since the effects of GHG emissions are reduced, especially if module D is taken into account. EPS always exhibits the highest impact, even if a reduced amount of material is requested for the structure.

4.1.2 Cumulative radiative forcing and global warming potential

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. The three different DSs are compared and shown in *Figure 5*.

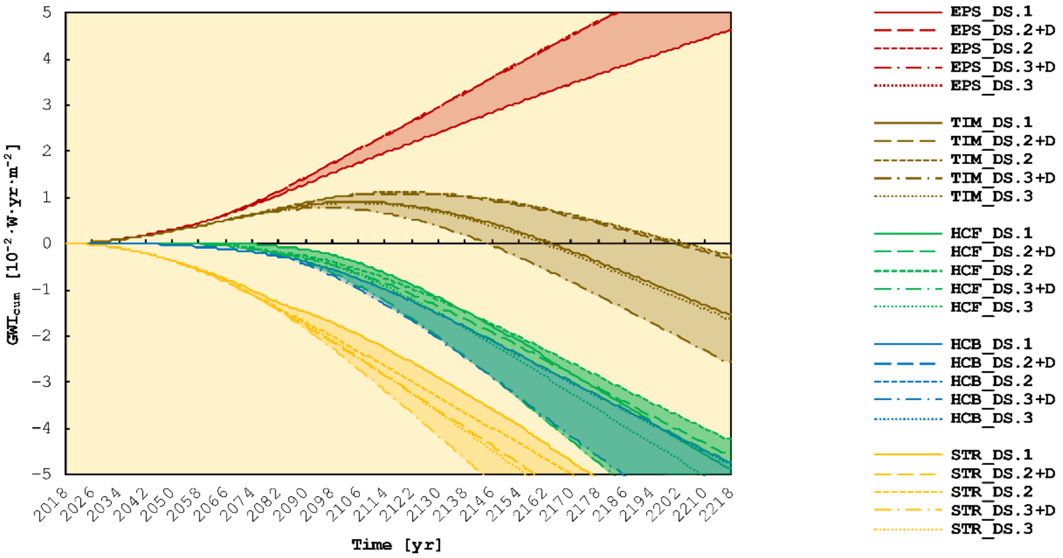


Figure 6. Cumulative radiative forcing for all scenarios. DS1, 2, 3 stand for disposal scenario with landfill, energy recovery and material recycling respectively. DS +D stands for disposal scenario with module D and DS for disposal scenario without module D.

In general, the sensitivity to the EoL is relatively high for each alternative. STR, since the early stage after the first three years, starts to turn into negative GWI values, increasing constantly its positive effect on global warming. The negative environmental effect due to the released GHG in sanitary landfill starts to be relevant from 2078, when the first renovation systems applied 60 years earlier are dismissed. Contrarily, HCF and HCB increase slightly the cumulative GWI value until 2040 and 2030 respectively, with a maximum pick of 5.67E-2 W/m^{2}yr and 2.35 W/m^{2}yr. Then, additional 34 and 13 years are needed respectively to achieve the climate neutrality. In TIM, a relatively long time is required to achieve the climate neutrality, with a maximum positive pick registered around year 2116. Contrarily to STR HCB and, partially, CHF, DS2 accounts for the most negative impact, with a climate neutrality that is reached only in 2200, when module D is included. DS3, due to the avoided virgin materials extraction and manufacturing, is potentially able to reduce by 55 years the time for achieving the climate neutrality. EPS, the only alternative with no bio-based products into the structure, results as the only one that is never able to reach the carbon neutrality in the selected TH, with a cumulative GWI that constantly increases over time.

Finally, the results are converted from GWI_{cum} to GWP according to the IPCC method (Krey et al., 2014), in order to quantify dynamically the carbon emissions/removals in terms of kg CO_2-eq.

The dynamic values of the GWP for each alternative and each DS are shown in Figure 7.

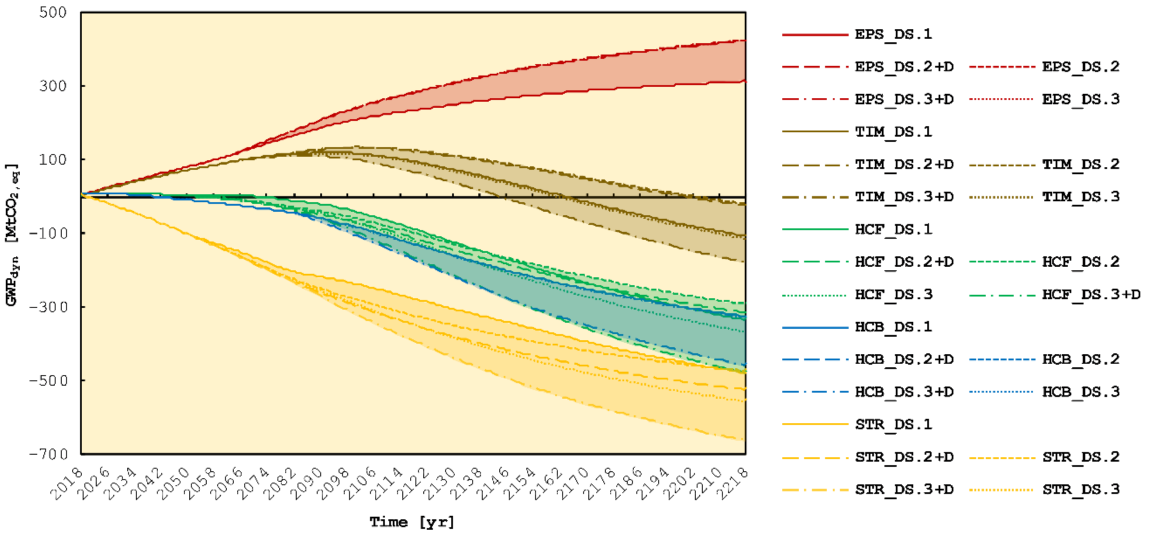


Figure 7 Dynamic GWP for all scenarios. DS1, 2, 3 stand for disposal scenario with landfill, energy recovery and material recycling respectively. DS +D stands for disposal scenario with module D and DS for disposal scenario without module D.

After an initial positive emission in 2018 of 7.64 Mt of $CO_{2,eq}$, the GWP impact of 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 (Eurostat, 2017a). In 2100, the carbon removal grows up to 281 Mt of $CO_{2,eq}$ (mean value of the three DSs assumed), which is equivalent to a reduction by 75% of carbon emissions from industrial processes and product use, or 64% of emissions from agriculture in the same year or 7% of total carbon emissions from all sectors in EU-28 in 2015. In 2050, the materials required to renovate the BRS 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. The removal potential is almost 7 Mt of $CO_{2,eq}$. This is equivalent to a minor reduction (roughly 2%) of carbon emissions from industrial processes and product use or a negligible (0.2%) reduction of emissions from all sectors. The carbon removing potential grows up to 84 Mt of $CO_{2,eq}$ in 2100, which is equivalent to a reduction by 22% of carbon emissions from industrial processes and product use and 2% from all sectors. 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.

4.1.3 Discussion

According to Paris Agreement, the first target to maintain the temperature raising "well below 2 °C" is a goal that should be achieved shortly, by 2050. Then, a long-term target for an extra carbon reduction is required by 2100 to lead the world community to a zero-carbon society. As shown in Figure 6 and Figure 7, the only alternatives which demonstrate an efficient CCS potential are the fast growing materials (STR, and, only partially, HCF and HCB). A real benefit from temporary carbon storage in construction products can be achieved only when the carbon is rapidly reabsorbed by the crops. An avoided warming effect from storing carbon in fast-growing materials is achieved for every all DSs by 2050. The only exception being HCF, which becomes neutral in 2056.

Sensitivity analysis

Many uncertainties may affect the discussed results. One of the most influencing is the amount of material inflow expected to be added in the RBD each year. This parameter is mainly controlled by the RR, which for EU-28 is considered roughly 1%, according to Table 2. In Figure 8, the sensitivity of cumulative GWI to the variation of the RR is presented, considering each year the average value from the three DSs. Three different RR were assumed: 1% (base scenario), 2% and 4%. The values are supposed to be yearly applied by the year zero (2018) of the calculation.

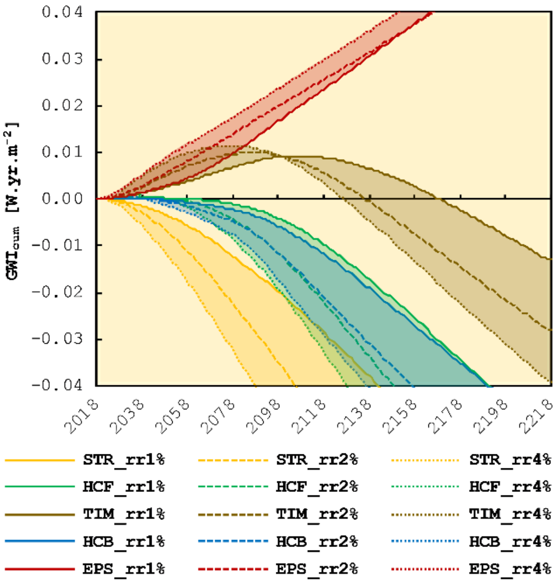


Figure 8. Sensitivity of cumulative radiative forcing to the variation of the mean renovation rates (RR).

The effect of increasing the speed of renovation linearly affects positively the results for STR, HCF and HCB. Contrarily, an increased annual material inflow is not beneficial for TIM in the short-term prospective, since the peak is shifted backwards and an increased global warming effect is expected. The second parameter that significantly influences the calculation is the service life (SL) considered within the FU. To assess its influence on the results, three different SL of the construction alternatives were assumed: 60, 30 and 20. As shown in Figure 9, a reduced SL leads to an increased cumulative GWI impact, which slightly reduces the carbon storage efficiency of STR, HCF and TIM when the SL is reduced to 30 years, while a higher reduction is expected in case of SL=20 years. Contrarily, non-preassembled construction alternatives, such as HCB and EPS, decrease their impact in terms of cumulative GWI if their SL is reduced.

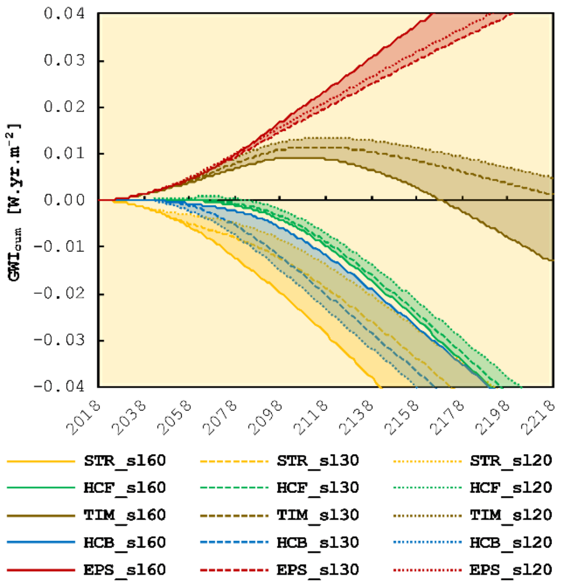


Figure 9. Sensitivity of cumulative radiative forcing to the variation of the service life (SL) of the five alternative construction solutions.

The combined effect of the uncertainties on the cumulative radiative forcing is shown in Figure 10. All the parameters are linearly combined, and the maximum variation in the results is calculated in terms of the GWI_{cum} in 2100.

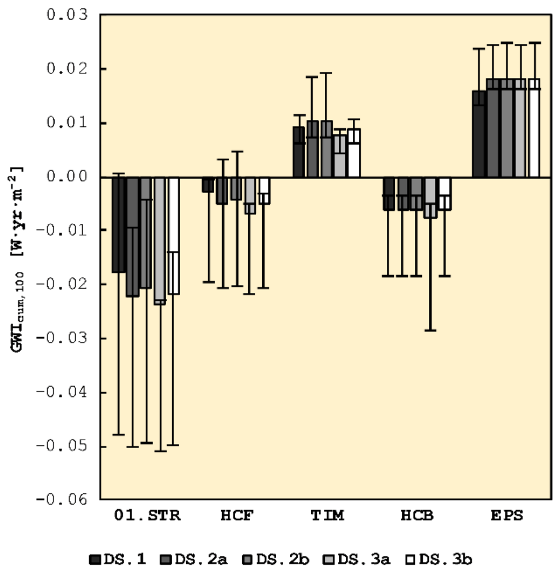


Figure 10. Combined effect of the uncertainties on the cumulative radiative forcing in 2100. The solid bars represent the results of cumulative radiative forcing evaluated in 2100 upon considering the base scenario (RR=1%; SL=60 years), and an average value from the three defined DSs. The error bars represent the max and min deviation evaluated as a triangular distribution.

For some alternative, the effect of the uncertainties leads to relevant variations in the results, especially in STR, when a combined increasing of RR with a base SL of 60 years drops by more than two-folds and a half the cumulative GWI. Contrarily, if an adverse combination is taken into account (lowest RR and lowest SL) the cumulative GWI rises significantly for every DS. Similarly, the cumulative GWI for HCF and HCB drops down if the favourable combination is taken into account, while an increasing mean value is expected for HCB if an unfavourable combination is assumed. Finally, TIM and EPS account for the highest cumulative GWI, even if a favourable combination is adopted.

5. 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 EU-28. The results show that they have an increased potential to act as a carbon sink compared to timber, which represents an important strategy towards the Paris climate Agreement goals. In particular, if straw is used as insulation material, 3% of the $CO_{2,eq}$ emitted from all sector in 2015 can be remove by 2050. Hemp-based alternatives start to be carbon negative slightly after 2050, with a carbon removal potential in 2100 of almost 54 Mt of $CO_{2,eq}$, roughly 2% of the emissions from all sectors in EU-28 in 2015. Clearly, EPS, which is nowadays the most used renovation system widely spread in Europe for energy retrofit, reduces the extra loads on the existing facades, but is not able to contribute actively to the CO_2 removal from the air. Moreover, its large-scale spread would generate an additional impact from materials along the service life, as well as a large amount of non-recyclable waste from demolition at end of life.

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Supplementary Information

Appendix A.1: Age distribution of the Residential Building Stock per Geocluster

Appendix A.2: Calculation of Multi-family (MF) and Single-family (SF) houses per Geocluster

Appendix A.3: Geometry characterization of the Residential Building Stock per Geocluster

Appendix A.4: Calculation of exterior walls to be renovated per Geocluster

Appendix A.5: Calculation of the additional thermal resistance of exterior wall per Geocluster

Appendix A.6: Calculation of the thickness of insulation and material intensity per Geocluster

Appendix B.1: Ecoinvent 3.2 process inventory for materials production

Appendix B.2: Ecoinvent 3.2 process inventory for off-site assembly/construction and replacement

Appendix B.3: Ecoinvent 3.2 process inventory for waste treatments

Appendix B.4: GHG Inventory

Retrofit as a carbon sink: the carbon storage potentials of the EU housing stock

Cover Letter

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Co-Editor-in-Chief
Purdue University
Paulista University
São Paulo, Brazil

Zurich, 20 April 2018

Subject : Submission in Journal of Cleaner Production
Reference: Retrofit as a carbon sink: the carbon storage potentials of the EU housing stock

Dear Editor,

I am pleased to have the opportunity to submit to your journal the present research paper.

The objective of the paper is to investigate the potential of massively storing carbon in bio-based construction products when used for the renovation of existing facades in Europe. Five alternative construction solutions were compared, and a statistic-based Geocluster model was developed to predict the future material flow for building renovation in EU-28. A dynamic life cycle assessment was performed in order to verify the contribution of construction materials in reducing/increasing the carbon emissions over time.

Fast-growing bio-based materials, such as straw and hemp, have a considerable potential to act as a carbon sink, which represents an important strategy towards the Paris climate Agreement goals. Unlike forest products, the CO_2 is rapidly sequestered in crops, and the capacity for storing carbon increases when they are used as construction material due to a long service life.

I hope you will appreciate this contribution.

Yours sincerely,

Francesco Pittau

Attached files: 1 Manuscript, 1 Page Title, 1 Word file Highlights, 2 Excel Table, 11 Figures, 1 Abstract, 2 Excel file for Supplementary Information

HIGHLIGHTS

1. A large amount of insulation will be used for building renovation in EU-28
2. CO_2 emission from material process can hinder the transition to low-carbon society
3. Carbon storage in biogenic materials can contribute to climate mitigation
4. Forest regeneration for timber products is too long to reach the goals in 2050
5. Fast-growing materials are an effective opportunity for CO_2 removal

Figure 01

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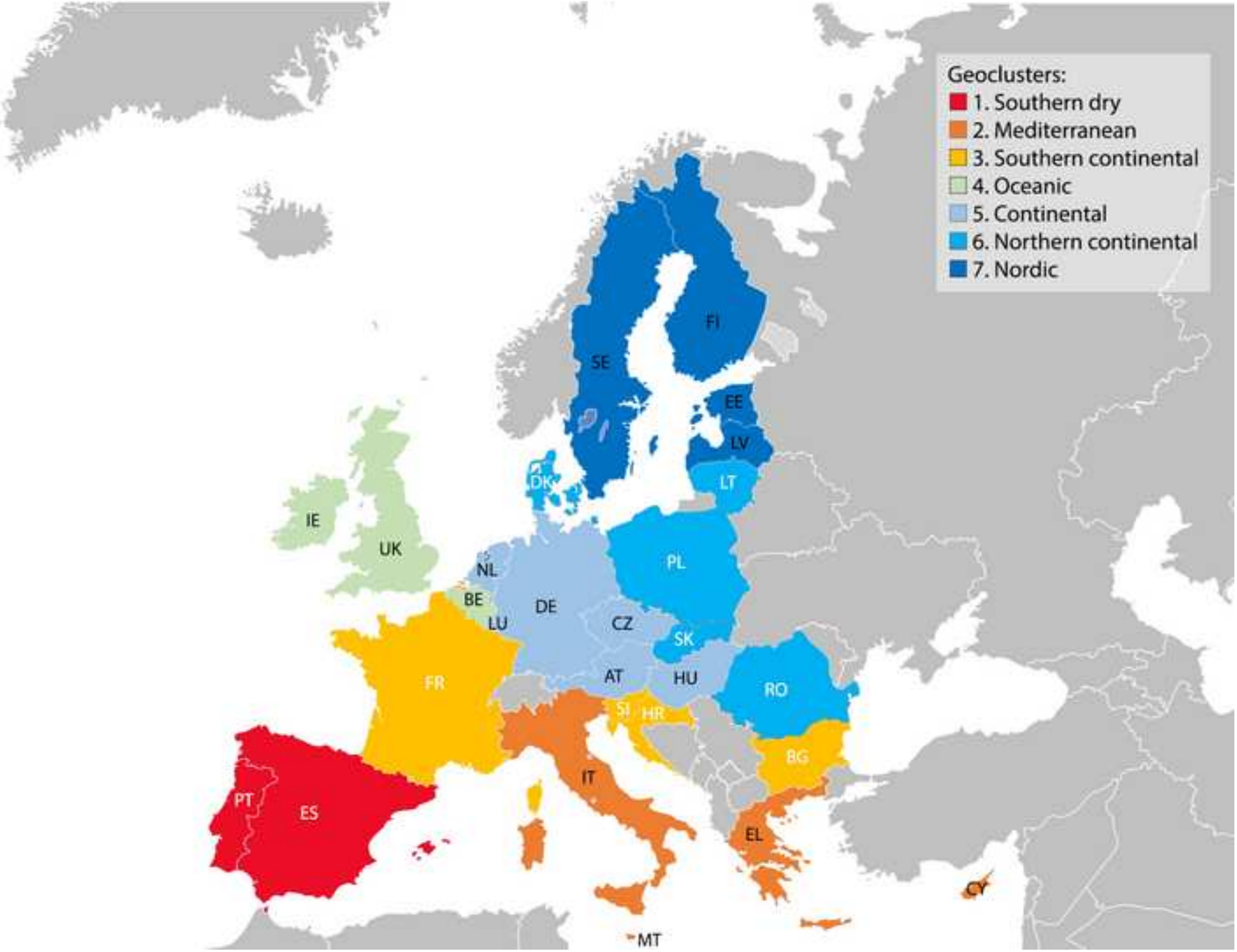

Figure 01_Tab 01

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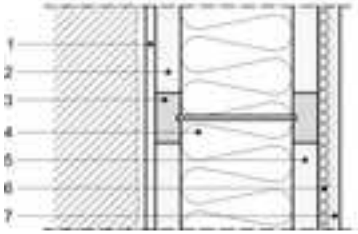
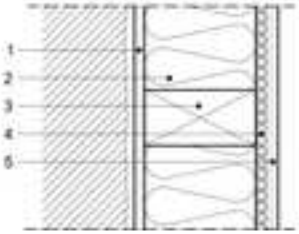


HCF



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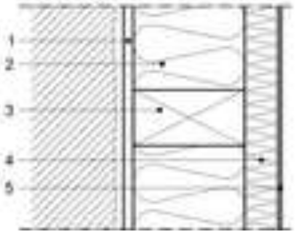

HCB

EPS

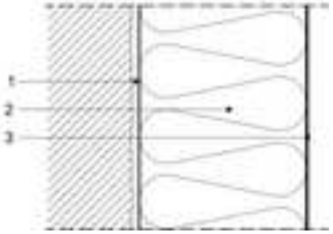

Figure 02

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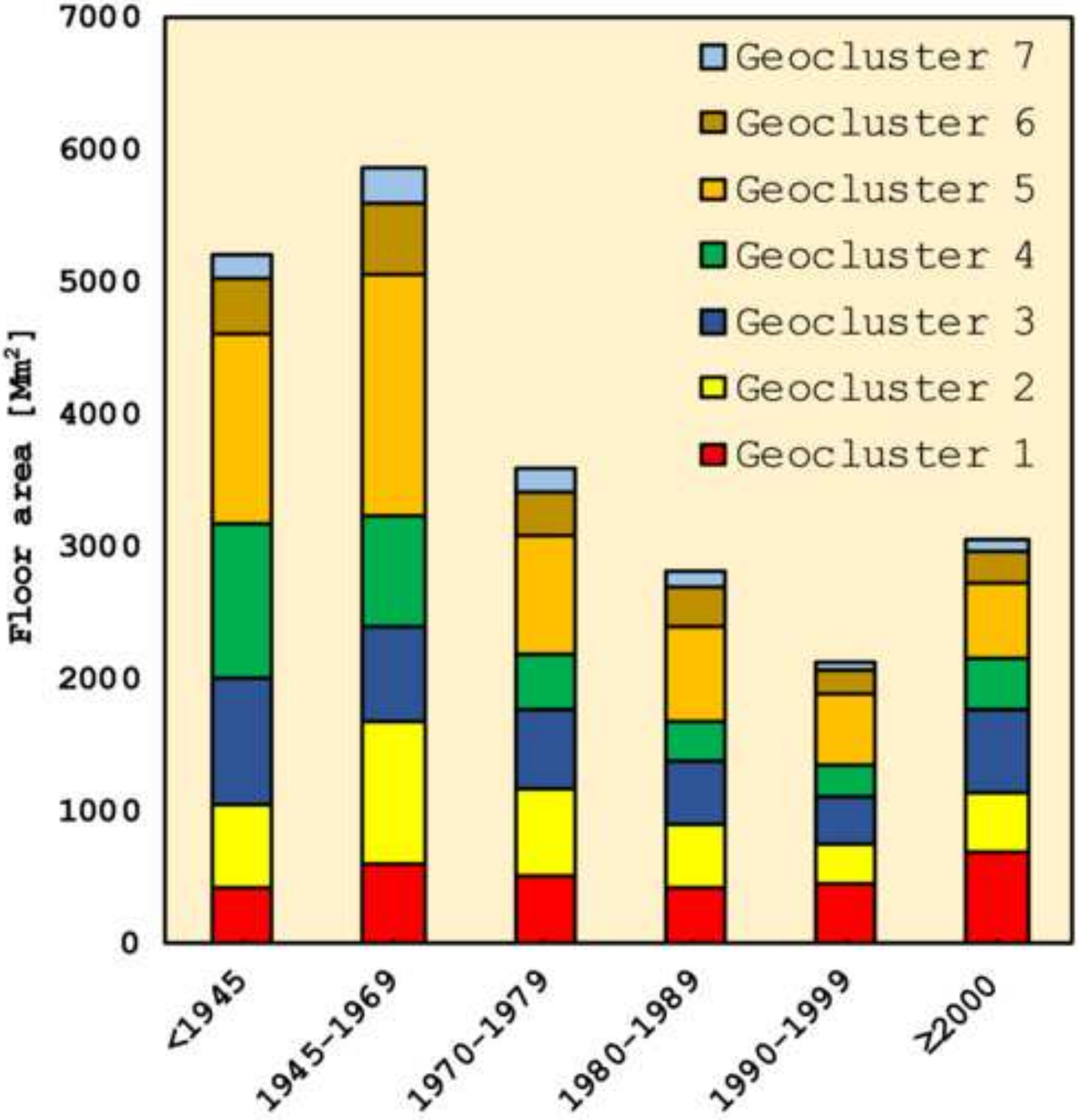

Figure 03

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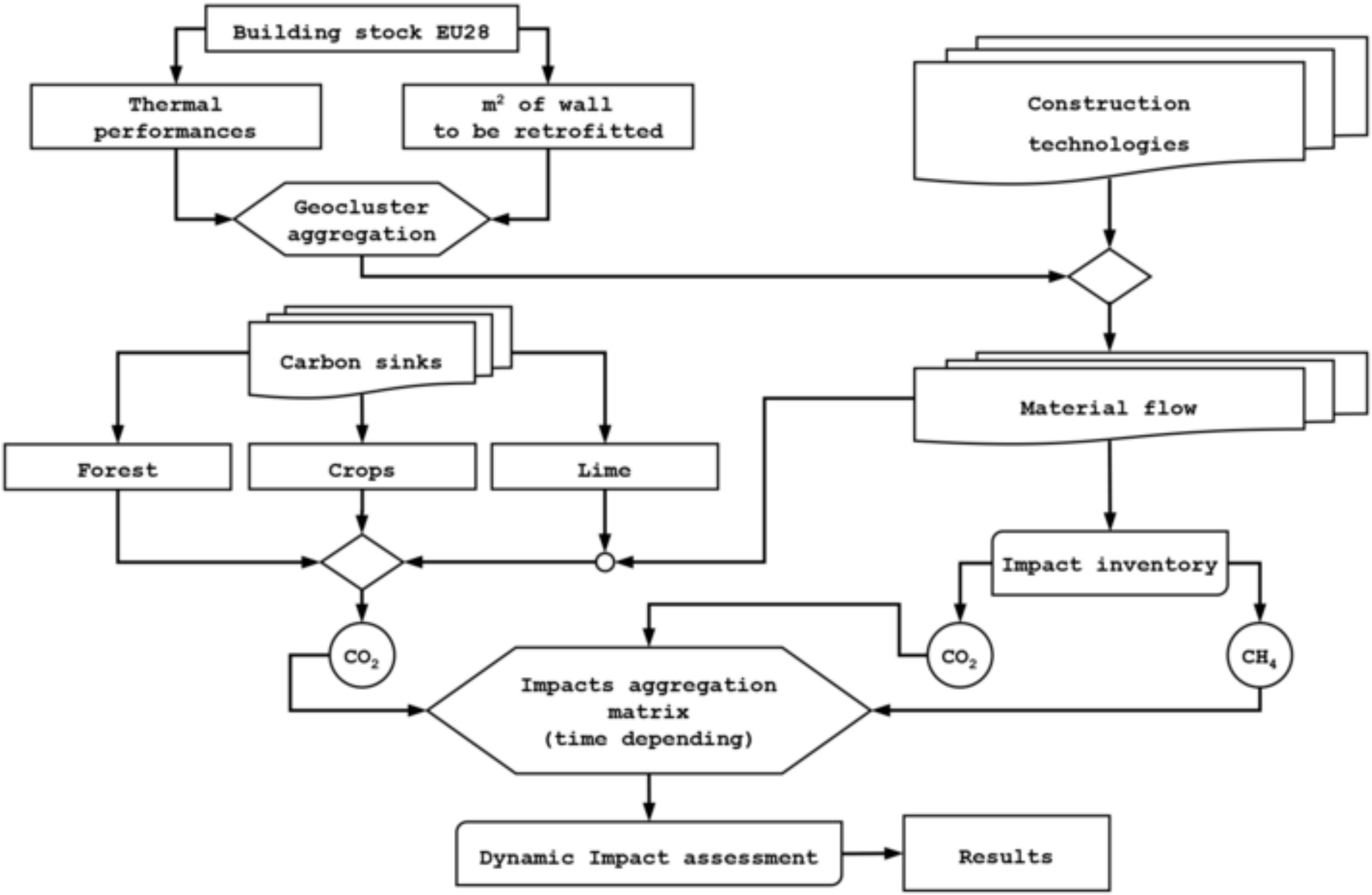

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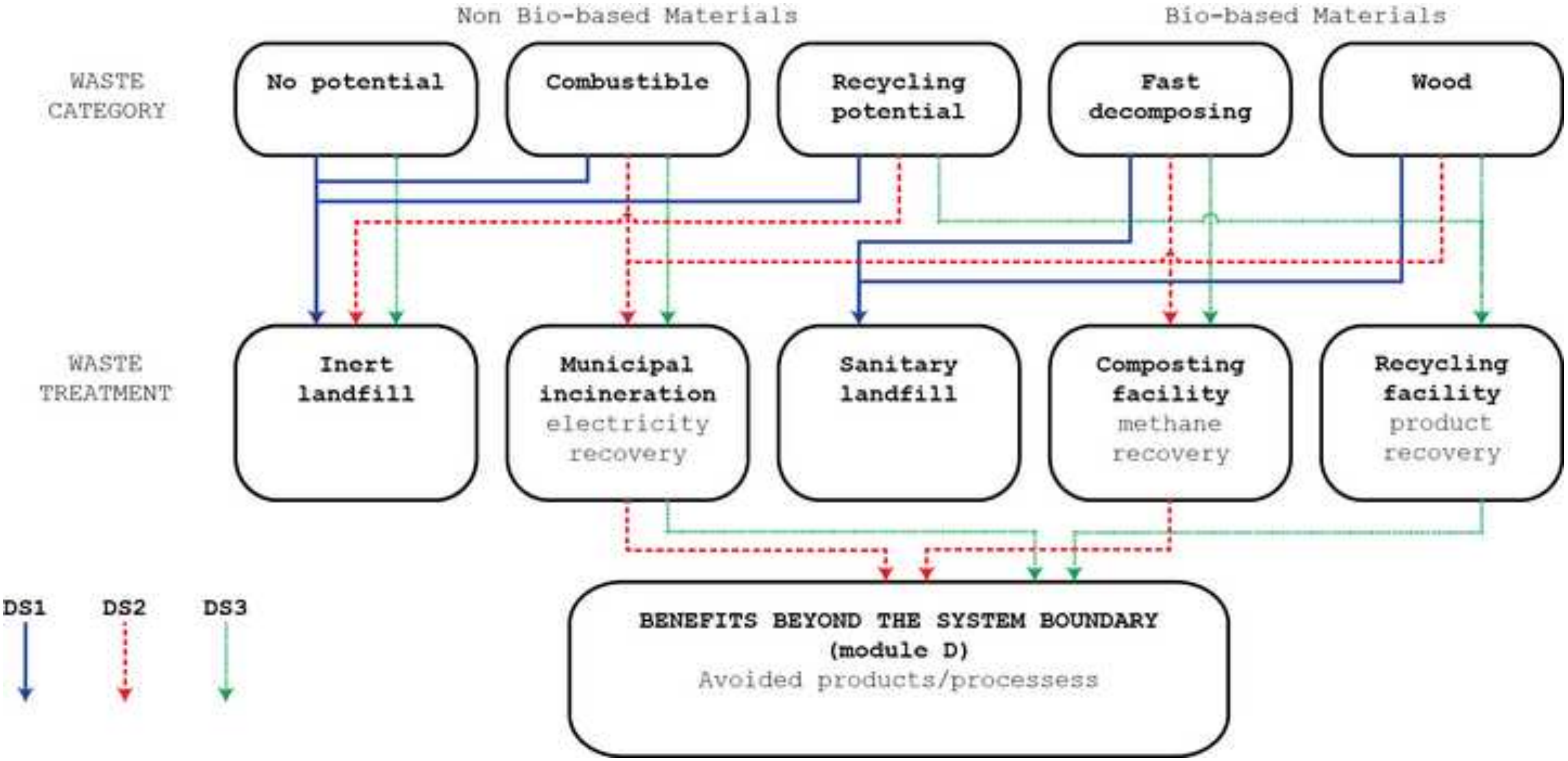

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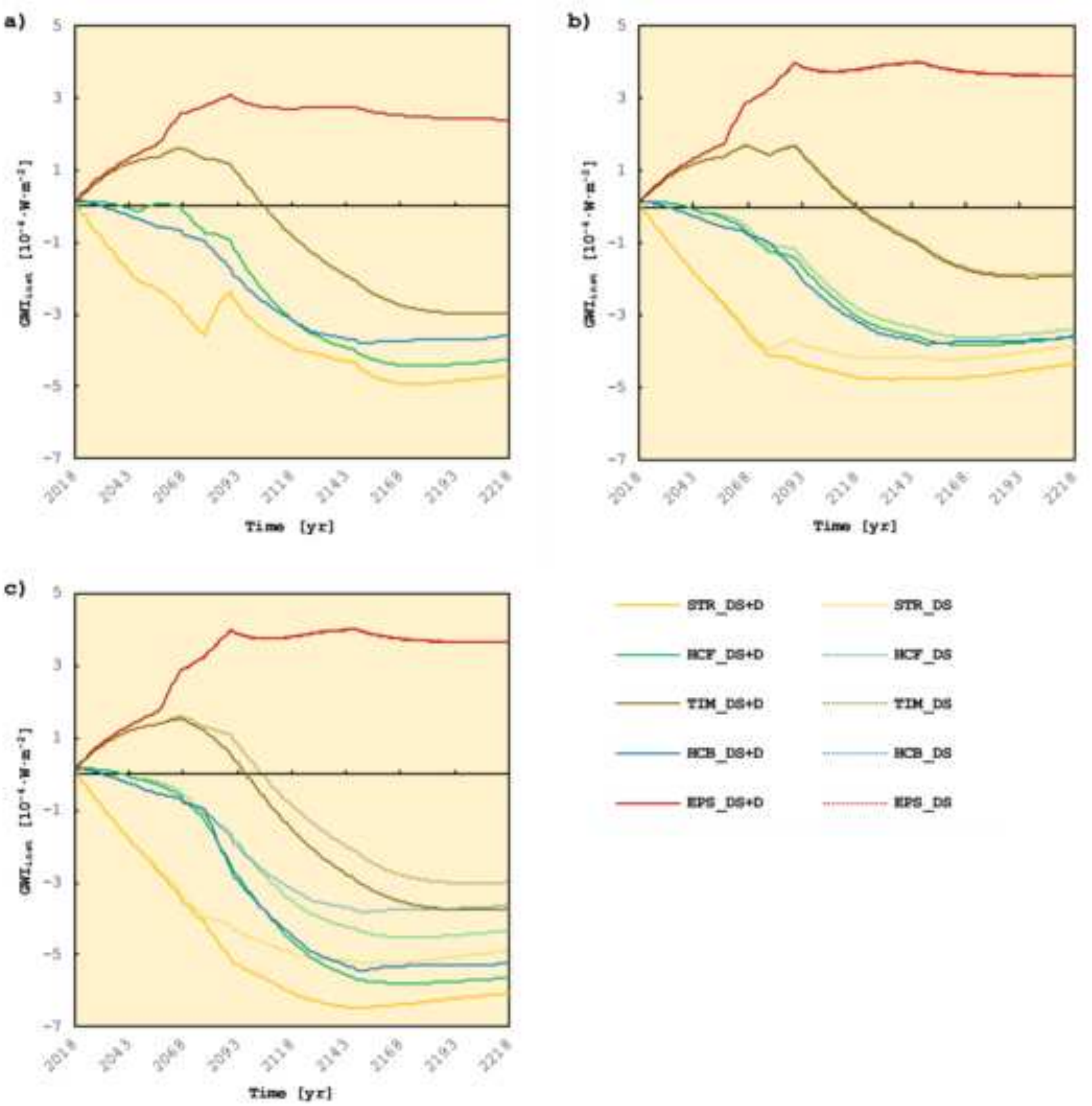

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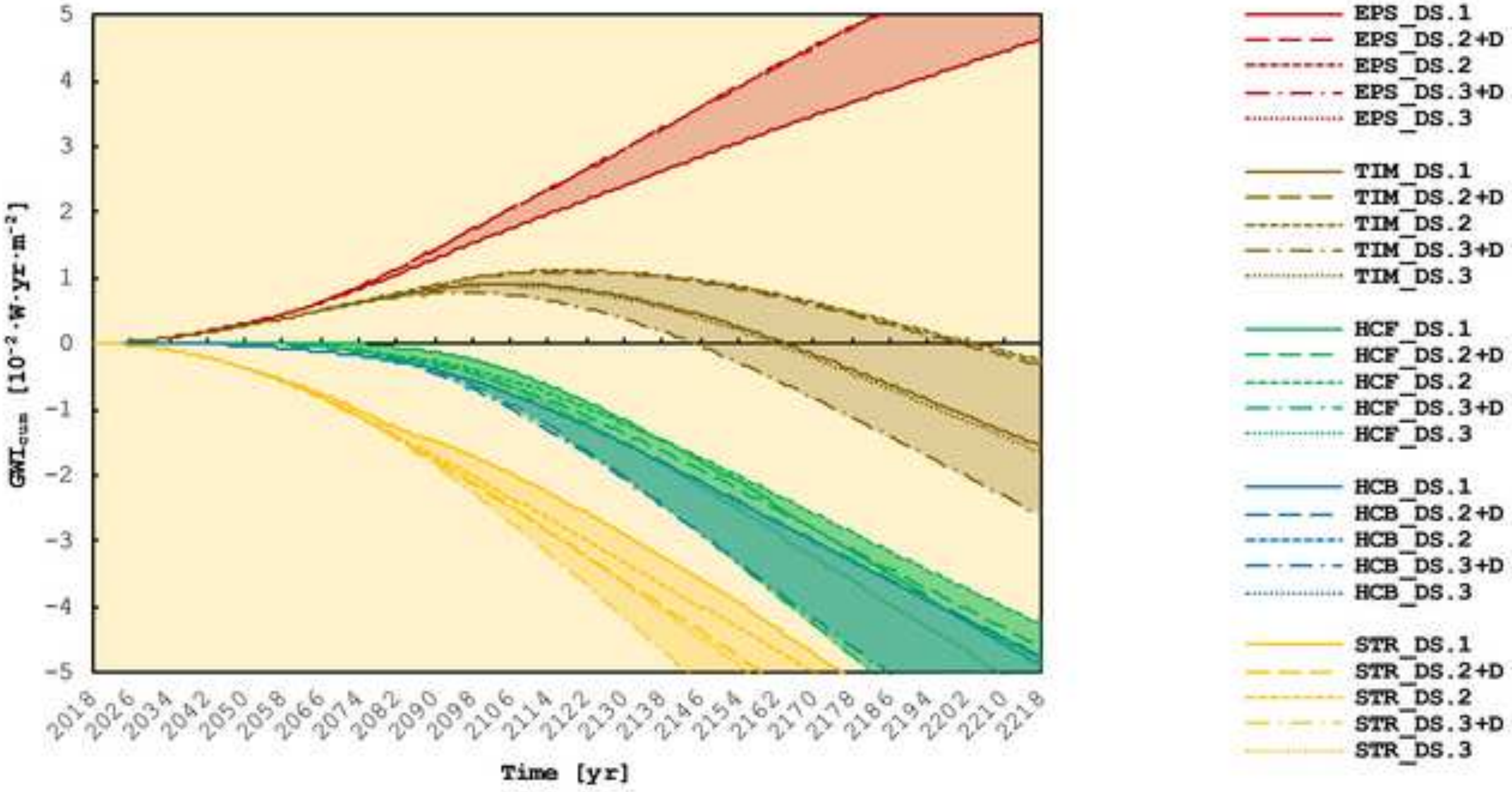
5
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3
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−4
−5
GWI$_{cus}$ [10^{-2}·W·yr·m^{-2}]
2018
2026
2034
2042
2050
2058
2066
2074
2082
2090
2098
2106
2114
2122
2130
2138
2146
2154
2162
2170
2178
2186
2194
2202
2210
2218
Time [yr]
EPS_DS.1
EPS_DS.2+D
EPS_DS.2
EPS_DS.3+D
EPS_DS.3
TIM_DS.1
TIM_DS.2+D
TIM_DS.2
TIM_DS.3+D
TIM_DS.3
HCF_DS.1
HCF_DS.2+D
HCF_DS.2
HCF_DS.3+D
HCF_DS.3
HCB_DS.1
HCB_DS.2+D
HCB_DS.2
HCB_DS.3+D
HCB_DS.3
STR_DS.1
STR_DS.2+D
STR_DS.2
STR_DS.3+D
STR_DS.3

Figure 07

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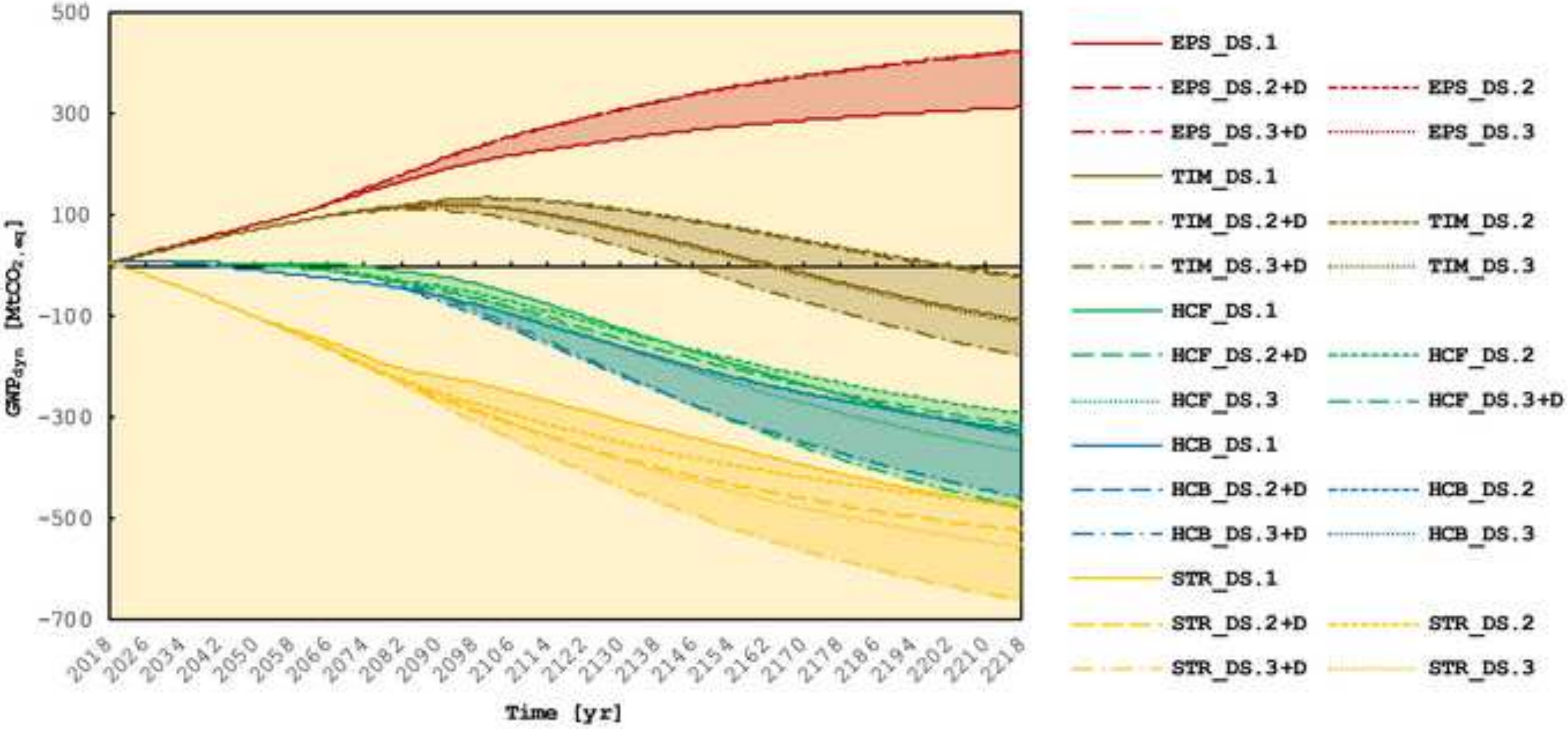

Figure 08

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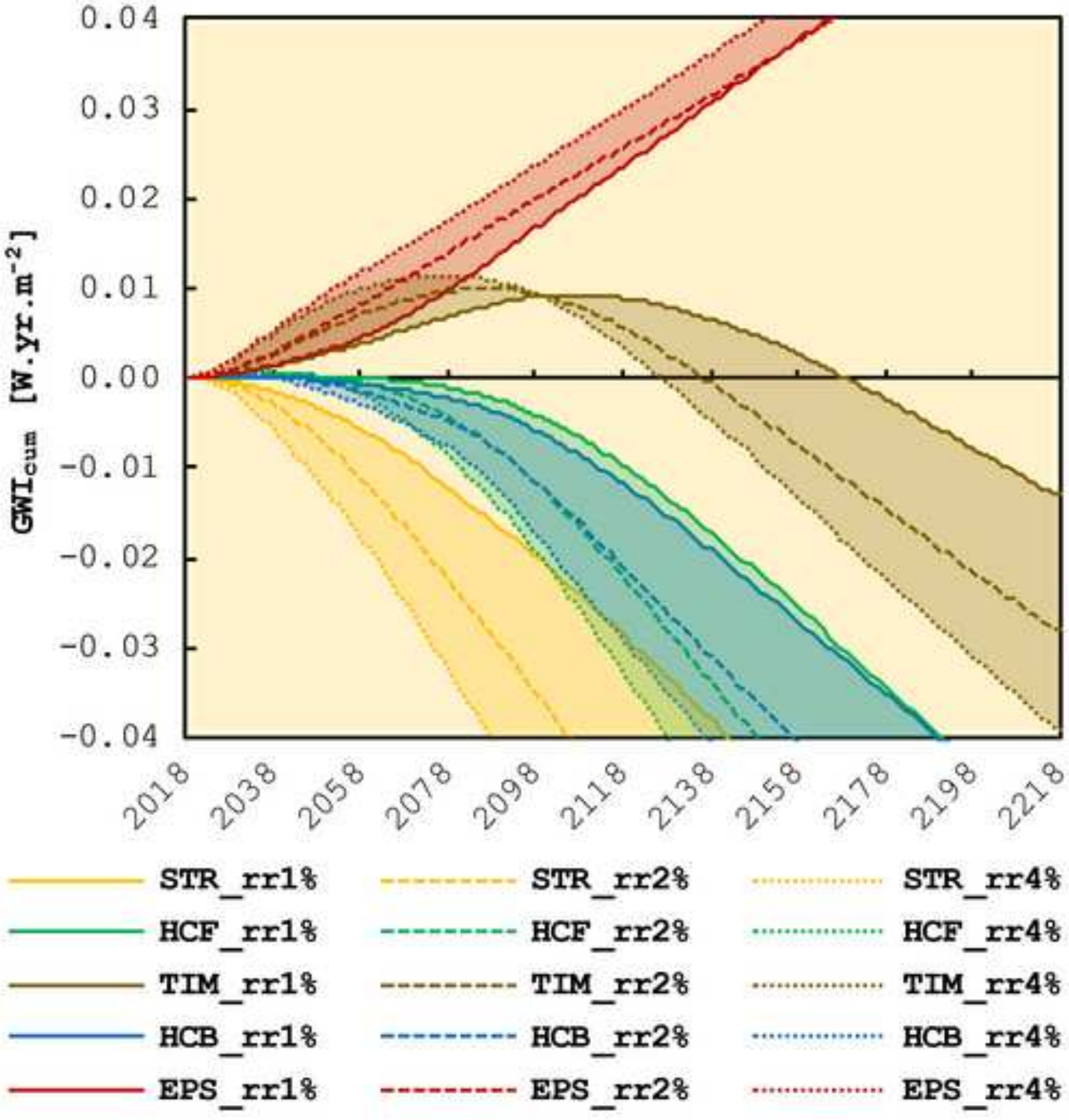

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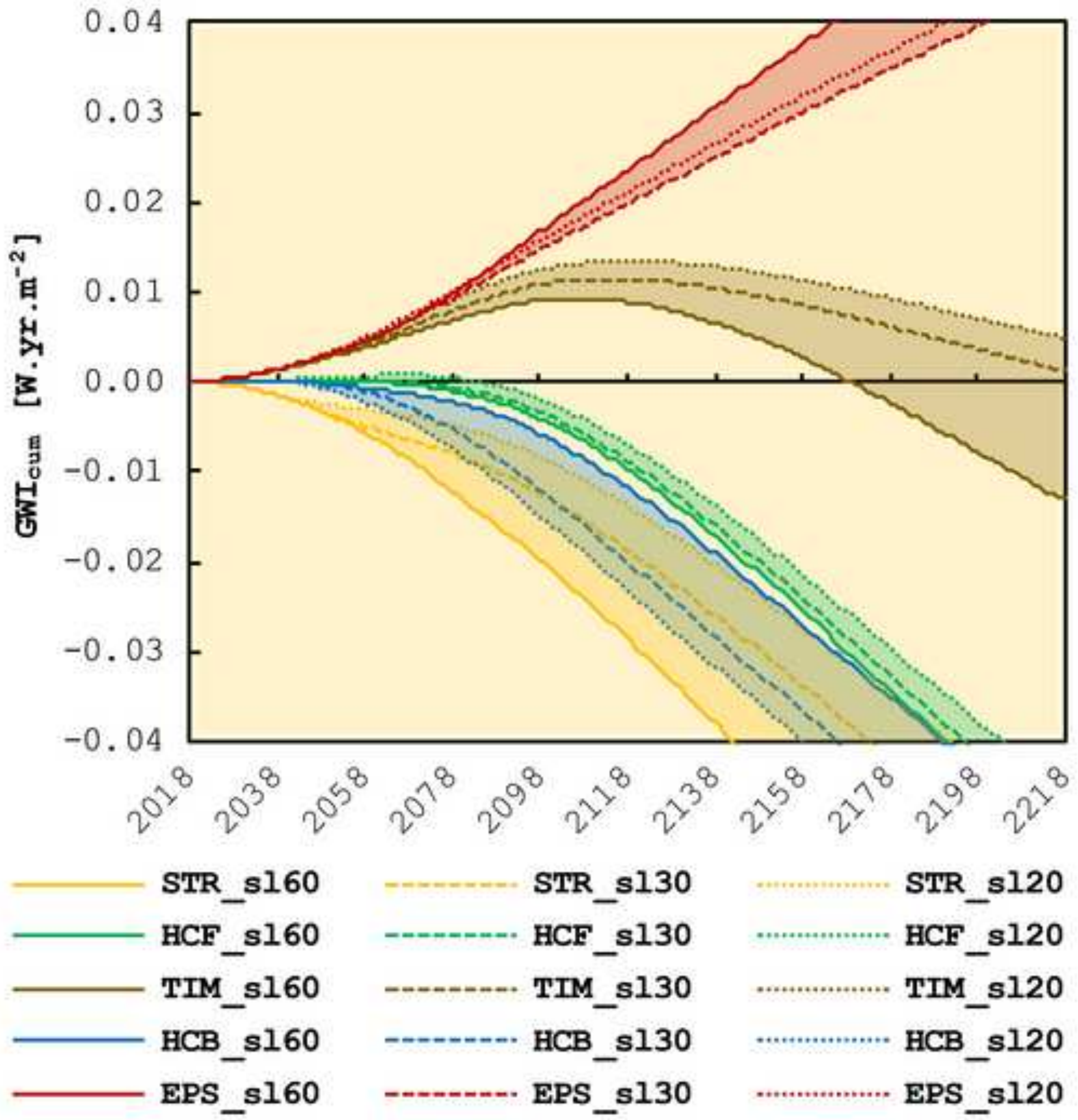
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
GWI_{cum} [W.yr.m^{-2}]
2018
2038
2058
2078
2098
2118
2138
2158
2178
2198
2218
STR_sl60
STR_sl30
STR_sl20
HCF_sl60
HCF_sl30
HCF_sl20
TIM_sl60
TIM_sl30
TIM_sl20
HCB_sl60
HCB_sl30
HCB_sl20
EPS_sl60
EPS_sl30
EPS_sl20

Figure 10
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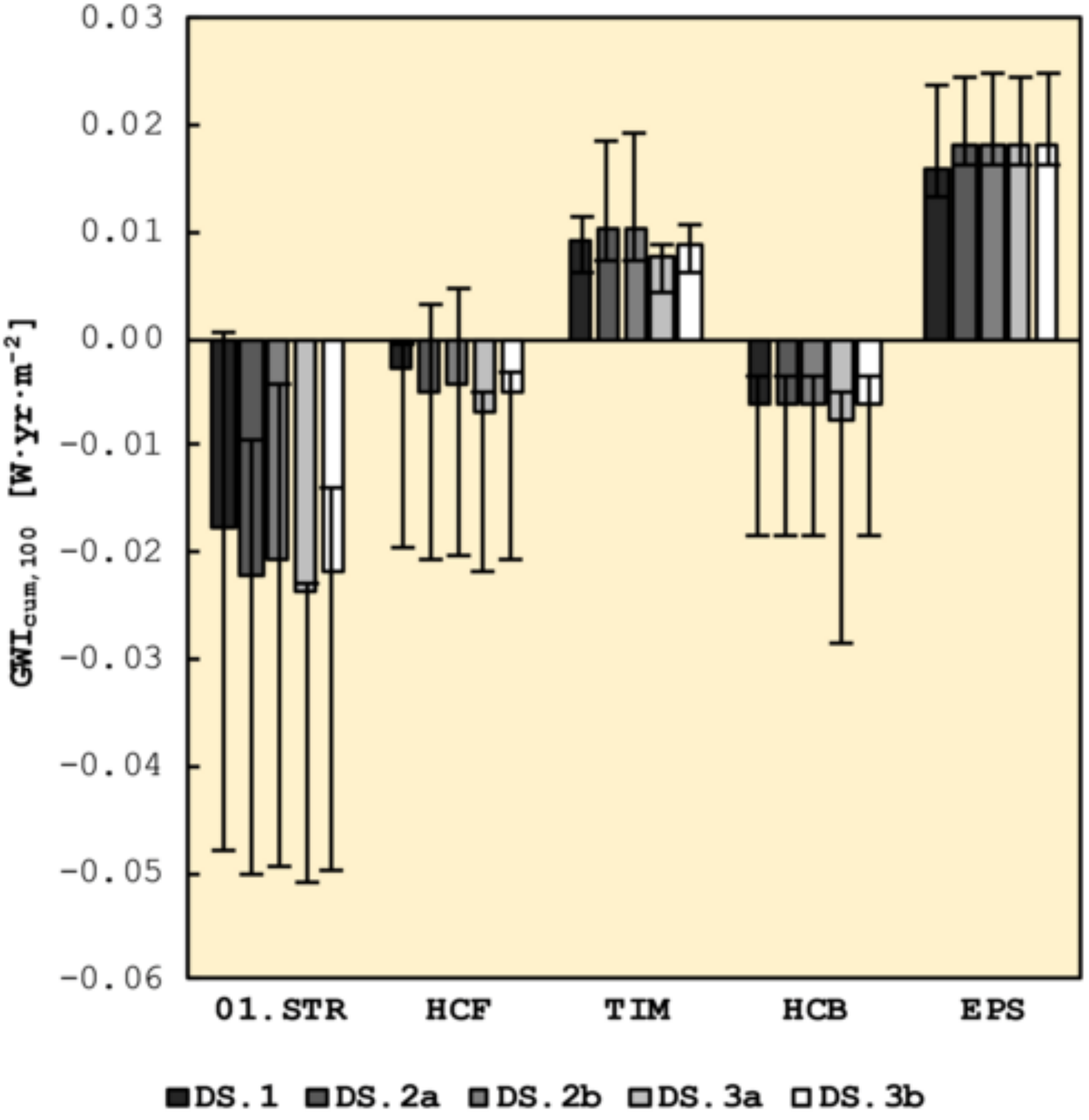
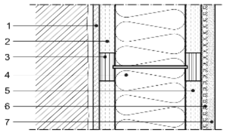


Table 01

STR



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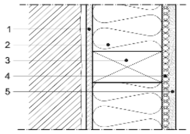

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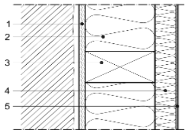

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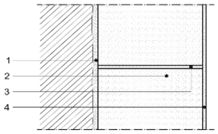

Cod.	Material	Thickness	Density	Thermal conductivity (λ)	Mass	Life span
		mm	kg·m^{-3}	W·m^{-1}·K^{-1}	kg·m^{-2}	yr
01. STR - I-joist frame with pressed straw						
1	OSB	18	650	0.13	12	60
2	Light clay straw	45	600	0.16	27	60
3	Timber I-joist	var*	500	0.12	var*	60
4	Straw chips	var*	100	0.051	var*	60
5	Light clay straw	45	600	0.16	27	60
6	Reed mat	20	145	0.06	3	30
7	Lime plaster	20	1800	0.67	36	30
02. HCF - Preassembled frame with injected hempcrete						
1	OSB	18	650	0.13	12	60
2	Injected hempcrete	var*	200	0.054	var*	60
3	Timber frame	var*	500	0.12	var*	60
4	Reed mat	20	145	0.06	3	30
5	Lime plaster	20	1800	0.67	36	30
03.TIM - Timber frame						
1	OSB	18	650	0.13	12	60
2	Glass wool	var*	18	0.038	var*	40
3	Timber frame	var*	500	0.12	var*	60
4	Wood fibreboard soft	60	130	0.05	8	40
5	Cover plaster	6	1800	0.8	11	40
04. HCB - Hempcrete blocks						
1	Cement mortar	10	1800	0.8	18	60
2	Hempcrete blocks	var*	330	0.07	var*	60
3	Light lime mortar	-	500	0.1607143	6	60
4	Lime plaster	20	1800	0.67	36	40
05. EPS – Expensed polystyrene for external thermal insulation composite system (ETICS)						
1	Cement mortar	1	1800	0.8	2	60
2	EPS	var*	16	0.04	var*	40
3	Base plaster	2	1800	0.8	4	40

Table 02

		Geocluster						
	Unit	1	2	3	4	5	6	7
Floor area	10^6 m^2	2,406	3,203	3,059	2,979	5,398	1,775	781
Multifamily (MF)	%	58%	69%	33%	15%	35%	40%	40%
	$S_w \cdot S_f^{-1}$	1	0.98	0.85	0.6	0.64	0.49	0.62
Single family (SF)	%	42%	31%	67%	85%	65%	60%	60%
	$S_w \cdot S_f^{-1}$	1.34	1.34	1.38	0.76	1.03	1	1.13
Renovation Rate (RR)	%	0.10%	0.80%	2.00%	0.30%	1.40%	0.50%	0.90%
Walls yearly renovated	10^6 $m^2 \cdot yr^{-1}$	2.05	25.57	68.55	6.81	65.21	6.47	5.53
Current U-value of ext. walls	$W \cdot m^{-2} \cdot K^{-1}$	1.9	1.42	1.36	1.6	1.14	1.07	0.44
Min U-value from legislation	$W \cdot m^{-2} \cdot K^{-1}$	0.54	0.33	0.35	0.29	0.27	0.29	0.18
U-value target after retrofit	$W \cdot m^{-2} \cdot K^{-1}$	0.38	0.22	0.24	0.18	0.17	0.16	0.15

Retrofit as a carbon sink: the carbon storage potentials of the EU housing stock

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Abstract

In the next decades, a large share of residential buildings in EU-28 is expected to be renovated to achieve the 2 °C target requested by the Paris Agreement by 2050. Bio-based materials used for increasing the thermal insulation and temporary store carbon in construction elements might be a valuable opportunity that can contribute to accelerate the transition to a zero-carbon society. This article investigates the effect of massively storing carbon in bio-based construction products when used for the renovation of existing facades. Five alternative construction solutions were compared, three with a large amount of fast-growing biogenic material used as insulation, one with timber used for the frame and additional fibrewood as insulation, and the last one with synthetic insulation. A statistic-based Geocluster model was developed to predict the future material flow for building renovation in EU-28 and a dynamic life cycle assessment performed in order to verify the contribution of construction materials in reducing/increasing the carbon emissions over time. The results show that fast-growing biogenic materials have an increased potential to act as a carbon sink compared to timber. In particular, if straw is used as an insulation material, the capacity to store carbon from the atmosphere is effective in the short-term, which represents an important strategy towards the Paris climate Agreement goals.

Data Statement

Supplementary Info_Appenix A

Appendix A.1: Age distribution of the Residential Building Stock per Geocluster

Geocluster	ISO code	**< 1945**			**1945 - 19**	
		[-]	$[m^2]$		[-]	[m
Geocluster 1	PT	16%	108,594,085	421	21%	141,046,730
	ES	13%	312,502,488		19%	453,177,284
Geocluster 2	CY	3%	1,997,100	640	10%	6,716,913
	EL	7%	42,507,920		24%	140,136,000
	IT	20%	591,368,580		31%	935,138,901
	MT	17%	4,456,896		17%	4,491,632
Geocluster 3	BG	19%	64,153,992	939	32%	106,923,320
	FR	27%	832,394,800		18%	561,991,100
	HR	13%	20,441,124		27%	43,934,616
	SI	30%	21,684,320		21%	15,214,689
Geocluster 4	BE	34%	145,174,750	1,183	25%	105,558,250
	IE	19%	40,695,825		14%	29,020,275
	UK	37%	996,656,365		25%	694,796,284
Geocluster 5	AT	27%	118,734,255	1,445	19%	84,656,853
	CZ	22%	82,084,671		22%	82,572,600
	DE	25%	955,548,540		34%	1,291,732,020
	HU	25%	112,214,568		30%	137,216,208
	LU	19%	5,598,642		19%	5,460,546
	NL	19%	170,423,952		24%	213,583,840
Geocluster 6	DK	32%	113,409,358	397	27%	95,868,900
	LT	22%	19,250,565		37%	32,087,172
	PL	19%	199,820,063		23%	239,825,212
	RO	11%	39,935,553		37%	132,759,700
	SK	14%	24,667,452		32%	55,253,034
Geocluster 7	EE	17%	7,136,325	182	27%	11,174,037
	FI	12%	35,243,856		21%	61,878,306
	LV	23%	15,473,710		25%	17,402,775
	SE	26%	123,889,176		34%	162,347,328
	EU-28	23%		5,140	26%	

* Reference year 2014

Source: Odyssee
http://ec.europa.eu/energy/en/eu-buildings-database

Supplementary Info_Appenix B

Appendix B.1: Ecoinvent 3.2 process inventory for materials production

Cod.	Material description	Ecoinvent materials/process	Amount	Unit
STR - I-joist frame with pressed straw				
1	Oriented Strand Board	Oriented strand board {RER}| production | Alloc Def, U	1	kg
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm
2	Light clay straw	Straw, stand-alone production {CH}| production | Alloc Def, U	0.24	kg
		Clay {CH}| clay pit operation | Alloc Def, U	0.76	kg
		Tap water {CH}| market for | Alloc Def, U	0.11	kg
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.038	tkm
		Electricity, medium voltage {CH}| market for | Alloc Def, U	0.5	kWh
		Industrial machine, heavy, unspecified {GLO}| market for | Alloc Def, U	0.000005	kg
3	Steico Joist	Joist, engineered wood {RoW}| engineered wood joist production | Alloc Def, U [kg]	1	kg
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm
4	Straw Chips	Straw, stand-alone production {CH}| production | Alloc Def, U	1	kg
		Chipper, stationary, electric {RER}| production | Alloc Def, U	0.0000002	p
		Electricity, medium voltage {CH}| market for | Alloc Def, U	0.00166	kWh
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm
5	Light clay straw	See n.2		
6	Reed mat	Reed production {CH}| production | Alloc Def, U	0.91	kg
		Steel, unalloyed {RER}| steel production, converter, unalloyed | Alloc Def, U	0.09	kg
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.75	tkm
		Industrial machine, heavy, unspecified {GLO}| market for | Alloc Def, U	0.0015	kg
		Electricity, medium voltage {AT}| market for | Alloc Def, U	0.01388	kWh
7	Lime Plaster	Lime, hydrated, packed {CH}| production | Alloc Def, U	0.25	kg
		Sand {CH}| gravel and quarry operation | Alloc Def, U	0.75	kg
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm
HCF - Preassembled frame with injected hempcrete				
1	Oriented Strand Board	Oriented strand board {RER}| production | Alloc Def, U	1	kg
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm
2	Hempcrete Injected	Chemical, organic {GLO}| production | Alloc Def, U	0.00069	kg
		Conveyor belt {RER}| production | Alloc Def, U	9.99E-09	m
		Electricity, medium voltage {IT}| market for | Alloc Def, U	0.00834	kWh
		Industrial machine, heavy, unspecified {RER}| production | Alloc Def, U	2.001E-06	kg
		Lime, hydraulic {RoW}| production | Alloc Def, U	0.12	kg
		Packing, cement {RoW}| processing | Alloc Def, U	0.3	kg
		Portland cement, strength class Z 42.5, at plant/CH U	0.03	kg
		Transport, lorry 16-32t, EURO4/RER U	0.006	tkm
		Maize seed, Swiss integrated production, at farm {CH}| production | Alloc Rec, U	0.00513	kg
		Diesel {CH}| market for | Alloc Def, U	0.00025	kg
		Tap water, at user/RER U	0.4	kg
		Electricity, medium voltage {IT}| market for | Alloc Def, U	0.00428	kWh
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm
3	Reed mat	Reed production {CH}| production | Alloc Def, U	0.91	kg
		Steel, unalloyed {RER}| steel production, converter, unalloyed | Alloc Def, U	0.09	kg
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.75	tkm
		Industrial machine, heavy, unspecified {GLO}| market for | Alloc Def, U	0.0015	kg
		Electricity, medium voltage {AT}| market for | Alloc Def, U	0.01388	kWh
4	Timber frame	Sawnwood, softwood, dried (u=20%), planed {RER}| production | Alloc Def, U [kg]	1	kg
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm
5	Lime Plaster	Lime, hydrated, packed {CH}| production | Alloc Def, U	0.25	kg
		Sand {CH}| gravel and quarry operation | Alloc Def, U	0.75	kg
		Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U	0.05	tkm