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Master's thesis

Dynamic life cycle assessment to compare conventional and bio-based building construction impact on global warming

Aalto University
School of Science
Master's Programme in Advanced Materials for Innovation and Sustainability (AMIS)
Academic year 2018-2019

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"Each generation doubtless feels called upon to reform the world.

Mine knows that it will not reform it, but its task is perhaps even greater.

It consists in preventing the world from destroying itself."

Albert Camus' Nobel Prize speech (1957)

Abstract

In a context of climate emergency, storing temporarily carbon in biogenic construction materials seems a particularly attractive strategy to mitigate important building sector impact on global warming. Usually, environmental impacts are assessed using standard Life Cycle Assessment (LCA), a product-based method that gives notably the global warming potential (GWP). In LCA, all greenhouse gas emissions linked to the product are assumed to be released in the first year even if they are emitted at different times within the chosen time horizon. Their GWP is calculated at this time horizon, which is usually 100 years. Moreover, biogenic carbon is often excluded of the calculation assuming a balance between captured and emitted carbon. On the other hand, new global warming impact calculation methods such as dynamic LCA propose to include timing in the calculation and to assess the value of temporarily storing carbon in long-lived products such as building structures.

The aim of this study was to investigate the impact of these hypotheses on the estimated GWP of building materials, by comparing the static and a dynamic LCA approach.

Two types of exterior walls were compared: one made with conventional materials (concrete and glass wool), the other mostly composed of bio-based materials such as straw and timber. Several parameters are discussed in detail: the real lifespan of buildings in France, carbon storage by forests and annual crops, the time horizon used to calculate GWP, the different greenhouse gases emitted, the accuracy of CO_2 equivalent as an indicator of global warming. Finally, the overall impact on the global warming of different building construction and renovation materials is estimated under different scenarios applied to the French context.

Acknowledgements

I would like to acknowledge M. Thibaut Lecompte, Senior Lecturer at the Université Bretagne Sud, for his time, his advices and the great conversations ourhad together.

I also would like to acknowledge, M. Arthur Hellouin de Menibus, who gave me very interesting post-master thesis perspectives. He encourages me to continue my way with a civic service in eco-construction.

A special thanks to my colleagues Theo Vinceslas, Yann Guévec, Julien Troufflard, Luc Grasson, with whom I had very funny discussions as well as serious one about nonsenses in our society. Thanks to them I had a great time in Lorient.

Lastly, I would like to acknowledge my referent professors: Mrs Erini Sarigiannidou (Phelma – Grenoble INP), M. Robin Ras and Janne Halme (Aalto University). They all are close to their students, which is very pleasant. They put a lot of energy to make this new AMIS master on a great way.

Presentation of the institute

The IRDL is located in Brittany, France. It is a research institute coming from the consortium of an engineering material laboratory and a mechanics and systems laboratory. This bring together all the necessary competences from the sample to the big structure, especially for the shipbuilding sector and marine energy. IRDL had in 2018, 110 lecturers, 120 doctoral students, 10 post-doctoral researchers as well as 55 engineers, technicians or administrative personnel. Researches conducted by IRDL are separated into five complementary and multidisciplinary topics:

- Composites, nanocomposites, biocomposites
- Multi-materials assembling
- Durability of heterogeneous materials
- Energetical systems
- Structures and interactions

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List of the symbols and abbreviations

CaO	Calcium oxide
CH4	Methane
CO	Carbon monoxide
CO2	Carbon dioxide
CO2e	Carbon dioxide equivalent
dLCA	Dynamic life cycle analysis
DOC	Degradable organic carbon
DOCf	Degradable organic carbon fraction
EoL	End of life
EPD	Environmental Product Declarations
EU	European Union
FU	Functional unit
GHG	Greenhouse gases
GWIinst	Instantaneous global warming impact
GWIcum	Cumulative global warming impact
GWP	Global warming potential
GWP100	Global warming potential at the 100-year time horizon
LCA	Life cycle assessment
MCF	Methane correction factor
N2O	Dinitrogen oxide
R	Thermal resistance
RF	Radiative forcing
SF6	Sulphur hexafluoride
SWDS	Solid waste disposal site
yr	Year

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Introduction

As the Great Acceleration study showed, we are living an exponential period of : energy use, population, GDP, transportation, fertilizer consumption, greenhouse gases emissions, tropical forest loss and so on [1]. Environmental limits within which humanity can safely operate are getting crossed (see Figure 1). Our global industrialized civilization is too complex, generates too much pollution, and is then likely in an already begun process of collapse ([2]–[4]).

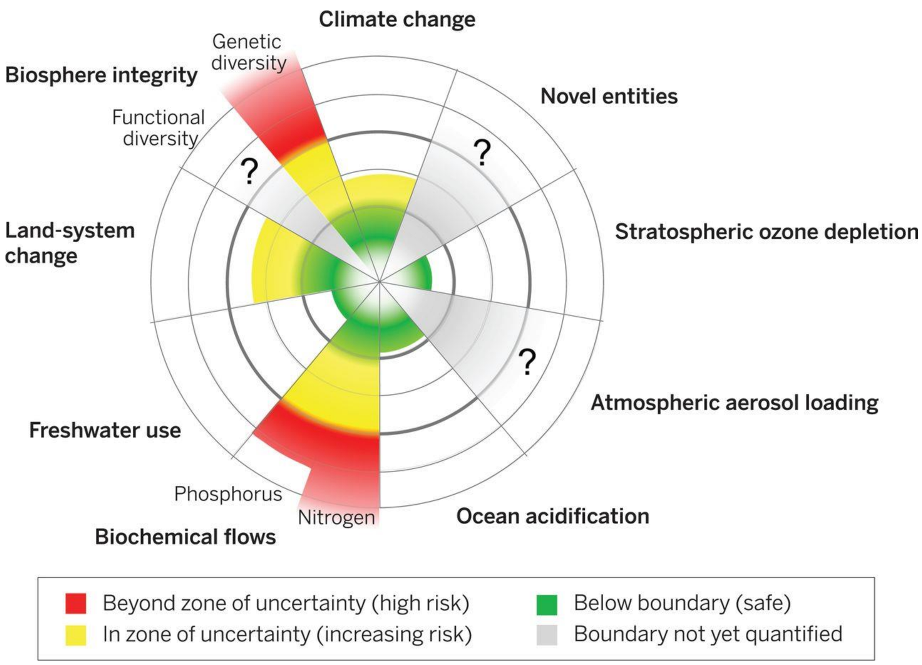


Figure 1 : Planetary Boundaries (from [5])

Global warming is one increasing risk parameter to deal with. In this context, European Union (EU) has signed the Paris Agreement at COP21. EU members recognised the need to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C", that "sustainable lifestyles and sustainable patterns of consumption and production [...] play an important role in addressing climate change" and aimed to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century"

[6]. The EU has made quantified commitments such as at least 40 % cuts in greenhouse gas emissions (from 1990 levels) for the year 2030. France being part of it, has set objective to be carbon neutral by 2050, meaning reduce GHG emissions by 6 to 7 [7].

The building sector is a big contributor to global warming: worldwide, it consumes 30-40% of primary energy and contributes up to one-third of GHG emissions ([8]–[10]). In France, this sector represents 43% of French energy consumption (660 TWh), and around 25% of carbon dioxide (CO_2) emissions [4], [5]. Including both construction and demolition, it accounts for 50% of all natural resources exploited, 40% of the waste produced and 16% of the water consumed [6].

The French metropolitan housing stock comprises around 34.5 million houses, of which 56% are individual homes and 44% are collective [1]. More than half were built before the first French thermal building regulations were introduced in 1974 [11], [12]. In addition, the tertiary activity park extends over more than 800 million m², one third of the total housing stock area ([12]–[14]).

Building new buildings and undertaking energy efficiency renovation of existing buildings will require a significant amount of work and the construction materials, together with their global warming impact (GWI) due to greenhouse gas emission from embodied energy need to be calculated. The embodied energy of a building material is the total energy consumed for its production, use and disposal, from the extraction of the raw materials to the end-of-life treatment. The embodied energy of a building technology is the embodied energy's sum of its components, plus the energy needed for transportation and construction/destruction.

The building sector is then a key sector in terms of mitigation potential. For this reason, biogenic materials have been identified by the French government as a sector to be developed, notably because it is able to reduce fossil origin raw material consumption, to capture emitted carbon and to create new economic fields [15].

Wood and straw products used in bio-based construction enable carbon storage due to photosynthesis. The proportion of carbon that may be released at the end of life, for instance if the materials are burned, is called temporarily stored carbon.
The global warming potential (GWP) of products or systems is calculated using Life Cycle Assessment (LCA). However, the main problem with this method is that it does not take the time scale into consideration: emissions within a set time horizon are treated equally. According to the the same logic, biogenic CO_2 is generally considered to be climate neutral, i.e. for wood there is balance between carbon sequestration at forest level and re-emission at end of life (EoL) of wood products [16], [17], and for straw short biomass cycle do not alter natural carbon cycle [18]. Temporary storage of carbon is totally neglected. Different authors have addressed these issues [19]–[21]. Levasseur et al. ([22], [23]) used an interesting dynamic LCA (dLCA) methodology based on timing the capture and emission of greenhouse gases (GHG) on a year-by-year basis.

Robust methodologies are required to evaluate the environmental impacts of different materials for design guidance. In the present work, three different methods are compared: static LCA, dynamic LCA and simplified dynamic LCA. The three methods are applied to two walls, one representative of conventional building, and one composed of biobased materials (straw and timber). The present analysis focusses on the global warming potential (GWP). The results of the comparison of three LCA methodologies are discussed in terms of the lifespan of buildings, the time horizon at which GWP is calculated and the accuracy of CO_2 equivalent as an indicator of global warming. Then, the impact of different French strategies regarding the use of bio-based materials in buildings is evaluated.

1. Bibliographic review

First, the French building context is presented to better understand the current needs of the sector. Then, data were collected to investigate whether a lifespan of 50 years for a building is representative of the real situation. Finally, reviews on carbon sequestration of timber and straw as well as GHG emissions due to decay of these biogenic materials and to cement and lime carbonation were done to properly assess carbon storage and release dynamics.

1.1 Housing stock in France

Currently, concrete buildings are very much the rule and the use of bio-sourced materials is exceptional in the building sector. In terms of structure, wood construction only accounts for 9% of new individual houses and 4% of new collective housing [24], only 7% of insulating materials are bio-sourced (50% are mineral wool and 40% are plastic foam). Table 1 gives an overview of the current building stock in France.

Table 1: Overview of the current French building stock [12], [25], [26]

Construction types		Number of existing buildings	Construction period of existing housings			
			before 1948	1948-1974	1974-2000	after 2000
Residential (70% of the floor area - 2011.10^6 m² of which 33,8.10^6 m² built in 2017 (+1.7%))	Individual houses	19 million	33%	22%	33%	12%
	Collective housing	15 million	28%	41%	23%	8%
Tertiary (30% of the floor area - 862 10^6 m² of which 25.10^6 m² built in 2017 (+2.9%))		1.46 million	(before 1960) 10%	(1960-1974) 35%	43%	12%
Mean area of houses			75 m²	75 m²	82 m²	80 m²
Main materials used in the respective time periods			Stone; solid brick; adobe ; timber frame + earth.	Stone ; solid and hollow brick ; Hollow concrete block	Hollow concrete block Hollow and solid brick	
Main insulating materials			none		Mineral wools Synthetic foams	
Proportion of inefficiently insulated houses (F and G in the Energy Efficiency Rating)		Individual houses	26%	44%	17%	2%
		Collective housing	38%	30%	11%	13%

1.2 Building lifespan and in-service life of products and systems

The longer the lifespan of a product or a building, the longer biogenic materials temporarily store the carbon, and the less petro-sourced materials are used. This parameter thus requires particular attention in LCA. The main issue is that estimating a building's lifespan does not only depend on ageing of the structure but also on social and aesthetic considerations. Data were gathered to evaluate if building lifespan of 50 years is a figure representative of the real situation.

The average increase in the construction of housing in France in the last 20 years has been about 1% [25]. Hence the replacement rate of existing buildings is around 0.7% of the housing stock, which represents 70% of the floor surface (see Table 1).

Assuming the average growth rate remains constant, the building stock will be completely renewed in 90 years, which can be considered as representative of the lifespan of a building. Another way to estimate the lifespan is the average age of existing buildings. In France, this is about 50 years ([25], [27], [28]), which means the average lifespan is clearly more than 50 years. In addition, two studies conducted in Norway propose a statistical way to define the lifespan: a Weibull distribution for housing with a lifespan of between 40 and 300 years, a median value of 100 years and a mean of 125 years ([29], [30]).
It thus seems reasonable to prescribe a lifespan of 50 years for tertiary buildings (offices and shops) and a lifespan of 100 years for residential buildings. Administrative buildings (town halls, libraries, museums) are generally thought to last more than 150 years. For unspecified buildings, a default value of 75 years is assigned.

During a building's lifetime, the building materials will be changed, i.e., they have an in-service life. Brand theorized the notion of shearing layers of change: because of the different rates of change of its components, a building is always tearing itself apart [31]. He proposed "the six S's":

- Site which outlasts generations of buildings;
- Structure (foundation and load-bearing elements) whose lifetime ranges from 30 to 300 years;
- Skin which consist of exterior surfaces. They last around 20 years to keep pace with technology and trends;
- Services : electrical and communications wires, fluid network which last between 7 to 15 years ;
- Space plan : interior facings and non-load-bearing partitions. They last 3 years in commercial spaces and up to 30 in individual houses ;
- Stuff: chairs, desk, phones, pictures, kitchen appliances, lamps, and furniture that have high turnovers.

The lifespan of the component materials used in the types of wall studied here are inspired by this layer approach and their impacts are counted as many times as they are replaced. As a building, they have both a physical lifespan and an in-service lifespan, the latter being shorter. The in-service lifespans is defined as follows:

- 100 years for the structure (concrete or timber beam);
- 50 years for the insulator (glass wool or straw bale compressed by timber battens) as well as for gypsum plasterboard;
- 25 years for renders made of cement, lime or earth;
- 15 years for the paint.

1.3 Greenhouse gas dynamics linked to bio-based materials

1.3.1 Carbon sequestration

Biogenic materials play a fundamental role in the carbon sequestration, since the biomass absorbs carbon dioxide (CO_2) during plant growth due to photosynthesis.
One kilogram of straw can sequester 1.34 to 1.5 $kgCO_2$ ([32], [33]) and additional literature data are summarized in Appendix 1. A straw carbon content of 45% is here considered. With 15% moisture content [34], this leads to a carbon uptake of 1.40 $kgCO_2$/kg of wet straw.
Timber materials are often referred as being "carbon neutral" because the CO_2 released at the EoL due to decay or incineration refers to the CO_2 captured during plant growth. Wiloso & al. [35] showed that assuming biogenic carbon neutrality leads to biases in the 'true' values based on a complete inventory. It can either underestimate or overestimate GWI, depending on the system boundaries chosen, the form of carbon emissions, and biomass valuation[35]. For instance, burning biomass for energy provision increases the amount of carbon in the air just like burning fossil fuels if harvesting the biomass reduces the amount of carbon stored in plants and soils [36]. He Hence, flows from carbon biomass are counted as inputs into and outputs from the system. Concerning inputs, carbon content of wood is considered to be negative if the wood was produced under sustainable forest management ([37], [38]). After a literature review (see Appendix 1), the carbon content of wood is considered to be 50.6%, and so carbon uptake is 1.86 $kgCO_2$/kg of dry wood ([33], [39]).

Since decomposition of organic material derived from biomass sources is the primary source of CO_2 released from waste [40], it should be carefully analysed. But EoL impacts of biogenic materials are not clear in the literature. The following literature review was thus undertaken to assess the real impacts of biogenic carbon decay.

1.3.2 Reemission of captured biogenic carbon in landfill and composting sites

2006 IPCC Guidelines for National GHG Inventories aim to estimate greenhouse gas (GHG) emissions from the waste sector. For biogenic carbon decomposition of landfilled waste, these guidelines provide a default value for the fraction of degradable organic carbon that decomposes under anaerobic conditions (DOCf). DOCf equals 0.5 [40]. No methodology is provided for N_2O emissions from SWDS because they are not significant. The DOCf value seems to be overestimated, especially for wood [101], [102]. Eq. 1 inspired by [100] corrects the amount of estimated methane (CH_4) emissions resulting from the decay of bio-based materials in a managed composting site.

Eq. 1 $$CH4x = W \times DOC \times DEGx \times DOCf \times MCF \times \frac{16}{12} \times OX$$

where *CH_4x* is the mass of methane generated at year x, *W* the deposited mass of waste, *DOC* the degradable organic carbon in the year of deposition, *DEGx* the percentage of degradation at year x, *DOCf* the DOC fraction that decomposes under anaerobic conditions, *MCF* the part of the waste that will decompose under aerobic conditions before the conditions become anaerobic in the SWDS, and *OX* is the oxidation factor.

Here, referring to semi-aerobic managed solid waste disposal sites, MCF is 0.5 and COR is 0.1 [40]. This leads to the following ranges of values:

- a carbon decomposition into the air as CO_2 (50% to 77.5% of the carbon) and as CH_4 (22.5% to 50%);
- a negligible emission of N_2O.

Moreover, according to Wisard™ software developed by Ecobilan/PwC for waste LCA [41], landfilled wood is 15% degraded after 100 years. Hence, 15% of carbon contained in wood degrades as CO_2 and CH_4. After that, residual carbon is permanently stocked in the soil of the SWDS.

When composted, 79% of the carbon in the straw is degraded at during the first year to form humus. The humus degradation rate is thus set at 0.8% per year for the 100-year horizon [42]. As a result, 9.5% of carbon straw remains in the soil. IPCC Guidelines also give default emission factors for composting sites : 10g CH_4/kg of treated waste and 0.6g N_20/kg of treated waste on a dry weight basis [43]. It is indicated that these values are based on a limited number of studies and it is thus good practice to use updated scientific information to improve emission factors. Hence, data from a literature review of industrial composting sites' emissions were preferred here. According to (Hermann, 2011) [42], without distinguishing short-term carbon storage, a mean of 97.55% of degradable carbon is released as CO_2 and 2.45% as CH_4 with extra emission of 0.787 gram N_20 per kilogram of carbon (gN_2O/kgC). For straw with 15% moisture content, this leads to 1 237 gCO_2/kg of straw and 11.8 gCH_4/kg of straw. These values are close to IPCC default values. Nevertheless, (Hermann, 2011) criticized some values and chose 0.11% CH_4 and 0.6 N_2O emissions. Moreover, French data gives 0.95 gCH_4/kg of composted matter [44].
More details are in Appendix 2.

1.4 Carbonation process

CO_2 present in gaseous state in the air penetrates materials like concrete or cement and lime renders through porosity and cracks. In the presence of water (which is present at least in the smallest pores), it causes a chemical reaction with the hydrated paste cement known as carbonation [45]. This is a CO_2 diffusion process, which is controlled by the saturation of the capillary system by water [46].
The carbonation process can be described by the following chemical equations [46]:
1. $CO_2(g) + H_2O = HCO_3^- + H^+$

2. $HCO_3^- = CO_3^{2-} + H^+$

3. The carbonate ion will react with Ca ions in the pore solution:

$Ca^{2+} + CO_3^{2-} = CaCO_3$

Thus, with carbonation, hydrates and particularly calcium hydroxide (portlandite) $Ca(OH)_2$ will dissolve and calcium carbonate $CaCO_3$ will precipitate until all of the $Ca(OH)_2$ is consumed.

As shown in Eq. 2, carbonation kinetics follows a square root law [46]–[48]:

Eq. 2 $$dc = k \times \sqrt{t}$$

where *dc* is the depth of carbonation, k the rate factor and t the time in years.

Thiery [49] proposed a law for the mass of CO_2 uptake (see Eq. 3) :

Eq. 3 $$\frac{MCO2}{MCO2max} = \frac{k \times \sqrt{t}}{e}$$

where *e* the thickness of the wall

Finally, Eq. 4 is used to calculate the CO2 uptake year by year:

Eq. 4 $$CO2uptake = \frac{Max(CO2uptake) \times k \times \sqrt{t}}{e}$$

where *Max(CO_2uptake)* is the total carbonation potential at t=0.

According to the Nordic Innovation Centre [46], the porosity of the carbonated concrete is related to the strength of the non-carbonated concrete. Hence, the authors propose k values which are determined by assigning the materials to categories based on strength as well as exposure conditions (buried, indoor, sheltered and outdoor).

In the EPD *conventional* wall scenario, concrete has a mechanical strength of 8 MPa and is exposed. The carbonation rate is then k=5 mm/year^{½}. Carbonation is not taken into account in the EPD scenario on mortar. In the *conventional* Ecoinvent scenario, only carbonation of cement render and mortar joints is considered during the use stage. Lime render is included in *biobased* carbonate as well.

To calculate the maximum uptake of carbon dioxide by cement-based materials, a mean of 64% of CaO in cement was used ([45], [50], [51]). It was assumed that hydration of lime has no impact on the carbonation process. Indeed, conversion of $CaCO_3$ into CaO can occur above 900◦C where the resulting CaO rapidly hydrates. Since Portland cement clinker is heat treated at 1 400 to 1 500◦C, it contains only a small amount of uncombined or hard-burnt CaO (which seldom exceeds 1% in modern concretes) [50]. Thus, the 64% CaO content is assumed to carbonate. The same assumption concerning hydrated CaO applies to the hydraulic lime render, where CaO content is 70% ([52]–[54]).

Lastly it is considered that not all the $Ca(OH)_2$ carbonates. Renders whose thickness is limited to a very few centimetres can be considered as having reached their final carbonation levels, i.e. 80% to 92% within 1 to 2 years [55]. The final carbonation level was set to the average value 86%. For mortar joints, the final carbonation levels progress at a rate of 1.9 mm/year starting from the side which is not insulated [55]. In this study, this rate is assumed to be 2 mm/year to include the carbonation that takes place ahead of the carbonation front.

Hence, for all materials, the CO_2 uptake in kg due to carbonation follow Eq. 5:

Eq. 5 $$CO2uptake(i) = CaO\%(i) \times 0.86 \times \frac{m(i)*M(CO2)}{M(CaO)}$$

where *i* is cement or lime, *m(i)* is the mass of *i* in kg which comprises mortar or render, *M(CO2)* is the molar mass of carbon dioxide, 44 g/mol, and *M(CaO)* is the molar mass of calcium oxide, 56 g/mol.

2. Methods

Global Warming Potential is a measurement that establishes the relative climate effects of greenhouse gases. The impact of a product on global warming is calculated using life cycle assessment (LCA). In this section standard LCA is first presented, followed by the dynamic LCA method and finally by a simplification of dynamic LCA.

2.1 Life cycle assessment (LCA)

As defined by ISO 14040, life cycle assessment is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Standard LCA is based on the ISO standards 14040:2006 and 14044:2006 [56], [57] and is therefore divided into four phases: 1) Goal and scope definition; 2) Life-cycle inventory (LCI); 3) Life-cycle impact assessment (LCIA); 4) Life-cycle interpretation.

All the referenced emission data for a given gas are first aggregated at year one. The aggregated emissions are then multiplied by the GWP of the gas at a given time horizon (usually 20, 100 or 500 years, as mentioned by the IPCC [58]), and converted into kilogram CO_2 equivalent ($kgCO_2e$). The overall impact is the sum of the GWI of each GHG.

To conduct LCAs of different wall designs, LCI data were obtained from the Ecoinvent 3.2 database. Data were analysed using Open LCA 1.5 software. Standard LCA focusses on GWP100 based on the IPCC 2013 impact assessment method [59]. This method sets the 100-year time horizon GWP values of GHG relative to CO_2. In the present study, the main gases emitted are carbon dioxide (CO_2), methane (CH_4), dinitrogen monoxide (N_2O) with GWP100 values of 1, 28 and 264.8 $kgCO_2eq$ respectively [58].

To make this study as local as possible, the Ecoinvent 3.2 dataset was sometimes manually modified to fit the French or European context.

The environmental impacts of building products manufactured by French companies are recorded in Environmental Product Declarations (EPD) (French acronym FDES). These declarations are established using the LCA approach according to the standard NF EN 15804+A1 [60] and are available in the INIES database (www.inies.fr). EPD are cradle-to-grave designed. EPD are designed to be cradle-to-grave. The EPD are filled in by the manufacturer and are then checked and validated by an accredited expert. Accordingly, the database contains several EPDs for similar products produced by different manufacturers. It is sometimes difficult to judge whether the differences between EPDs are due to different methodologies/hypothesis or to real differences in energy efficiency between producers.

For the purpose of comparison, LCA calculations were performed using both Ecoinvent database and the EPD database. As the Ecoinvent scenario is the reference, unless otherwise specified, the Ecoinvent database was used.

It has been observed that 50-year-lifespan buildings are mostly chosen as a standard for LCA without any explanations. The literature review showed this figure underestimate the lifespan of buildings.

2.2 Dynamic LCA (dLCA)

LCA results depend on an established time horizon, a time beyond which further impacts are no longer taken into consideration [22]. By convention, a 100-year time horizon is considered. Changing this time horizon will modify the GWP, since greenhouse gases have different lifetime in the atmosphere: CH_4 stays 12.4 years, N_2O 121 years whereas more than 20% of emitted anthropogenic CO_2 remains in the atmosphere ([58], [61], [62]). Thus, the cumulative effective global warming due to a process that emits carbon will always increase with time. Moreover, a time horizon of 100 years is problematic if a building with a 101-year lifespan is studied, since EoL will fall outside its scope.

Consequently, a dynamic approach makes real sense. One of the first dynamic approaches is the Lashof method [63]. As shown in Figure 2, it consists of calculating benefits against a time horizon of temporary carbon storage that implies delayed emission, meaning a delay in radiative forcing.

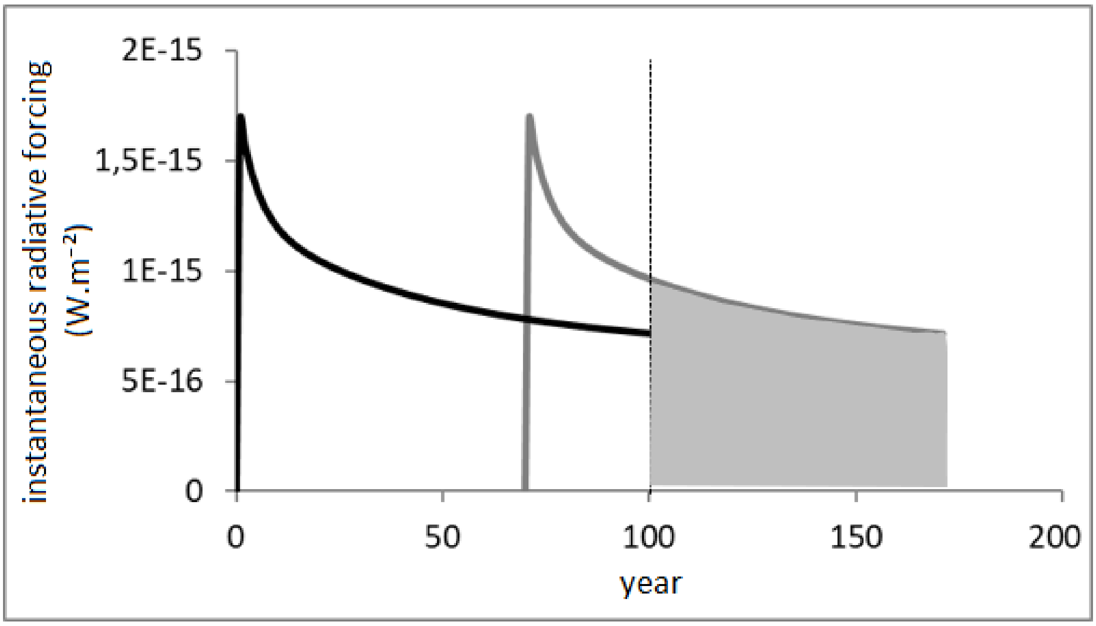


Figure 2 : Lashof method example: instantaneous impact for the emission of 1 kg of CO2 at year 1 or year 71, and a time horizon of 100 years.

This method was criticized because it still needs a time horizon and delaying emissions has no real advantage as it simply postpones the problem [64]. Thus the dynamic LCA proposed by Levasseur ([22], [23], [65]) appears to be the most relevant to estimate the effect of the storage or emission of GHGs over time. It resembles the Lashof method extended to all kinds of GHGs and time horizons. Levasseur and her co-authors developed dynCO_2, a spreadsheet which makes it possible to obtain time-dependent curves of the impact on global warming due to radiative forcing throughout the lifecycle [66]:

- the instantaneous impact of global warming GWI_{inst} in W.m^{-2} calculated with Eq. 7 thanks to Eq. 6:

Eq. 6 $$DCFinst_{GHG}(t) = \int_{t-1}^{t} a_{GHG} C_{GHG}(t)dt$$

Eq. 7 $$GWI_{inst}(t) = \sum_{GHG} \sum_{i=0}^{t} g_{GHG}(i) * DCFinst_{GHG}(t-i)$$

where:

- $DCFinst_{GHG}(t)$ is the dynamic characterization factor of a specific GHG emission that occurs at time t;
- a_{GHG} is the instantaneous radiative forcing per unit mass present in the atmosphere for a specific GHG ;
- $C_{GHG}(t)$ is the mass atmospheric load of a given GHG, t years after the emission;
- $g_{GHG}(i)$ is the dynamic inventory result for a given GHG in year i.

- the cumulative impact of global warming GWI_{cum} in W.m^{-2} (see Eq. 8):

Eq. 8 $$GWI_{cum}(t) = \sum_{i=0}^{t} GWI_{inst}(t)$$

- the relative impact in kgCO_2e, which refers to a "dynamic" GWP by comparing GWIcum at year i with GWIcum of 1 kg of CO_2 emitted in year 1.

Changes in GWP over the years are then available, instead of LCA values established at year 1 and integrated only over 20, 100 or 500 years. The time at which sequestration and emission occur are differentiated, which is indispensable if one is to evaluate the real impact of building material on global warming at different timescales. This interest to shift towards dLCA for the buildings has been shown [67], especially to address the biogenic carbon issue when bio-based materials are used ([54], [65], [68]).

2.3 Simplified dLCA

In France, a group of experts was brought together in 2019 to work out how to account for temporary carbon storage in environmental assessments in future French building regulations [69]. One idea that was put forward is to apply weight factors to the GWP100 indicator to depict shifts in time of GHG emissions that are generated over the course of the life cycle. This approach represents a simplified dLCA since corrective factors are determined using the Lashof method through the simulation of 1 kg CO_2 emission, but with a 100-year time horizon to fit with EPD data. Figure 3 shows that at the 100-year time horizon, the area under the grey instantaneous impact curve divided by the area of the black curve equals the corrective factor. The corrective factors used are listed in Table 2. The strong point of this method is that it is easy to use since only LCA data that are already available in EPD or in Ecoinvent are required.

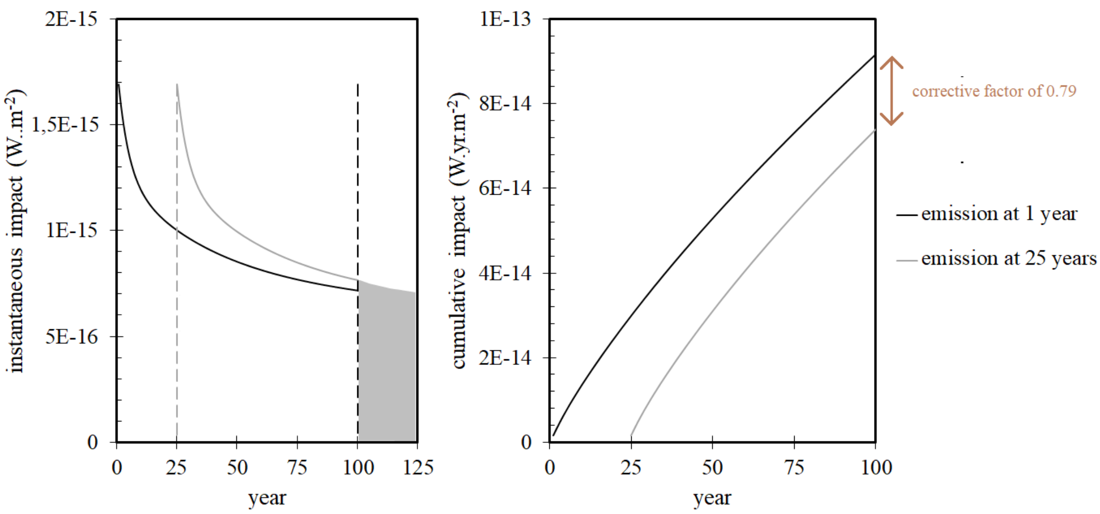


Figure 3: Radiative forcing of 1 kg of CO2 emitted at year 1 or year 25 to determine correction factors at a 100-year time horizon in simplified dLCA

Table 2 : Impact of shifting of 1 kg of CO2 GWP adjusted to a 100-year time horizon. The original table from [69] is in Appendix 3

Emission/capture year	0	15	25	50	101
Corrective factor	1	0,87	0,79	0,57	0

3. Experimental

3.1 Functional unit and system definition & boundaries

The two types of studied exterior walls have the same functional unit (FU). According to NF EN 15804 [70] and NF EN 16783 [71], a FU has to contain a thermal resistance value (R) to be applied to an insulated wall and usually to a surface in panel-like systems. Thus, the FU is defined as follows:

- 1 m^2 of wall whose main function is to form a load-bearing structure;
- R value of 7.3 $m^2.K.W^{-1}$ (U=0.137 $W.m^{-2}.K^{-1}$), which corresponds to passive house standards;
- a lifespan of 75 years.

The system with its boundaries refers to EN 15804 and is illustrated in Figure 4. It corresponds to a cradle-to-grave approach. The production of the wall known as module A includes five stages (A1 to A5): extraction of raw materials as well as biogenic captured carbon for bio-sourced materials, transport to the manufacturing plant, production, supply to the construction site, and construction of a 1m^2 wall. Given the scope of this analysis, in module B, only stage B1 (use due to carbonation) and stage B4 (replacement of some materials) were considered relevant. As part of B4, processes involved in the production of new materials and in replacing materials at the end of life (EoL) are counted. The EoL of the wall is included in module C (C1-C4). This module includes demolition of the wall, transport of the sorted materials to the proper waste treatment site, recycling processes in the case of recyclable materials, and disposal of non-recyclable materials. Module D covers benefits and charges that are beyond the system boundaries: production of aggregates from recycled concrete, of energy or chips from recycled wood, and of energy or compost from recycled straw. In standard LCA, this module is indicated as additional information but was not taken it into consideration in the comparison of LCA and dLCA.

During LCI some flows are excluded from the boundaries of the system. In accordance with EN 15804+A1, these flows are: lighting, heating and cleaning of workshops, activities of administrative departments, workers' transport, screws used in construction processes, biomass residues, electricity consumption during construction and replacement.

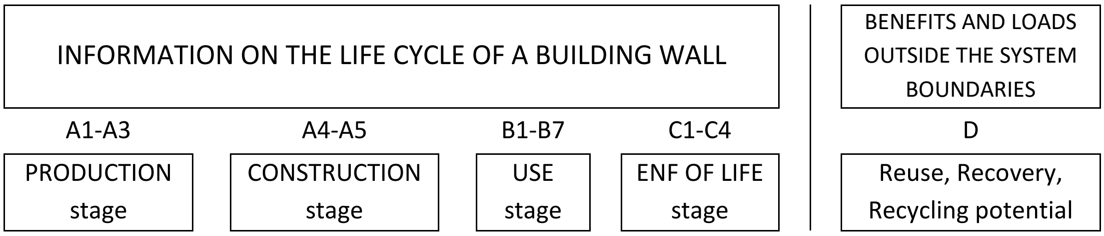


Figure 4 : System boundaries of the LCA model for the two types of walls

In dynamic LCA, the production stage accounts for year 0 or 1, the construction stage for year 1, use for year 1 to year 75, and end of life from year 76. Carbon uptake by straw and wood products are counted the year before these products are used in the FU (i.e. year 0 or 49 in the case of product renewal). Indeed, assumptions of an equilibrium state for fields of annual crops and that French forests produce sufficient biomass in one year to offset the volumes harvested are made.

3.2 Walls under study

The first wall named "Concrete with internal thermal insulation" (*conventional*) and is composed of materials commonly used by the building industry. It is compared to a second wall named "Timber and bales of wheat straw" (*biobased*), which is one of the well-known low-tech biobased construction methods. For the assessments, materials of specified thickness that can be found in the market are used.

These two types of wall were compared through LCA and dLCA by using Ecoinvent 3.2 database. To be able to properly compare them with French EPD results, the processes chosen are based on the French and European context. The results are incorporated in the "Ecoinvent scenario". More details on the materials used can be found in the paragraph below. Ecoinvent process are detailed in Appendix 4

For a comparison purpose, the same comparison was done using EPD.

3.2.1. Materials

Concrete: due to the thickness of joints a little less than ten 20x20x50 cm hollow concrete blocks are used per FU. The density of a concrete block varies between 885 and 1 080 kg/m^3 ([72], [73]). A density of 1 000 kg/m^3 was set to obtain a 20-kg concrete block as in the concrete EPD [74]. Since the selected concrete process gives a density of 2 315 kg/m^3, a correction factor to enter the proper concrete volume was applied. Concrete forms the structure of the *conventional* wall and has the same lifespan.

Cement mortar is used for the joints between the concrete blocks. The density of cement mortar varies between 1 800 kg/m^3 and 2 200 kg/m^3 ([75]–[77]). The usual composition is 67% sand, 22% cement, 11% water [78], [79], which gives a density of 1 900 kg/m^3. The mixing procedure is included in the Ecoinvent process. The horizontal joints between two layers of concrete blocks are 1 cm thick. There are 4 horizontal layers per FU. The vertical joints between the concrete blocks are also counted. Mortar joints have the same lifespan as concrete.

Cement render is used on the outside of *conventional* walls. The render is made of aerated mortar, whose density is 1 500 kg/m^3. It is 2 cm thick. The render has a lifespan of 25 years, but EPD recommends and French law requires renovation of the facade every 10 years in some municipalities including Paris [80].

Glass wool is an inorganic insulator made of silica and recycled glass by fusion up to 1 400 °C, centrifugation and extrusion [81]. A density of 25 kg/m^3 and a thermal conductivity of 0.035 W.m^{-1}.K^{-1} were set [82], [83]. Several different lifespans can be found in the literature: 30 years [81], 40 years[19], 50yrs [84]. A lifespan of 50 years was chosen according to NF EN 16783. This also corresponds to what is observed in the field: in France, buildings built before 1974 are subject to thermal renovation. Current installation of internal insulation in new buildings are considered to last as long as possible. No information was found in the literature on how performances might change during the lifetime of the material due to ageing or unexpected situations.

Gypsum plasterboard is a standardized product with a thickness of 12.5 mm. Its in-service life is 50 years [85].

Paint is only applied inside the building. The yield of typical paints available on the market is 0.1 L/m². The density was set at 1 500 kg/m^3 [86]. The solvent is water at 10 w%. Two to three layers are applied, which leads to 0.35 kg/FU. Paint's lifespan is 15 years [87].

Straw: wheat straw grown in intensive farming system was chosen. Two-string bales of straw 47x37x100 cm in size are usually used in building applications. The minimum required density is 85 kg/m^3 [88] and density can go up to 180 kg/m^3, but is often around 100 kg/m^3, which is enough to ensure material homogeneity as well as lighter to carry for workers. Its thermal conductivity is 0.052 W.m^{-1}.K^{-1} ([32], [89]). The lifespan was set at 50 years to match the NF EN 16783 norm.

Wood: softwood was chosen such as Douglas fir, a species whose wood does not require treatment. Its density at 15% moisture content is 550 kg/m^3 [90]. Two 220x45 mm beams and three 27x32 mm battens are made out of it. Beam lifespan is the same as the wall, since it is the bearing element. The function of the battens is to compress the bales of straw bales and they thus have the same lifespan.

Clay plaster is composed of 55% clay, 25% sand and 20% water in weight [91], its density is 1 800 kg/m^3. Its thickness is 3cm and it has a 25-year lifespan. The mixing procedure is included in the Ecoinvent process.

Lime render: the process was created. According to building site data, the composition of render (in weight) is 12% hydrated lime, 70% sand and 18% water, giving a density of 1 400 kg/m^3. The mixing procedure is the same as for clay. The render is then applied in a 2-cm thick layer. Its lifespan is 25 years.

Table 3 gathers figures for each component of the walls presented in Figure 5. Figures found in EPDs for each constitutive materials of *biobased* and *conventional* walls are in Appendix 5.

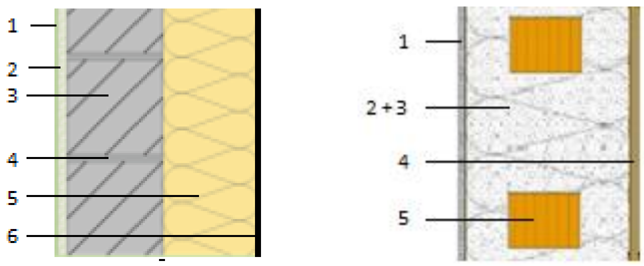


Figure 5: Wall compositions referring to Table 3;
conventional wall (left), biobased wall (right)

Table 3: Materials inventory for the two types of wall construction according to Ecoinvent database and literature - Ecoinvent scenario

Ref.	Material	Density Kg.m^{-3}	Thickness mm	λ W.m^{-1}.k^{-1}	Mass Kg/FU	Lifespan yr	Waste treatment
conventional - Concrete with internal thermal insulation							
1	Paint	1500	-	-	0.35	15	landfilled
2	Cement render	1900	20	1.2	30	25	Recycling potencial
3	OPC concrete blocks	1000	200	1	192	100	Recycling potencial
4	Cement mortar	1900	-	1.2	33.8	100	Recycling potencial
5	Glass wool	25	240	0.035	6	50	landfilled
6	Gypsum plasterboard	770	12.5	0.3	10	50	landfilled
biosourced - timber and bales of wheat straw							
1	lime render	1400	20	0.8	28	25	landfilled
2	Straw	100	370	0.052	37	50	Composted, incinerated
3	Wood battens	550	-	0.14	1.4	50	landfilled,
4	Timber beam	550	-	0.14	10.9	100	incinerated, recycled
5	Clay plaster	1800	30	0.8	54	25	landfilled

Considering the thermal resistances of the interior and exterior surfaces, Rsi and Rse, as 0.13 and 0.04 m².K.W^{-1}, the global R values are 7.36 for the conventional wall and 7.33 for the *biobased* wall.

3.2.2 Impacts of the materials on climate change – production and construction stages

Some of the materials used in the FU involve several processes in the Ecoinvent 3.2 database. In order to ensure the GWP of the materials is consistent, the values were compared with values in the literature. Table 4 shows there are few discrepancies between the Ecoinvent processes and the literature.

Table 4: Processes chosen in Ecoinvent 3.2 to ensure their impact matches the literature review

Material (unit)	GWP100 of process in Ecoinvent 3.2 $kgCO_2e$/unit	Average GWP100 from literature $kgCO_2e$/unit	Standard deviation in literature data	Source
Cement (t)	-	838.2	60.9	[44], [51], [92]–[100]
Aggregates (t)	-	2.87	0.52	[100]–[103]
Water (kg)	-	3.10^{-4}	-	Ecoinvent 3.2
OPC Concrete (m^3)	314.0	332.5	27.6	[92], [100], [103]
Cement mortar (t)	198.6	201.7	37.2	[75], [104], [105]
Glass wool (kg)	1.4	1.33	0.13	[82], [106], [107]
Gypsum plasterboard (kg)	0.19	0.26	0,03	[85], [108], [109]
15%moisture wood - CO2 uptake ($kgCO_2$/kg of wood)	-	1.56	0.064	Appendix 1
Process of timber beam / timber battens (m^3)	44.1 / 31.7	36.6 / 31.6	16.4 / 11.4	[44], [109]
15%moisture straw - CO_2 uptake ($kgCO_2$/kg of straw)	-	1.66	0.055	Appendix 1
Straw baling processes (kg)	0.142	0.127	0.063	[32], [39], [110]
Lime render (kg)	0.142	0.16	0.07	[111], [112]
Earth plaster (kg)	0.029	0.04	-	[111]

Due to cement, concrete will have a high environmental impact in the *conventional* wall. Figure 6 compares concrete production processes in Ecoinvent 3.2, reconstituted concrete and mean impact taken from the literature. For concrete production, a volume of matter was determined to form a hollow concrete block. Some data were modified to fit the European context.

Since the production of concrete of 25 MPa and 35 MPa in Ecoinvent is not destined for hollow blocks, Eq. 9 was applied the get the proper mass per FU. "Reconstructed concrete" was obtained by mixing the mean impact of cement, aggregates and water in the literature (see Table 4) at respective proportions of 9%, 86% and 5% , and then adding transport and manufacturing.

The 35 MPa concrete process matched the average in the literature. Moreover, with carbonation its impact was similar to that in low impact Ecoinvent processes.

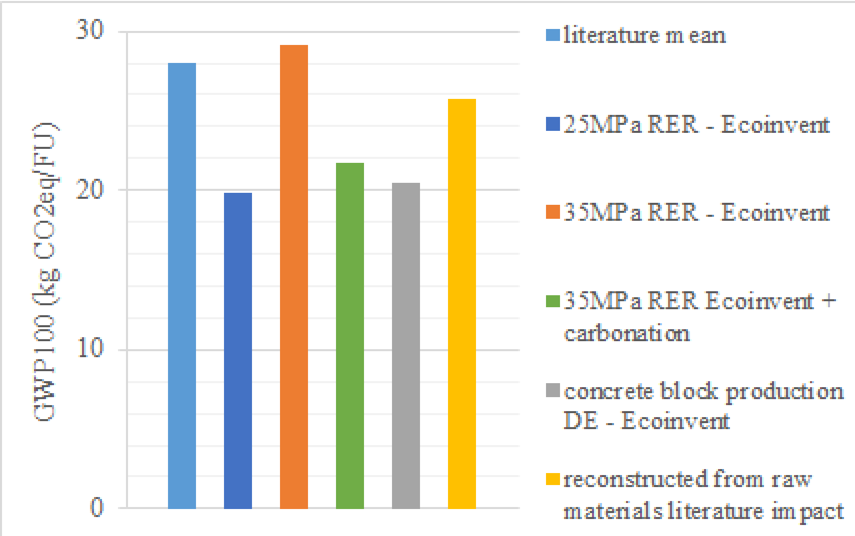


Figure 6: comparison between concrete production processes in Ecoinvent 3.2, a reconstituted concrete and mean impact found in the literature review.

For concrete production, a volume of matter has been determined to form hollow concrete block (cf. Eq. 9). Some data have been modified to fit with the European context. Reconstructed concrete" has been obtained by mixing mean literature impact of cement, aggregates and water (cf. Table 4) with a proportion of 9%, 86% and 5% respectively, and by adding transport and manufacturing

Eq. 9 $$impactconcrete\frac{25}{35}MPa = impactEcoinvent\frac{25}{35}MPa \times \frac{dhollowconcreteblock}{decoinventconcrete\frac{25}{35}MPa}$$

where *d* is the density in kg/m^3.

The impact of growing the wheat straw was allocated based on the knowledge that straw represents 10% of income from the sale of wheat [113]. Hence, the impact of wheat straw is 10% of "soft wheat grain" one, a process included in the French Agribalyse database. For the production of baled straw, a process was created

comprising pressing, grouping and storage using diesel powered baling machines and including fertilisers so as to model nutrient losses from the field caused by exporting straw. These losses are 7 kg nitrogen (N), 1.2 kg phosphorous (P_2O_5) and 12.3 potassium (K20) per ton of exported straw [39].
As stated before, carbon uptake of biogenic materials are: 1.40 kgCO_2/kg of wet straw 1.86 kgCO_2/kg of dry wood.

For each type of wall, a 16–32 metric ton truck, EURO4, is used for transport in sub-module A4. For the *conventional* wall, transport concerns the delivery of concrete blocks from the ready-mix plant to the construction site (200 km [114]) and cement mortar transported from the packing facility to the construction site, which is assumed to be located at a distance of 50 km [19]. Plasterboard and insulator are also transported over a distance of 50 km. For the *biobased* wall, the reference distance for French Douglas fir wood is 200 km [115]. As clay is a locally available material, it is conservatively assumed that it is transported for 50 km. Lime is assumed to be transported over a distance of 500 km [116]. An exception was made in the means of transport for straw: 50% of the straw is assumed to be transported 10 km by tractor, 40% 40 km by truck and 10% 80 km by truck ([89], [113]). The electricity consumed at the building site and for the transport of the workers are not included.
Table 5 lists the amounts of CO_2, CH_4, N_2O, CO and SF_6 generated by the materials used in *conventional* and *biobased* construction.

*Table 5: GHG emissions during the manufacturing of building materials (GWP at the 100-year horizon [59]: CO2 = 1, CH4=29.7, N20=264.8, CO=4.06, SF6=23506.8). * mean carbon storage is not shown here*

Material production	quantity u	% CO_2 emission	kg CO_2/u	kg CH_4/u	kg N_20/u	kg CO/u	kg SF_6/u	CO_2e/u
Concrete	1 kg	97%	$3,04.10^{-1}$	$2,52.10^{-4}$	$2,13.10^{-6}$	$3,33.10^{-4}$	$5,34.10^{-9}$	0.314
Mortar	1 kg	95%	$1,88.10^{-1}$	$2,67.10^{-4}$	$1,95.10^{-6}$	$4,26.10^{-4}$	$5,07.10^{-9}$	0.199
Glass wool	1 kg	74%	$9,82.10^{-1}$	$3,92.10^{-3}$	$7,55.10^{-4}$	$2,23.10^{-3}$	$1,47.10^{-7}$	1.330
Gypsum plasterboard	1 kg	90%	$2,34.10^{-1}$	$6,57.10^{-4}$	$1,21.10^{-5}$	$2,56.10^{-4}$	$2,21.10^{-8}$	0.260
Painting	1 kg	87%	4,58	$1,27.10^{-2}$	$4,79.10^{-4}$	$3,32.10^{-2}$	$2,67.10^{-7}$	2.240
Transport	1 t x km	96%	$1,63.10^{-1}$	$1,56.10^{-4}$	$3,08.10^{-6}$	$3,52.10^{-4}$	$2,89.10^{-9}$	0.170
Diesel burned	1 MJ	95%	$8,97.10^{-2}$	$7,22.10^{-5}$	$3,12.10^{-6}$	$3,24.10^{-4}$	$8,00.10^{-10}$	0.094
Straw bale*	1 kg	49%	$7,13.10^{-2}$	$1,05.10^{-4}$	$2,64.10^{-4}$	$8,53.10^{-5}$	$2,11.10^{-9}$	0.146
Wood beam*	1 kg	79%	$6,33.10^{-2}$	$1,84.10^{-4}$	$6,27.10^{-6}$	$2,34.10^{-3}$	$6,14.10^{-9}$	0.080
Wood batten*	1 kg	79%	$4,84.10^{-2}$	$1,37.10^{-4}$	$2,87.10^{-6}$	$1,96.10^{-3}$	$2,87.10^{-9}$	0.061
Clay	1 kg	91%	$2,67.10^{-2}$	$7,22.10^{-4}$	$7,90.10^{-7}$	$6,89.10^{-3}$	$2,26.10^{-9}$	0.029

3.2.3 Use stage

In this study, only carbon uptake due to cement and lime carbonation and the impact of replacement materials influence the use phase. It is considered that cement and lime render carbonate in 2 years and mortar joints render carbonate at a rate of 2 mm/year. Carbonation reactions are detailed in 1.4.

Materials whose lifespan is shorter than that of the wall are replaced. Replacement is simulated using the same process as that used to produce the wall. As specified in EN 15804+A1:2014, end-of-life processes of replaced materials are also included in B4. Transport is modelled by a 16–32 metric ton truck, EURO4. For each material, truck distances include the transport of the material supplied plus waste disposal. As prescribed by FD norm P01-015, waste with no potential and compostable waste are landfilled at a distance of 30 km from the construction site, whereas recycled waste is treated at a distance of 100 km from the construction site [74].

3.2.4 End of Life stage

Demolition of the *conventional* wall is performed by a high load diesel machine whose power is more than 74.57 kW, e.g. a Volvo EC 300DL 170 kW. A 100-m²-house with

4-metre high walls, e.g. 160 m² walls, takes 3 to 4 hours to demolish. A 1-minute-operation is attributed to the FU demolition and the sorting of materials. A diesel power saw is used for the demolition of the *biobased*, wall for 0.1 h/m² [113]. Waste transport is the same as in 3.2.3.

Glass wool is eliminated on landfill sites ([84], [117], [118]) along with painted gypsum plasterboard ([118], [119]). In France, 68% of concrete blocks are recycled and 32% are landfilled [117]. Recycled concrete is crushed to be used as a base layer in road construction. The mortar and cement render applied to the concrete blocks are assumed to be recycled the same way. Physical allocation with the mass of used material is applied. Taken together, for the *conventional* construction mode, 173.4 kg(waste)/FU are recycled, and 97.6 kg(waste)/FU are landfilled. Complete carbonation of concrete blocks can be rapid, since the blocks are in contact with air and crushed. Since mortar did not totally carbonate during the use phase, the rest is added at this stage. Total carbonation in *conventional* EoL is 8.3 $kgCO_2e$, while in the use phase, it is 10.9 $kgCO_2e$.

For the demolition of the *biobased*, carbonation of the wall lime is 1.56 $kgCO_2e$ and is attributed to the use phase. In the EoL, clay plaster and lime render are landfilled. Wood beams and battens follow the mean French EoL scenario for wood building products prescribed by FCBA: 17.3% is dumped in solid waste disposal sites (SWDS), 25.5% is incinerated, and 57.2% is reused as raw material by wood chip panel plants [41]. According to recommendation by the sector, wheat straw is incinerated or composted [33]. Thus, there are two end of life scenarios for *biobased*:

- “composted”, meaning 100% of straw is composted;
- “incinerated”, meaning 100% of straw is incinerated.

From the review about GHG emissions at EoL of biogenic materials, two emissions scenarios (min and max) for composted straw and landfilled wood are used in this study to respect the broad range of GHG emission data in the literature (see Table 6). These modifications were made to Ecoinvent processes which already include other

GHG emissions. This makes two curves, min and max, for each "*biobased* GHG" curve. As a result, some Ecoinvent processes were modified (see Appendix 6).

Table 6: CO2, CH4 and N20 emission scenarios (min and max) for composted straw and landfilled wood, both with 15% moisture content, at a 100-year time horizon. Details can be found in Appendix 2

	min	
	g(gas)/kg wood	g(gas)/kg straw
CO_2	116.9	1236.9
CH_4	42.5	11.75
N_2O	0.63	0.6

	max	
	g(gas)/kg wood	g(gas)/kg straw
CO_2	183.3	1266.6
CH_4	19.35	0.95
N_2O	0.63	0.787

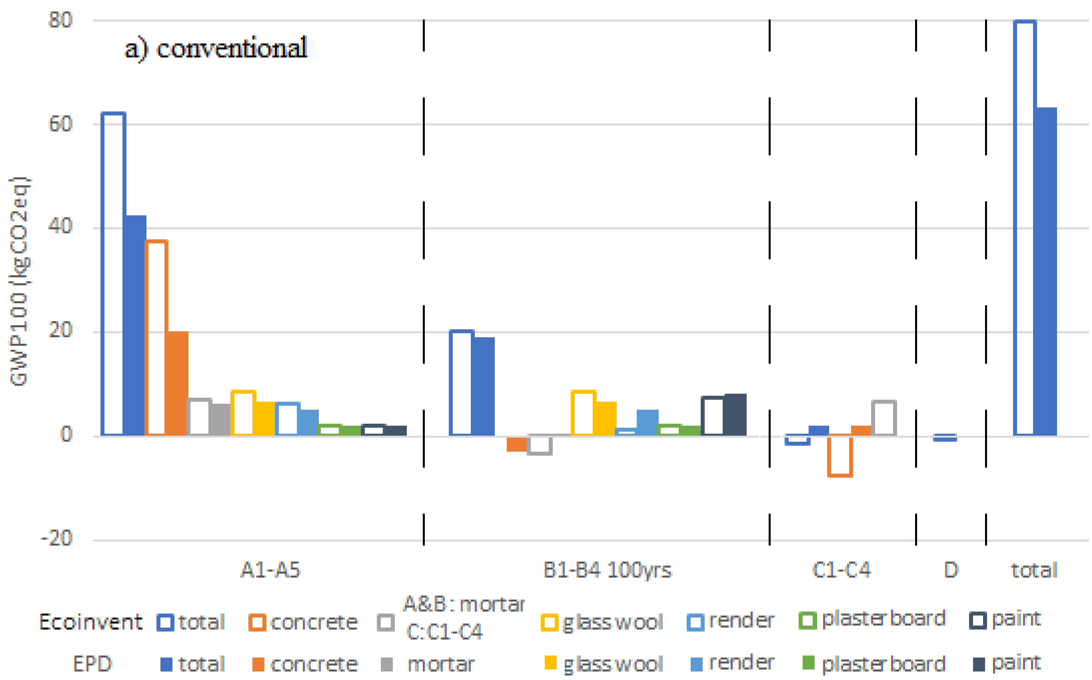
3.2.5 Reuse, recovery and recycling potential

As described by EN 15 804, benefits due to reuse as a new source for material or for energy production are affected in module D. Hence, recycled concrete is counted as crushed gravel with a negative impact. The same goes for recycled wood counted as chips: the benefits are avoided embodied energy of forest management and of the sawmill. Incineration of biowaste cogenerates heat and electricity. These benefits are counted by calculating the net outgoing energy flow that replaces production by the downstream energy system. In France, waste incineration provides 293.6 kWh of electricity per ton of waste and 583 kWh of thermal energy per ton of waste [120]. Avoided emissions due to this co-generation are 79 gCO_2/kWh of produced electricity (French mix) and 279 gCO_2/kWh of produced thermal energy (European mix) [44]. Lastly, compost made from straw is used instead of fertilisers.

4. Results

4.1 Standard LCA

The impacts of materials at each stage of their life cycle are shown in Figure 7. Ecoinvent and EPD scenarios are both shown. The GHG emissions profile is quantified in terms of CO_2 equivalent.



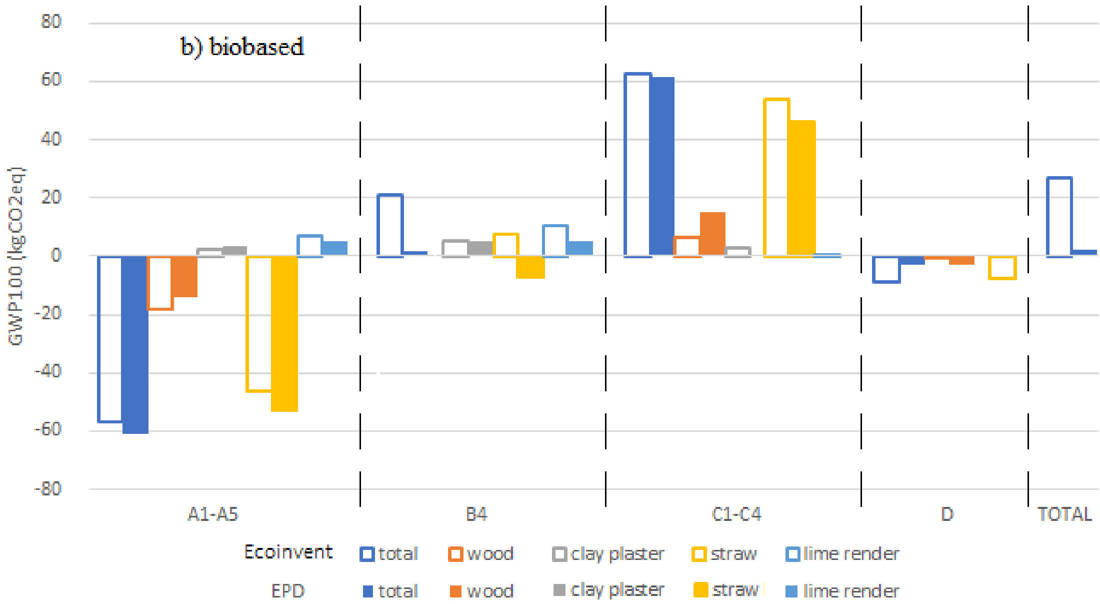


Figure 7: Results of standard LCA for (a) a conventional wall and (b) a biobased wall using EPD or Ecoinvent data, with details of the impacts of materials processes - (in the biobased wall 50% of the straw is composted and 50% is incinerated)

Conventional LCA results give a GWP100 of 63.1 kgCO_2e in the EPD scenario and 79.8 kgCO_2e in the Ecoinvent scenario. For the *biobased* wall, the GWP100 is 4.1 kgCO_2e in the EPD scenario and 25.5 kgCO_2e in the Ecoinvent scenario. In both cases, the Ecoinvent scenario has a higher impact but the two scenarios show similar trends.

The material with the most impact in the *conventional* wall is concrete, which accounts for 35.3 of the overall impact, transport and carbonation included. Construction professionals can mitigate the impact of a concrete building by choosing aerated, porous concrete blocks with optimised cement content. In this case, by selecting the 25-MPa-concrete process instead of the 35-MPa-concrete, the impact of concrete in the FU drops by 15%. Nonetheless, concrete remains a source of carbon emissions, whereas using wood as an alternative structural material would stock carbon. Glass wool and paint have a high impact in terms of their mass in the FU.

In the *biobased* wall, wheat straw drives both carbon uptake and carbon release and wood plays a smaller role in both scenarios (see Table 7). This is partly due to the difference in mass per FU between the two materials. Lime and mortar renders differ significantly in the Ecoinvent and EPD scenarios, notably due to the difference in their lifespan: 25-year-lifetime renders are used in the Ecoinvent scenarios and 50-year lifespans are used in EPD to more accurately reflect building sector practices. This highlights the importance of double checking if the input data matches the practices in the geographical region being studied. Carbonation significantly reduces the impact of renders. Most of the lime render’s impact is due to transport. Here, clay plaster has a significant impact according to the Ecoinvent database. Since clay plaster might be made with local materials and almost no processing, the process in the Ecoinvent database is a conservative one.

The EoL of biomaterials is stated in terms of GHG emissions due to biogenic carbon decay and needs to be precisely described in LCA. There is no consensus on GHG emissions, first, due to the composting process: IPCC guidelines give a wide range for composted materials ([0.08-20] gCH_4 per kg of waste), while Hermann gives (0.11% to 5.1% carbon degraded as CH_4). In practice, compost needs to be aerated on a regular basis at composting sites. Second, emissions from landfilled wood are not clearly defined in the literature: methane emissions range from 10% [121] to 50% [40] of carbon content.

Like for the *conventional* wall, EoL processes have a low impact, but apart from concrete, cannot be recycled.

Biobased Module D is significant in terms of negative carbon impacts. Bio-sourced materials have high reuse, recovery or recycling potential which is not yet fully exploited.

Table 7 : Outcome of wood and straw biogenic carbon sequestration and emission for the FU

	Uptake ($kgCO_2$)	Landfilled wood (17.3%) composted straw (100%) ($kgCO_2e$)/FU	Incinerated wood (25.5%) incinerated straw (100%) ($kgCO_2e$)/FU	Recycled wood (57.2%) ($kgCO_2e$)/FU	**Biogenic carbon assessment (sum) ($kgCO_2e$)/FU**
Wood (12.32 kg)	-19.48	min: 1.64 max: 2.96	4.62	0	**min: -13.42** **max: -11.90**
Straw (37 kg)	-51.89	min: 53.79 max: 66.40	51.89	-	**100% compost: [1.9 ; 14.51]** **100% incineration: 0**

4.2 Dynamic LCA

The results of LCA integrated in the dynCO_2 tool are given here. First, *conventional* and *biobased* constructions are compared from the point of view of the FU. Second, the influence of the building lifespan is presented. Also, *biobased* and *conventional* results are compared using the EPD database. Last, results when emissions are in CO_2 equivalent are plotted. Module D is not considered since it is beyond the system boundaries.

4.2.1 Results of the functional unit - EoL influence

Comparison of the two types of construction are presented in Figure 8. The two EoL *biobased* scenarios are plotted. The instantaneous impact curve shows the effects on radiative forcing of replacing materials.

Biobased curves with instantaneous radiative forcing have both negative areas under the curve until the EoL of the building, whereas areas under *conventional* curves are directly positive. Hence the cumulative impact clearly distinguishes between the two types of construction: the *conventional* wall contributes to climate change, whereas the *biobased* wall has a cooling effect, at least for several decades. This information is new compared to standard LCA results.

Moreover, the longer the time horizon, the bigger the difference in impact between the two types of construction. Also, when straw is incinerated, the min and max scenarios are very similar. There is a bigger difference between the minimum and maximum *biobased* wall when the straw is composted. Lastly, one can observe that composting straw has a higher impact in the first decades, but a lower impact in the long term. This is due to significant CH_4 emissions at 50 and 75 years, which have a higher GWP but do not last long in the atmosphere compared to CO_2.

Overall, dLCA curves highlight the importance of distinguishing time trends when storage and emission of CO_2 occur, especially for biogenic carbon in biobased constructions.

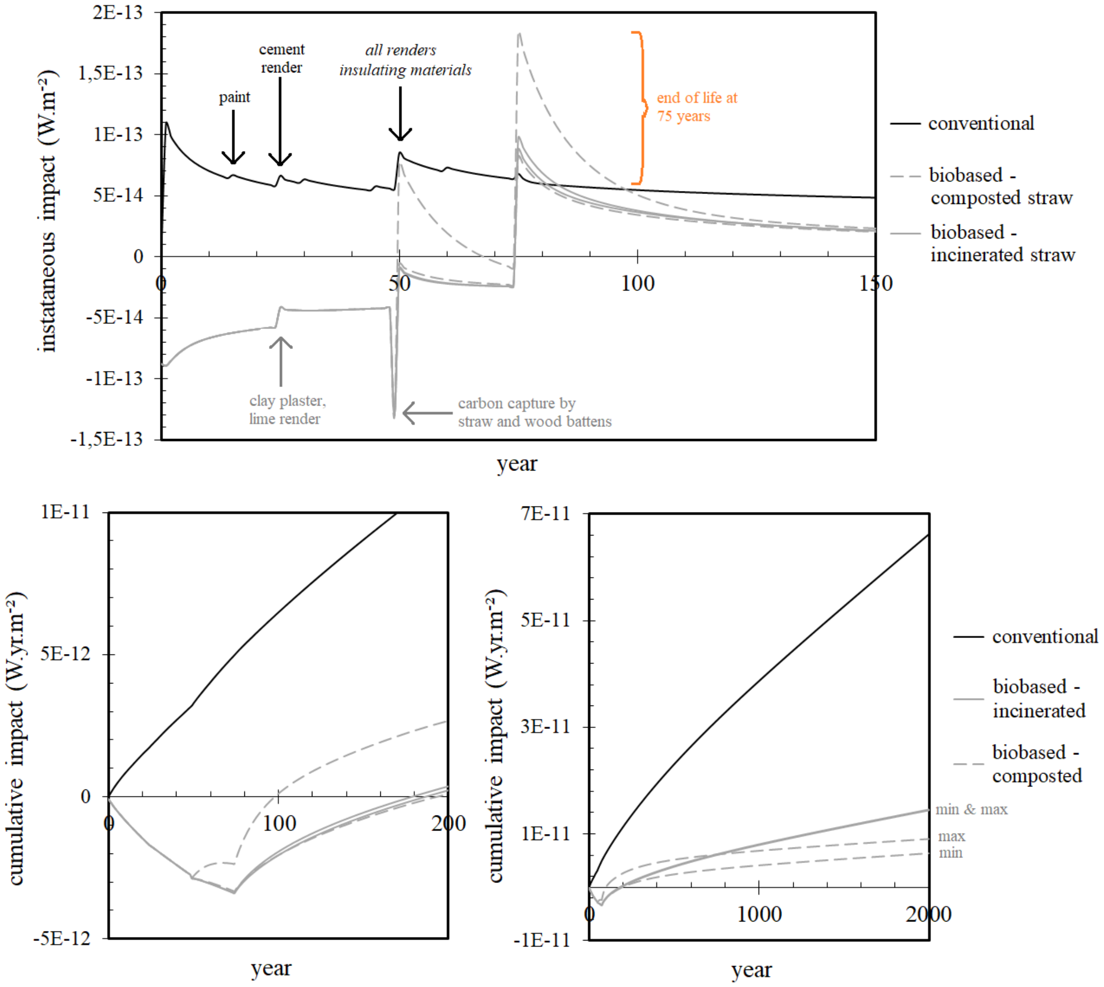


Figure 8: dLCA of biobased and conventional scenarios from the Functional Unit

From now on, based on the cumulative impact curves, the specification is made that "*biobased* min" will be the lower curve of "*biobased* - composted", and "*biobased* max" will be the higher curve of "*biobased* - incinerated".

4.2.2 Influence of the building's lifespan

In this subsection, the following FU is considered: 1m² of wall (R=7.3 $m^2.K.W^{-1}$) that perform the housing function at the same site for 300 years.

Figure 9 shows the impact of construction and demolition of *biobased* and *conventional* walls over a period of 300 years with either a 50-year or 100-year building lifespan. This figure shows that the differences in impact on global warming between the two types of construction are even more significant than the 75-year building lifespan comparison. In the case of a *conventional* wall, the longer the wall lasts, the lower the impact. A *biobased* wall with a 50-year lifespan has less impact than a *biobased* wall with a 100-year lifespan, which seems strange. In fact, in the present study, wood stores more carbon than it releases, thus by increasing the use of timber beams, the impact is reduced.

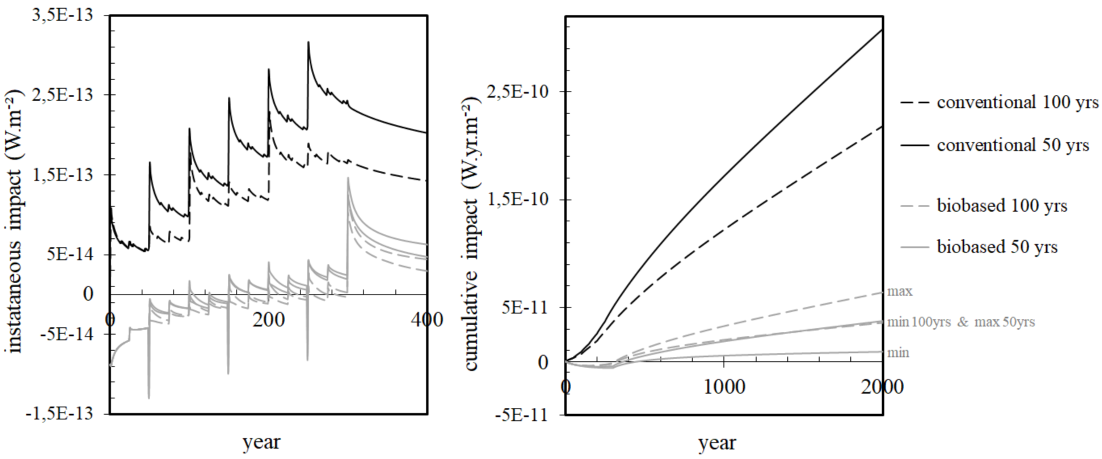


Figure 9 : comparison of construction and demolition at one site of biobased *and* conventional *housing with a 50- or 100-year lifespan over a 300-year time period*

4.2.3 Influence of the database

Figure 10 shows dLCA results for the EPD and Ecoinvent scenarios. It is important to note that in both scenarios GHG emissions are modelled as CO_2 equivalent since EPD data are all in CO_2e. EPD data seem to underestimate the impact of materials, since both *conventional* and *biobased* EPD scenarios have lower impacts than their equivalent with Ecoinvent data. But analysis of EPD or Ecoinvent data does not affect the difference between the two types of construction: the difference in cumulative radiative forcing in *conventional* and *biobased* walls is very similar in the two scenarios.

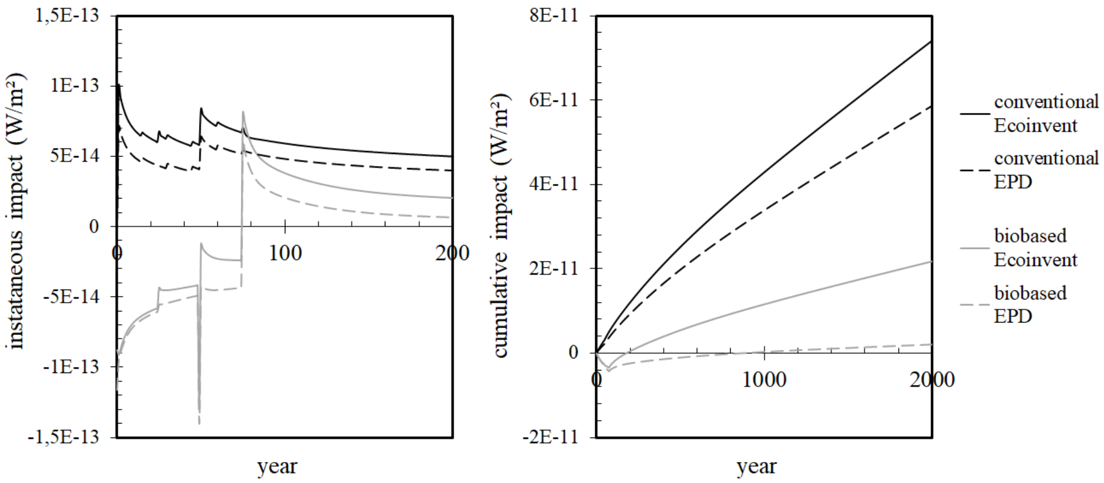


Figure 10 : Instantaneous and cumulative radiative forcing in the EPD and Ecoinvent scenarios. 75-year life span of housing - CO2e data used for Ecoinvent scenarios

4.2.4 Influence of CO_2 equivalent emissions

Almost all LCAs use CO_2 equivalent data. Figure 11 compares the results of the FU with CO_2 equivalent results. "CO_2e" means that CO_2 equivalent LCA data were used directly. "GHG" means that impacts resulting from LCA have been discretized into CO_2, CH_4, N_2O, CO and SF_6 emissions. Figure 11 highlights the fact that results in CO_2e always show higher impacts, especially in the long term. This is due to the fact that part of CO_2 remains in the atmosphere which is not the case of the other GHGs studied.

These results underline the fact that the choice of time horizon is decisive for assessments made using CO_2e data. Here, the CO_2e curve does not overestimate *conventional* constructions in the long term, whereas it overestimates *biobased* constructions when straw is composted because significant amounts of CH4 are released.

Nevertheless, Figure 11 shows that, by focusing on a 200-year horizon, *conventional* and *biobased* walls (with both incinerated or composted straw) can reasonably be compared with dynamic CO_2e results. In this case, the 100-year time horizon, which is the convention for GWP in CO_2e, is appropriate.

From these discussions, one can see that working with radiative forcing values over years, which shows the real effect of GHG emissions on global warming, makes it possible to ignore CO_2e and time horizon issues.

Table 8 compares "static" and "dynamic" GWPs. "Static" GWP100 appears to be similar to "dynamic" GWP1000 which reveals a problem in the standard LCA method. While dLCA represents the real impact of materials on global warming over time, the GWP100 is a matter of choice. Differences in impacts on global warming impact vary depending on whether "dynamic" GWP20, GWP100, GWP500 or GWP1000 are considered. Lastly, standard LCA seems more unfavourable in the case of *biobased* walls than *conventional* ones.

These comments are crucial since this environmental indicator is being used to steer design guidelines and regulations.

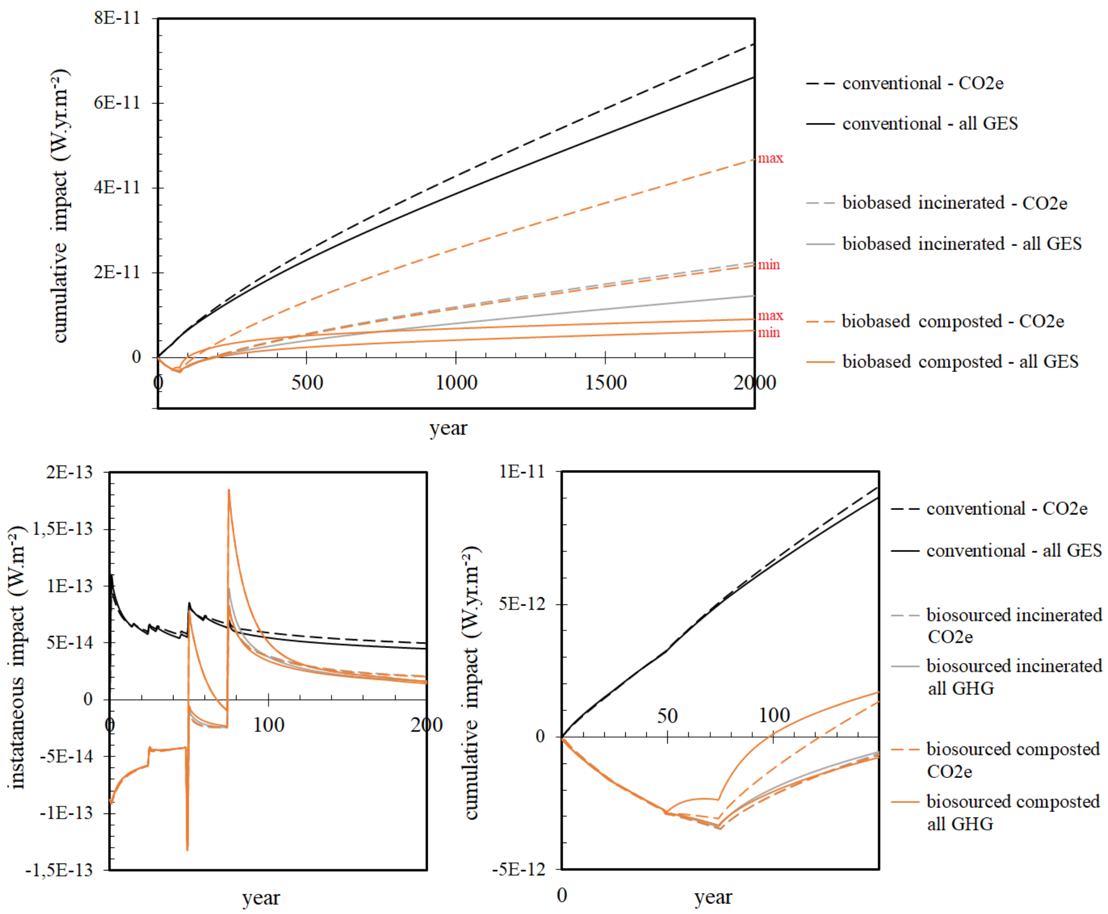


Figure 11 : Influence of CO2e and differentiated GHG Ecoinvent emissions data on dLCA for conventional and biobased - 75 years lifetime housing.

Table 8: relative Global Warming Potential calculated as "static" with LCA or "dynamic" with dLCA -75 years lifetime housing (straw's EoL is here 50% composted - 50% incinerated).

	Impact *conventional* $kgCO_2e/FU$		Impact *biosourced* $kgCO_2e/FU$	
« static » $\boldsymbol{GWP^{100}}$	79.8		26.3	
	CO_2e	GHG	CO_2e (min)	GHG (min /max)
« dynamic » $\boldsymbol{GWP^{20}}$	56.0	60.0	-57,4	-56.5 / -56.5
« dynamic » $\boldsymbol{GWP^{100}}$	71.6	70.8	-23.8	-22.2 / -9.8
« dynamic » $\boldsymbol{GWP^{500}}$	78.1	71.8	17.4	9.8 / 14.3
« dynamic » $\boldsymbol{GWP^{1000}}$	78.9	71.2	21.9	11.1 / 13.7

5. Discussion

5.1 Comparison of results obtained with static LCA, dLCA and simplified dLCA

Conventional constructions have a relatively higher impact on global warming than constructions made with *biobased* materials. *Biobased* constructions even have a cooling effect for several decades. A similar comparison was made by (Pittau et al., 2018) [19]. Their cumulative impacts on global warming of concrete walls insulated with expandable polystyrene (EPS) range from 8.10^{-12} to 14.10^{-12} $W.yr.m^{-2}$ at a 100-year horizon. In the present study, the GWIcum of *conventional* walls at a 100-year horizon is 6.5 10^{-12} $W.yr.m^{-2}$. The main difference is due to the type of insulation material used, EPS having more impact than glass wool. Otherwise, the impact of the *conventional* wall is of the same order of magnitude.

(Pittau et al, 2018) also studied a wall composed of light clay straw with a timber frame. For GWIcum, these authors found [-9 to -3].10^{-12} $W.yr.m^{-2}$ at the 100-year horizon. In the present study, *biobased* results are [-2.1 to 0.1].10^{-12} $W.yr.m^{-2}$ at the 100-year horizon. The straw and wood carbon content chosen are similar in the two studies, but the amount of biodegradable matter and emitted CO_2, CH_4 and N_20 during EoL differ. The present study underlines that one needs to be careful when considering data on EoL processes involving biomaterials since biogenic emissions are not properly counted and CH_4 emissions due to decay are not clearly stated in the literature. That is why EoL processes of straw and wood have been modified to include emitted CO_2 and CH_4 due to biogenic carbon decay as fossil GHG. Considering that every mechanised human activity always involves a positive GWI over time, it makes sense that GWIcum becomes positive for *biobased* constructions after a certain time.

However, building using *biobased* materials can be a great help in facing global warming in the coming decades, and would make it possible to continue building and renovating houses at a minimum environmental cost. Given that today more than 90% of buildings are made of conventional materials in France, the benefit from using biobased material should be considered as the difference between the impact of a *conventional* and a *biobased* solution. This difference is always in favour of *biobased* solutions, whatever the time scale.

Speaking of time scale, the interest of using dLCA for buildings has already been shown [67], especially to address the biogenic carbon issue when bio-based materials are used ([54], [65], [68]). This method makes it possible to:

- estimate the real radiative forcing impact as well as relative CO_2e impact ("dynamic GWP") over time instead of only one GWP value at the 100-year horizon. The shift to dLCA involves major changes in the interpretation of environmental impacts;
- differentiate between GHG emissions such as CO_2, CH_4 or N_2O. It was shown this is of second order importance to compare the two walls in the present study;
- account for emissions and storage when these processes actually occur in the defined scenario;
- model carbon uptake over time due to carbonation or plant growth thanks to physical laws.

Due to complexity and the need to change LCA tools, dLCA would be difficult to apply in the professional building sector. However, Figure 12 shows that using a simplified dLCA still enables accurate estimation of the real impact of materials on global warming. Using this method is attractive since it can be applied using data that are already available in databases. dLCA results are in "dynamic GWP100. There may be as small difference between dLCA and simplified dLCA when CO_2e data are used for simplified dLCA.

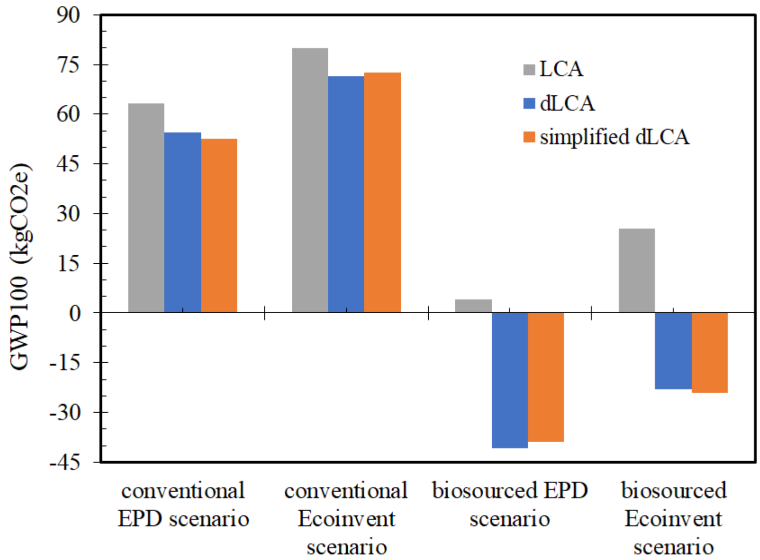


Figure 12: "GWP100" comparison of conventional and biobased walls using the 3 assessment methods and a 75-year life span for housing. CO2e data were used for Ecoinvent scenarios.

Also, even if it is scientifically meaningful to distinguish between greenhouse gases, in practice it is not easy in France since EPDs are based on equivalent carbon dioxide. Filling in EPDs is time consuming for companies. The present results show that only considering only carbon dioxide equivalent is apparently acceptable for the building sector, at least up to a 200-year time horizon. In the longer term (more than 500 years), if significant amount of GHG such as CH_4 or N_2O are emitted, dLCA shows that these gases should be considered.

5.2 Remark on the limits of carbon analysis of biogenic materials

On another note, a paradox was observed: changing timber more often reduces the impact of *biobased* walls. The reason is that 57% of the wood is recycled, and the decay of the second wood product is beyond the LCI system boundaries. Moreover, landfilled wood is assumed to permanently store a significant amount of carbon. Lecompte noticed a similar phenomenon [54]: the thicker a *biobased* wall, the more carbon it stores. In both cases, even if using a lot of biogenic materials is advantageous in terms of mitigation, prudent use of available resources is a key to sustainability. Thus, from a global environmental standpoint, material consumption should be optimized to needs and the lifespan of the material should be as long as possible.

Straw has a positive GWP over its whole life cycle. Nevertheless, the benefits of energy generation and composting are not counted. Based on the assumption that the bales of straw are composted, a cycle between wheat cropping and composting the straw is reached after 75 years: composted straw is spread on the field as nutrients. In that case, chemical inputs are no longer needed to compensate wheat straw removal and the impact of straw may become negative. Biological crop is another way to reduce straw impact.

5.3 Impact of a change of practice towards biobased walls in the French building sector

A scenario was designed to compare the impact of *biobased* and *conventional* walls at French scale. Based on an 80-m²-mean housing area with a 2.5-metre-high wall, this leads to 90 m² of wall per flat. In 2017, $33.8.10^6$ m² (floor area), meaning 38.10^6 m² of wall, were built. It is possible to calculate differences in GWI between *biobased* and *conventional* walls (Table 9) : The real savings at the 100-year horizon is 87 kgCO2e /FU (which consists in 1 m² of wall). This represents **8.1 tCO_2e savings** for a 90-m² wall in a house with a 75-year lifespan.

In 2016, French emissions were 464 $MtCO_2e$ [122], of which 23% originated in the building sector [123]. The impact of wall construction alone, if all the walls are made of *conventional* materials, corresponds to 38.10^6 m² x 71 $kgCO_2e$ (from *Table 9*) = 2.7 $MtCO_2e.year^{-1}$ which is about 2.5 % of building sector emissions. If biobased walls are built instead of conventional one, the savings are about 38 x 10^6 m² x 87 $kgCO_2e$ = 3.3 $MtCO_2e.yr^{-1}$.

However, the overall savings in France due to the use of biobased wall instead of conventional ones, 3.3 $MtCO_2e.yr^{-1}$, represent less than 1% of the current French emissions (464 $MtCO_2e$ in 2016).

In 2009, carbon emissions due to house heating were about 20 $kgCO_2.m^{-2}.yr^{-1}$ in France [124]. For 80 m² housing (90 m² wall), it represents 1600 $kgCO_2.yr^{-1}$ and 120 tCO_2 per 75 years, which is much higher than the 8.1 tCO_2e per 75 years savings due to *biobased* walls. Taking the poor performance of existing buildings into account, the largest reduction in carbon emissions in refurbishing comes from better thermal insulation, and in second place, from the choice of the construction material. Choosing biobased materials would add an additional benefit, but it should not be detrimental to the performance. In addition, current French recommendations for future regulations based on a carbon tax would artificially enable economic savings when *biobased* materials are used, which could be reinvested in additional improvements to energy efficiency including the renovation of existing buildings. Eventually, the climate change emergency of should lead us to drastically limit the release of fossil CO_2 for needed applications like heating. When a *biobased* option exists, it should be preferred.

One can expect newly constructed buildings to have a high thermal insulation performance. According to (D'Alessandro, 2017), in a passive house, thermal energy and electricity consumption in winter per m² of wall equals 8.19 and 2.34 $kWh.m^{-2}.yr^{-1}$ respectively (<15 $kWh.m^{-2}.yr^{-1}$). With the carbon intensity of the French electricity mix and with the European thermal energy mix [64], With the carbon intensity of the French electricity mix and with the European thermal energy mix [64], this leads to 1.3 $kgCO_2e/m^2$/year and 8.7 tCO_2e for a 75-year flat measuring 80 m². In such a case, the 8.1-tCO_2e-savings made by the use of *biobased* walls instead of *conventional* walls are almost equal to the carbon emitted for heating and represents a major source of potential carbon savings. Breels showed similar results [125]. savings. This analysis is limited to walls, but ecological practices can also be used for the whole building including floor slab, ceiling or roof. Thus, choosing *biobased* materials is becoming one of the most influential solutions to further reduce the impact of constructing new buildings.

Table 9 shows the overall savings in CO_2e if 20% or 50% of the built area (assumed to be similar to those in 2017) had been built using *biobased* materials instead of *conventional* materials.

Table 9: Impact of conventional and biobased construction from Table 8 and deduction of saved CO_2 emissions over the life cycle if 20% or 50% of yearly construction were biobased instead of conventional.

	impact *conventional* (kgCO_2e/FU)	impact *biobased* (kgCO_2e/FU)	Difference (kgCO_2e/FU)	50% *biobased* construction (saved tCO_2e/yr)	100% *biobased* construction (saved tCO_2e/yr)
static GWP100 CO_2e	80	26	53	**1 017 000**	**2 034 000**
dyn GWP100 GHG	71	-16	87	**1 650 000**	**3 301 000**
dyn GWP1000 GHG	71	12	59	**1 118 000**	**2 236 000**

This analysis was performed in CO_2e because data are available in this unit. However, as discussed above, this do not represent the real global warming potential, which is linked to the radiative forcing.

Hence, the impact of building all the new buildings in France using *biobased* material instead of *conventional* material in terms of radiative forcing was investigated.

Here, the FU is 1m² of wall that enables a house to last for 500 years on the same site. Figure 13 presents the instantaneous impacts for conventional and biobased walls, which have been linearized. The difference between the two impacts is also shown. One can see that the difference increases over time. One can also note that simply maintaining the existing housing stock using *conventional* materials is a significant source of carbon emissions.

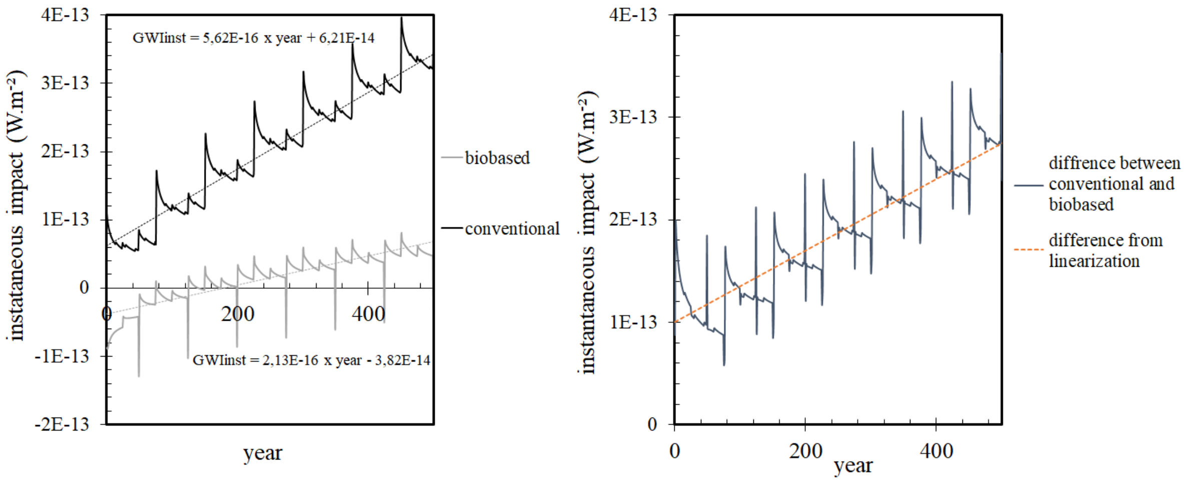


Figure 13: Instantaneous radiative forcing over a period of 500 years for conventional and biobased walls and their linearization (left), and difference between the two impacts (right).

Global radiative forcing equals 2.3 W.m^{-2} (1.1 to 3.3 W.m^{-2}) [126]. In 2015, world emissions were 46 400 MtCO$_2$e [127] and French emissions were 464 MtCO$_2$e [122], 1% of world emissions. It can thus be considered that current French radiative forcing is 2.3 x 0.01 = 23 mW.m^{-2} (11 to 33 mW.m^{-2}).

As the building sector produces 23% of French emissions, radiative forcing due to the French building sector is 23% x 23 = 5.3 mW.m^{-2} (2.5 to 7.6 mW.m^{-2}).

Table 10 shows the potential of *biobased* in terms of radiative forcing reduction. If all houses were built with *biobased* walls for now on, the impact of the building sector would drop by 0.8% (0.8 to 1.1%) per year. By extending it to all the housing stock, the savings are between 11% and 20% (8% to 43%).

This approach is based on some assumptions. But other emitting part of the house such as the roof, the floor are not considered. Insulation effect is also out of the scope of this table. Knowing that 77% of building sector emissions come from heating [124], *biobased* walls with passive properties would divide by five the heating needs (from 250 to 50 kWh.m^{-2}.yr^{-1}), saved emissions would be 65.7 MtCO$_2$e per year. Thus, if all the housing stock was *biobased* and passive, the building sector would reduce its radiative forcing by around 80%.

Table 10: *Radiative forcing (RF) saved if 100% of practices change to biobased wall, if 100% of the housing stock is biobased, this means it is passive. (38.10^6 m² are built per year, the stock extends over 2011.10^6 m²; French RF=0.023 W/m²; French building sector RF=0.0053 W/m²*)

	biobased impact (W/m²)	*conventional* impact (W/m²)	difference (W/m²)	100% biobased construction each year (saved W.m^{-2})	reduction in French RF	reduction in building sector RF per year	reduction in RF of building sector if 100% of the stock is *biobased*
dyn GWP1 - all GHG	-8.910^{-14}	1.1.10^{-13}	9.5.10^{-14}	3.6.10^{-6}	0.03%	0.8%	16.9%
dyn GWP100 - all GHG	-1.9.10^{-14}	1.1.10^{-13}	1.3.10^{-13}	5.0.10^{-6}	0.02%	0.8%	11.3%
dyn GWP500 - all GHG	7.9.10^{-14}	3.5.10^{-13}	2.8.10^{-13}	1.1.10^{-6}	0.04%	0.9%	20.5%

Hence, to reduce consumption by and the impact of the building sector, insulating houses should be a priority. However, changing the construction mode towards *biobased* walls would reduce significantly building sector's radiative forcing on the housing stock scale.

That analysis applied to global warming. For a systemic environmental evaluation, other aspects such as available local resources or impacts on biodiversity should be taken into consideration. Since *biobased* construction is very advantageous from the point of view of carbon, analyses on available straw and timber resources in France were performed. This is important, since changing construction to biobased buildings may imply changing the endpoint of crop products and changing land uses. The same concerns have emerged for instance in the energy sector with the development of biofuels ([128], [129]).

5.4 Available resources: timber from sustainable managed forest and/or annual plants?

Forests control the global carbon cycle. Carbon stored in forest soil and litter amounts to about 80 tC/ha, plus 85 tC/ha in standing trees, while the carbon stored in the soil under annual crops and orchards is around 50 tC/ha, plus around 1 tC/ha in harvested biomass ([130], [131]). In Europe, timber harvesting is not correlated with deforestation: forest area and carbon storage have increased in recent decades, even if part of forest biomass is used as softwood lumber, paper, furniture or energy. According to the IGN [132], forest area in France has increased at a rate of 0.7% per year since 1987, that is between 25 and 36 million m3 per year ([132], [133]), even if 38.3 million tons of wood have been harvested in 2017 [134]; 32.3% of French forest are certified and 90% of 3 000 wood processing plants are also certified ([135]–[137]). Sales of certified timber account for 56% of total sales [134], and up to 92% of sales to the building sector [137].

Recommendations are to maintain older, longer-rotation forests and protected old-growth forests and to optimise forest management to fulfil different objectives: wood production, climate change mitigation and prevention of biodiversity loss [138]. Sustainably managed forest is one way to maintain forests and to optimise tree growth. It is a key parameter in any plan to store carbon in buildings. Moreover, the extension of sustainably managed forest may prevent land use change, which are a major source of GHG emissions, and may encourage afforestation of unproductive agricultural lands.

Nevertheless, care must be taken with sustainable managed forest, since loss of biodiversity, monoculture, chemical inputs, degraded forest soil, and clear cutting can also be observed in such places. The closer the origin of the wood one uses, the more one knows about the harvesting practices of this renewable resource.

As annual crops are harvested every year, the order of magnitude of stored carbon is lower but nevertheless similar. In addition, annual crops already account for 12 million hectares in France, of which 5 million hectares are under wheat. Hence, unlike wood, there is almost no pressure on straw resources. Currently, wheat straw is only chopped and left on the surface of the field or used to feed livestock. Building walls with it is a valuable way out for this underused co-product

Table 11 summarises data on timber and wheat production in France. It shows that the cereal straw potential is massive, (50.5% of arable land), and as forest area is increasing, the generalisation of biobased walls made of around 11 kg of wood and

37 kg of straw per m^2 seems feasible to us. There is no particular reason to promote more one these two resources.

Table 11: yield per hectare and carbon storage in bio-sourced materials used for construction in France

Type of bio-sourced material	Biomass production per hectare per year	Quantity of carbon permanently stored in the field or forest [tons of carbon per ha]	Used surface area in France (ha)	Sources
Timber	5 $m3.ha^{-1}.yr^{-1}$, being around 3 $t.ha^{-1}.yr^{-1}$ (and 3 $m3.ha^{-1}.yr^{-1}$ harvested)	165 tC/ha (standing timber ~85 tC/ha Litter ~ 10 tC/ha Soil ~ 70 tC/ha)	17 x 10^6 ha	[130], [131], [133], [134], [139]
Wheat straw & grain	4-6 t/ha of wheat straw 7 t/ha of grain	51 tC/ha (Soil ~50 tC/ha Organic residues ~1 tC/ha)	Cereals : 9.3 x 10^6 ha (50,5% of arable lands)	[130], [140]

Conclusion

In the context of increasing awareness of global warming among citizens, policy makers and professionals, there is a pressing need to clarify how to evaluate the real environmental impact of materials and processes. This is especially the case for highly emitting sectors such as the building sector.

The method currently used to evaluate global warming potential in the building sector in France is based on a static LCA which assumes that all carbon storage and emissions occur the first year. In this work, this static method was compared with a dynamic LCA approach. Dynamic LCA describes contributions to global warming in much greater detail since, first, it considers the time at which each carbon storage and emission takes place, and it can distinguish the type GHG. This present study has shown that there are significant differences in GWP100 between the two methods. A second difference is that dynamic LCA can distinguish between the different greenhouse gases emitted. The obtained results show this does have an impact, although the impact does not drastically affect the conclusions.

It also has been proved that a simplified dynamic LCA is sufficient to model carbon sequestration and release over time. This approach is immediately applicable since the data are already available in LCA databases. The GHG distinction aspect could be neglected in a simplified approach adapted to the building sector.

Most important is that, regardless of the LCA method, it has been proved that biobased construction is an obvious way to mitigate GWI of the building sector. In addition, the present study shows that dLCA, simplified or not, can be used to support future policy makers in designing building regulations.

Some complementary results were found. First, a wide literature survey showed that a building with a 75-year-lifespan is probably more representative than a building with a 50-year lifespan, as currently considered. Increasing the lifespan improves the GHG impact of conventional buildings and reduces the “positive” impact of biobased buildings. Nonetheless, from a more global environmental point of view, increasing the lifespan meaningfully reduces anthropogenic impacts. Some differences were also found between the results based on data from Ecoinvent and French EPD database. French EPD data tend to be more optimistic than Ecoinvent data. This highlights one of the biggest difficulties in the assessment of environmental impacts: the questionable reliability of incoming data. For this reason, all the data used in the present study were checked in the scientific literature.

Also, an estimation as shown that forests can store about 165 tC/ha and in annual crops 51 tC/ha. Thus, it is not necessary to promote forest (slow growing) or annual crops (fast growing) since both contribute to carbon storage in the same order of magnitude. It is more important to consider available local resources grown using sustainable practices.

Finally, some scenarios were designed to evaluate the impact of building future houses with bio-based walls instead of conventional walls. It was found that a 50% biobased wall significantly reduces the impact of the overall wall construction: it would contribute to the announced effort to reduce global French emissions since it represents [0.6-2.2]% saving of French radiative forcing. But alone, this is not sufficient, to bring emissions down to sustainable values (divided by a factor 4 to 8), a systemic change will be needed.

To sum up the results of this study:

- bio-based walls mitigate emissions by the building sector, and even have a temporary cooling effect;
- conventional walls clearly contribute to climate change;
- dynamic LCA is more relevant than classical LCA to assess the real global warming potential in the building sector, especially when bio-based materials are used. Simplified dLCA is a rapid method that produces reliable results;
- using CO_2 equivalent produces acceptable results, especially in the short- and medium-term. In the long term, care must be taken with CO_2e if CH4 is released;
- Insulation of buildings is the priority. When buildings use less than 50 $kWh.m^{-2}.yr^{-1}$, the impact of the materials is significant. Hence, this work enables to

recommend including the embodied energy of a wall (construction, replacement during use and end of life impacts) in passive house certification.

As a perspective, other types of walls that are not as different as the two studied *conventional* and *biobased* walls would be interesting to assess. For instance, one can study bio-based construction materials such as hemp hurds mixed with a more or less impacting binders (earth, lime, cement). Moreover, biogenic materials do not always mean environmentally friendly materials since chemical stabilisers can be added. Hence, it would be interesting to compare wood wool, earth or hemp fibres with or without polyester resin using dLCA.

References

[1] W. Steffen, W. Broadgate, L. Deutsch, O. Gaffney, and C. Ludwig, 'The trajectory of the Anthropocene: The Great Acceleration', *The Anthropocene Review*, vol. 2, no. 1, pp. 81–98, Apr. 2015.

[2] D. Meadows, D. Meadows, and J. Randers, *The Limits to Growth: The 30-Year Update*. 2004.

[3] J. A. Tainter, 'The Collapse of Complex Societies. Cambridge University Press, Cambridge.', 1988.

[4] S. Motesharrei, J. Rivas, and E. Kalnay, 'Human and nature dynamics (HANDY): Modeling inequality and use of resources in the collapse or sustainability of societies', *Ecological Economics*, vol. 101, pp. 90–102, May 2014.

[5] W. Steffen *et al.*, 'Planetary boundaries: Guiding human development on a changing planet', *Science*, vol. 347, no. 6223, p. 1259855, Feb. 2015.

[6] United Nations, 'Paris Agreement'. 2015.

[7] Daunay, J. and Dugast, C., 'LE BATIMENT, UN SECTEUR EN PREMIERE LIGNE DES OBJECTIFS DE NEUTRALITE CARBONE DE LA FRANCE EN 2050', *Carbone 4*, 14-Jan-2019.

[8] IEA, 'Transition to Sustainable Buildings - Strategies and Opportunities to 2050'. 2013.

[9] 'Lucon O., D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L. F. Cabeza, N. Eyre, A. Gadgil, L. D. D. Harvey, Y. Jiang, E. Liphoto, S. Mirasgedis, S. Murakami, J. Parikh, C. Pyke, and M. V. Vilariño. Buildings. In: Climate Change 2014: Mitiga-tion of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.' 2014.

[10] UNEP, 'Buildings and climate change'. 2007.

[11] Pacte, 'Analyse détaillée du parc résidentiel existant'. 2017.

[12] MEEM and MLHD, 'Stratégie à long terme pour mobiliser les investissements dans la rénovation du parc national de bâtiments à usage résidentiel et commercial, public et privé'. 2016.

[13] ADEME, 'Bâtiments tertiaires : obligations d'amélioration énergétique'. [Online]. Available: https://www.rt-batiment.fr/batiments-existants/obligations-batiments-tertiaires.html. [Accessed: 08-Jul-2019].

[14] énergies et avenir, 'La rénovation énergétique des bâtiments d'enseignement'. 2015.

[15] Ministère de la Cohésion des territoires et des Relations avec les collectivités territoriales, 'Matériaux de construction biosourcés et géosourcés'. [Online]. Available: https://www.cohesion-territoires.gouv.fr/materiaux-de-construction-biosources-et-geosources. [Accessed: 25-Jul-2019].

[16] F. Røyne, D. Peñaloza, G. Sandin, J. Berlin, and M. Svanström, 'Climate impact assessment in life cycle assessments of forest products: implications of method choice for results and decision-making', *Journal of Cleaner Production*, vol. 116, pp. 90–99, Mar. 2016.

[17] L. Gustavsson and R. Sathre, 'Variability in energy and carbon dioxide balances of wood and concrete building materials', *Building and Environment*, vol. 41, no. 7, pp. 940–951, Jul. 2006.

[18] G. Venturini, A. Pizarro-Alonso, and M. Münster, 'How to maximise the value of residual biomass resources: The case of straw in Denmark', *Applied Energy*, vol. 250, pp. 369–388, Sep. 2019.

[19] F. Pittau, F. Krause, G. Lumia, and G. Habert, ‘Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls’, *Building and Environment*, vol. 129, pp. 117–129, Feb. 2018.
[20] W. Liu, Q. Zhu, X. Zhou, and C. Peng, ‘Comparative analyses of different biogenic CO2 emission accounting systems in life cycle assessment’, *Science of The Total Environment*, vol. 652, pp. 1456–1462, Feb. 2019.
[21] A. Albers, P. Collet, D. Lorne, A. Benoist, and A. Hélias, ‘Coupling partial-equilibrium and dynamic biogenic carbon models to assess future transport scenarios in France’, *Applied Energy*, vol. 239, pp. 316–330, Apr. 2019.
[22] A. Levasseur *et al.*, ‘Valuing temporary carbon storage’, *Nature Climate Change*, vol. 2, pp. 6–8, Dec. 2011.
[23] A. Levasseur, P. Lesage, M. Margni, and R. Samson, ‘Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment’, *Journal of Industrial Ecology*, vol. 17, Jan. 2012.
[24] Codifab, ‘Enquête nationale de la construction bois, Activité 2016’. 2017.
[25] Arnold C., ‘Le parc de logements en France au 1er janvier 2016 - Insee Focus - 73’. [Online]. Available: https://www.insee.fr/fr/statistiques/2533533. [Accessed: 17-Jun-2019].
[26] Programme d’Action pour la qualité de la Construction de la Transition Énergétique, ‘Analyse détaillée du parc résidentiel existant’. 2017.
[27] Commissariat général au développement durable, ‘Travaux d’amélioration de la performance énergétique dans les bâtiments existant (2007-2009), Marché de l’entretien des bâtiments en 2007’. Etudes & Document n°29, 2010.
[28] Commissariat général au développement durable, ‘Conjoncture de l’immobilier Résultats au quatrième trimestre 2017, Datalab Essentiel’. 2018.
[29] I. Sartori, N. H. Sandberg, and H. Brattebø, ‘Dynamic building stock modelling: General algorithm and exemplification for Norway’, *Energy and Buildings*, vol. 132, pp. 13–25, Nov. 2016.
[30] R. A. Bohne, H. Brattebø, H. Bergsdal, and P. Jostein Hovde, ‘Estimation of the Service Life of Residential Buildings, and Building Components, in Norway’, 2006.
[31] Brand S., ‘How buildings learn, What happens after they’re built, Penguin’. 1994.
[32] F. D’Alessandro, F. Bianchi, G. Baldinelli, A. Rotili, and S. Schiavoni, ‘Straw bale constructions: Laboratory, in field and numerical assessment of energy and environmental performance’, *Journal of Building Engineering*, vol. 11, pp. 56–68, May 2017.
[33] L. Floissac, ‘Impacts environnementaux de la construction paille’.
[34] Coop énergie, ‘Les pailles de céréales’. 2009.
[35] E. I. Wiloso, R. Heijungs, G. Huppes, and K. Fang, ‘Effect of biogenic carbon inventory on the life cycle assessment of bioenergy: challenges to the neutrality assumption’, *Journal of Cleaner Production*, vol. 125, pp. 78–85, Jul. 2016.
[36] H. Haberl *et al.*, ‘Correcting a fundamental error in greenhouse gas accounting related to bioenergy’, *Energy Policy*, vol. 45, pp. 18–23, Jun. 2012.
[37] A. Rabl, A. Benoist, D. Dron, B. Peuportier, J. Spadaro, and A. Zoughaib, ‘How to account for CO2 emissions from Biomass in an LCA. Editorials.’, *International Journal of Life Cycle Assessment*, vol. 12, p. 281, Aug. 2007.
[38] ‘NF EN 16485 Bois ronds et sciages - Déclarations environnementales de produits - Règles de définition des catégories de produits en bois et à base de bois pour l’utilisation en construction’. 2014.
[39] Cerema, ‘FDES Remplissage isolant en bottes de paille (issues de l’agriculture conventionnelle)’. 2015.

[40] Pipatti, R. and Svardal, P., ‘Chapter 3: Solid Waste Disposal - IPCC Guidelines for National Greenhouse Gas Inventories’. 2006.
[41] FCBA, and CSTB, ‘Volet 2 – Prise en compte de la fin de vie des produits bois ; Phase 3 : Modélisation ACV et calculs d’impacts pour le recylcage matière et la réutilisation’. 2012.
[42] B. G. Hermann, L. Debeer, B. De Wilde, K. Blok, and M. K. Patel, ‘To compost or not to compost: Carbon and energy footprints of biodegradable materials’ waste treatment’, *Polymer Degradation and Stability*, vol. 96, no. 6, pp. 1159–1171, Jun. 2011.
[43] Pipatti & al., ‘Chapter 4: Biological treatment of solid waste - IPCC Guidelines for National Greenhouse Gas Inventories’. 2006.
[44] ADEME, ‘Base Carbone’. 2014.
[45] A. Merah and B. Krobba, ‘Effect of the carbonatation and the type of cement (CEM I, CEM II) on the ductility and the compressive strength of concrete’, *Construction and Building Materials*, vol. 148, pp. 874–886, Sep. 2017.
[46] Nordic Innovation Centre, ‘Carbon dioxide uptake during concrete life cycle – State of the art’. 2006.
[47] K. Van Balen, ‘Carbonation reaction of lime, kinetics at ambient temperature’, *Cement and Concrete Research*, vol. 35, no. 4, pp. 647–657, Apr. 2005.
[48] A. Morandeau, M. Thiéry, and P. Dangla, ‘Investigation of the carbonation mechanism of CH and C-S-H in terms of kinetics, microstructure changes and moisture properties’, *Cement and Concrete Research*, vol. 56, pp. 153–170, Feb. 2014.
[49] M. Thiery, P. Dangla, P. Belin, G. Habert, and N. Roussel, ‘Carbonation kinetics of a bed of recycled concrete aggregates: A laboratory study on model materials’, *Cement and Concrete Research*, vol. 46, pp. 50–65, Apr. 2013.
[50] Monteiro and Kumar Mehta, ‘Concrete: Microstructure, Properties and Materials’, 2001. .
[51] K. Celik, C. Meral, A. Petek Gursel, P. K. Mehta, A. Horvath, and P. J. M. Monteiro, ‘Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended portland cements containing fly ash and limestone powder’, *Cement and Concrete Composites*, vol. 56, pp. 59–72, Feb. 2015.
[52] D. Zhang, J. Zhao, D. Wang, C. Xu, M. Zhai, and X. Ma, ‘Comparative study on the properties of three hydraulic lime mortar systems: Natural hydraulic lime mortar, cement-aerial lime-based mortar and slag-aerial lime-based mortar’, *Construction and Building Materials*, vol. 186, pp. 42–52, Oct. 2018.
[53] A. Vavričuk, V. Bokan-Bosiljkov, and S. Kramar, ‘The influence of metakaolin on the properties of natural hydraulic lime-based grouts for historic masonry repair’, *Construction and Building Materials*, vol. 172, pp. 706–716, May 2018.
[54] Lecompte, Levasseur, and Maxime, ‘Lime and hemp concrete LCA: A dynamic approach of GHG emissions and capture’. 2017.
[55] E. Despotou, A. Shtiza, T. Schlegel, and F. Verhelst, ‘Literature study on the rate and mechanism of carbonation of lime in mortars / Literaturstudie über Mechanismus und Grad der Karbonatisierung von Kalkhydrat im Mörtel’, *Mauerwerk*, vol. 20, no. 2, pp. 124–137, 2016.
[56] ISO, ‘Environmental management—Life cycle assessment: Principles and framework. ISO14040’. 2006.
[57] ISO, ‘Environmental management—Life cycle assessment: Requirements and Guidelines. ISO14044’. 2006.
[58] IPCC, ‘AR5, Chapter 8 : Anthropogenic and Natural Radiative Forcing’, 2013.
[59] ‘Ecoinvent 3.2 Impact assessment method: IPCC 2013’.

[60] CSTB, 'NF EN 15804+A1 : Contribution des ouvrages de construction au développement durable - Déclarations environnementales sur les produits - Règles régissant les catégories de produits de construction'. 2014.
[61] 'Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA'. .
[62] F. Joos *et al.*, 'Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis', *ATMOSPHERIC CHEMISTRY AND PHYSICS*, vol. 13, Mar. 2013.
[63] P. Fearnside, D. A. Lashof, and P. Moura-Costa, 'Accounting for time in Mitigating Global Warming through land-use change and forestry', *Mitigation and Adaptation Strategies for Global Change*, vol. 5, pp. 239–270, Jan. 2000.
[64] M. Kirschbaum, 'Temporary Carbon Sequestration Cannot Prevent Climate Change', *Mitigation and Adaptation Strategies for Global Change*, vol. 11, pp. 1151–1164, Sep. 2006.
[65] M. Fouquet *et al.*, 'Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment', *Building and Environment*, vol. 90, pp. 51–59, Aug. 2015.
[66] CIRAIG, 'DynCO2 Dynamic Carbon Footprinter'. [Online]. Available: http://www.ciraig.org/en/dynco2.php. [Accessed: 14-Apr-2019].
[67] W. O. Collinge, A. E. Landis, A. K. Jones, L. A. Schaefer, and M. M. Bilec, 'Dynamic life cycle assessment: framework and application to an institutional building', *Int J Life Cycle Assess*, vol. 18, no. 3, pp. 538–552, Mar. 2013.
[68] D. Peñaloza, M. Erlandsson, and A. Falk, 'Exploring the climate impact effects of increased use of bio-based materials in buildings', *Construction and Building Materials*, vol. 125, pp. 219–226, Oct. 2016.
[69] 'GE3: Stockage temporaire du carbone Rapport du groupe d'expertise'. 2019.
[70] CSTB, 'NF EN 15804/CN : Contribution des ouvrages de construction au développement durable - Déclarations environnementales sur les produits - Règles régissant les catégories de produits de construction'. 2016.
[71] CSTB, 'NF EN 16783 Produits isolants thermiques - Règles régissant les catégories de produits (RCP) pour les produits manufacturés et formés en place, destinées à la préparation des déclarations environnementales des produits'. 2017.
[72] SOCRAMAT FABRICATION, 'LES BLOCS COURANTS ET BLOCS ACCESSOIRES'.
[73] Point.P, 'Bloc béton creux CE 2+ - 3 alvéoles - classe B60 - 500x200x200 mm - FABEMI - '. [Online]. Available: https://www.pointp.fr/gros-oeuvre-bpe-voirie-tp/bloc-beton-creux-ce-2-3-alveoles-classe-b60-500x200x200-mm-A6238055. [Accessed: 19-Feb-2019].
[74] Alkern, 'FDES Bloc Confort City'. 2017.
[75] E. R. Teixeira, R. Mateus, A. Camões, and F. G. Branco, 'Quality and durability properties and life-cycle assessment of high volume biomass fly ash mortar', *Construction and Building Materials*, vol. 197, pp. 195–207, Feb. 2019.
[76] J. Kerienė, V. Antonovič, R. Stonys, and R. Boris, 'The influence of the ageing of calcium aluminate cement on the properties of mortar', *Construction and Building Materials*, vol. 205, pp. 387–397, Apr. 2019.

[77] P. Priyadharshini, K. Ramamurthy, and R. G. Robinson, ‘Reuse potential of stabilized excavation soil as fine aggregate in cement mortar’, *Construction and Building Materials*, vol. 192, pp. 141–152, Dec. 2018.
[78] A. A. Gheni, H. H. Alghazali, M. A. ElGawady, J. J. Myers, and D. Feys, ‘Durability properties of cleaner cement mortar with by-products of tire recycling’, *Journal of Cleaner Production*, vol. 213, pp. 1135–1146, Mar. 2019.
[79] B. Çomak, A. Bideci, and Ö. Salli Bideci, ‘Effects of hemp fibers on characteristics of cement based mortar’, *Construction and Building Materials*, vol. 169, pp. 794–799, Apr. 2018.
[80] Ville de Paris, ‘Ravalement obligatoire des immeubles à Paris’. 2000.
[81] S. Breels, ‘Impact environnemental & choix des matériaux d’isolation en construction passive’. 2015.
[82] URSA France SAS, ‘FDES URSA PURE 35 QP / PUO35KP 220 mm R= 6,25 m2·K/W’. 2017.
[83] Ecoinvent 3.2, ‘glass wool mat production, Saint-Gobain ISOVER SA’. 2015.
[84] KNAUF Insulation, ‘FDES Laine de Verre ECOSE Acoustilaine 035’. 2017.
[85] PLACO, ‘FDES PLACOPLATRE SP 13’. 2010.
[86] Guittet, ‘Recueil Fiches techniques’. 2018.
[87] SIPEV, ‘FDES Peintures de ravalement en phase aqueuse, classe D2’. 2014.
[88] RFCP, ‘Règles professionnelles de construction en paille - Règles CP 2012 révisées’, 2e édition., Le Moniteur, 2017.
[89] RFCP, ‘FDES Remplissage isolant en bottes de paille’. 2015.
[90] Scierie Germain-Mougeno, ‘Info’s Techniques : Douglas’.
[91] Ecoinvent 3.2, ‘clay plaster production’. 2015.
[92] R. Robayo-Salazar, J. Mejía-Arcila, R. Mejía de Gutiérrez, and E. Martínez, ‘Life cycle assessment (LCA) of an alkali-activated binary concrete based on natural volcanic pozzolan: A comparative analysis to OPC concrete’, *Construction and Building Materials*, vol. 176, pp. 103–111, Jul. 2018.
[93] K. Humphreys and M. Mahasenan, ‘Toward a sustainable cement industry’, 2002.
[94] Hendriks & all, ‘Emission reduction of greenhouse gases from the cement industry’, 1998.
[95] P. Van den Heede and N. De Belie, ‘Environmental impact and life cycle assessment (LCA) of traditional and “green” concretes: Literature review and theoretical calculations’, *Cement and Concrete Composites*, vol. 34, no. 4, pp. 431–442, Apr. 2012.
[96] C. Chen, G. Habert, Y. Bouzidi, and A. Jullien, ‘Environmental impact of cement production: detail of the different processes and cement plant variability evaluation’, *Journal of Cleaner Production*, vol. 18, no. 5, pp. 478–485, Mar. 2010.
[97] ATILH, ‘Environmental inventory of French cement production’. 2002.
[98] D. J. M. Flower and J. G. Sanjayan, ‘Green house gas emissions due to concrete manufacture’, *Int J Life Cycle Assess*, vol. 12, no. 5, p. 282, May 2007.
[99] A. Josa, A. Aguado, A. Heino, E. Byars, and A. Cardim, ‘Comparative analysis of available life cycle inventories of cement in the EU’, *Cement and Concrete Research*, vol. 34, no. 8, pp. 1313–1320, Aug. 2004.
[100] Z. Guo, A. Tu, C. Chen, and D. E. Lehman, ‘Mechanical properties, durability, and life-cycle assessment of concrete building blocks incorporating recycled concrete aggregates’, *Journal of Cleaner Production*, vol. 199, pp. 136–149, Oct. 2018.
[101] Ecoinvent 3.2, ‘quarry operation, gravel, crushed CH and quarry operation, gravel round/sand CH’.
[102] UNPG, ‘MIE de la production de granulats à partir de roches meubles’. 2017.

[103] S. Marinković, V. Radonjanin, M. Malešev, and I. Ignjatović, 'Comparative environmental assessment of natural and recycled aggregate concrete', *Waste Management*, vol. 30, no. 11, pp. 2255–2264, Nov. 2010.
[104] A. Brás and V. Gomes, 'LCA implementation in the selection of thermal enhanced mortars for energetic rehabilitation of school buildings', *Energy and Buildings*, vol. 92, pp. 1–9, Apr. 2015.
[105] A. Moropoulou, C. Koroneos, M. Karoglou, E. Aggelakopoulou, A. Bakolas, and A. Dompros, 'Life cycle analysis of mortars and its environmental impact', *MRS Proceedings*, vol. 895, Jan. 2011.
[106] J.-P. Oliva and S. Courgey, *L'isolation thermique écologique*, Terre vivante. 2010.
[107] Ecoinvent 3.2, 'glass wool production CH'.
[108] A. Jiménez Rivero, R. Sathre, and J. García Navarro, 'Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union', *Resources, Conservation and Recycling*, vol. 108, pp. 171–181, Mar. 2016.
[109] S. M. Fufa, C. Skaar, K. Gradeci, and N. Labonnote, 'Assessment of greenhouse gas emissions of ventilated timber wall constructions based on parametric LCA', *Journal of Cleaner Production*, vol. 197, pp. 34–46, Oct. 2018.
[110] L. Brojan, A. Petric, and P. Clouston, 'Comparative study of brick and straw bale wall systems from environmental, economical and energy perspectives', *ARPN Journal of Engineering and Applied Sciences*, vol. 8, pp. 920–926, Nov. 2013.
[111] P. Melià, G. Ruggieri, S. Sabbadini, and G. Dotelli, 'Environmental impacts of natural and conventional building materials: a case study on earth plasters', *Journal of Cleaner Production*, vol. 80, pp. 179–186, Oct. 2014.
[112] S. Pretot, F. Collet, and C. Garnier, 'Life cycle assessment of a hemp concrete wall: Impact of thickness and coating', *Building and Environment*, vol. 72, pp. 223–231, Feb. 2014.
[113] A. Lopez and L. Floissac, 'FDES Analyse de cycle de vie d'un remplissage de mur en terre-paille'. 2016.
[114] brgm, 'Inventaire des carrières l'approvisionnement des cimenteries en France métropolitaine'. 2009.
[115] FCBA, 'FDES Mur ossature bois avec montant d'une largeur de 145 mm et un entraxe de 60 cm non isolé, fabriqué en France'. 2018.
[116] Construire en chanvre, 'FDES Structure de mur non-porteuse en béton de chanvre projeté'. 2015.
[117] SDES, 'Le recyclage des déchets produits par l'activité de BTP en 2014'. 2018.
[118] ADEME, 'Rapport final - Identification des gisements et valorisations des matériaux biosourcés en de vie en France'. 2014.
[119] Althaus & all, 'Manufacturing and Disposal of building Materials and Inventorying Infrastructure in ecoinvent', 2004.
[120] SVDU, 'QUELQUES CHIFFRES'.
[121] J. O'Dwyer, D. Walshe, and K. A. Byrne, 'Wood waste decomposition in landfills: An assessment of current knowledge and implications for emissions reporting', *Waste Management*, vol. 73, pp. 181–188, Mar. 2018.
[122] UNFCCC, 'National greenhouse gas inventory data for the period 1990–2016'.
[123] Insee, 'Émissions de CO2 par activité en 2017', 2018. [Online]. Available: https://www.insee.fr/fr/statistiques/2015759#tableau-Donnes. [Accessed: 25-Jun-2019].
[124] ADEME, 'Chiffres clés du bâtiment'. 2013.
[125] S. Breels, 'Formation Bâtiment Durable: Rénovation à haute performance énergétique: détails techniques'. .

[126] 'Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forc-ing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA'.

[127] 'Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Olivier, J.G.J., Peters, J.A.H.W., Schure, K.M., Fossil CO2 and GHG emissions of all world countries, EUR 28766 EN, Publications Office of the European Union, luxembourg, 2017, ISBN 978-92-79-73207-2, doi:10.2760/709792, JRC107877'. .

[128] J. Fargione, J. Hill, D. Tilman, S. Polasky, and P. Hawthorne, 'Land Clearing and the Biofuel Carbon Debt', *Science*, vol. 319, no. 5867, pp. 1235–1238, Feb. 2008.

[129] T. Searchinger *et al.*, 'Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change', *Science*, vol. 319, no. 5867, pp. 1238–1240, Feb. 2008.

[130] ADEME, 'SOLS ET FORÊTS LA SÉQUESTRATION CARBONE DANS VOTRE PCAET'. 2018.

[131] ADEME, 'L'outil ALDO, pour une première estimation de la séquestration carbone dans les sols et la biomasse - ALDO_V0403029'. [Online]. Available: https://www.territoires-climat.ademe.fr/actualite/loutil-aldo-pour-une-premiere-estimation-de-la-sequestration-carbone-dans-les-sols-et-la-biomasse. [Accessed: 11-Jul-2019].

[132] IGN, 'Le mémento - Inventaire forestier'. 2018.

[133] Inventaire Forestier National, 'l'IF n°27: Volume de bois sur pied dans les forêts françaises : 650 millions de mètres cubes supplémentaires en un quart de siècle'. 2011.

[134] Agreste Chiffres et Données Agriculture - n° 249, 'Récolte de bois et production de sciages en 2017'. 2018.

[135] PEFC, 'Statistiques PEFC France'. 2018.

[136] Ministère de l'agriculture, de l'agroalimentaire et de la forêt & al., 'Le marché du bois en France - situation actuelle et à court terme'. 2016.

[137] L'union nationale pour l'habitat, 'Evaluation d'opérations de construction de logements sociaux collectifs bois'. 2015.

[138] German National Academy of Sciences Leopoldina, 'AESAC policy report 32. - Multi-functionality and sustainability in the European Union's forests'. 2017.

[139] EUROFOR (coordinated by the ONF (France)) for the European Parliament, 'L'Europe et la Forêt - Section IV.1.1 Les forêts de l'Union Européenne'. [Online]. Available: http://www.europarl.europa.eu/workingpapers/agri/s4-1-1_fr.htm. [Accessed: 04-Jun-2019].

[140] Agreste, 'Statistique agricole annuelle (SAA) - "Internet website of the French Ministry of Agriculture"'. [Online]. Available: https://stats.agriculture.gouv.fr/disar-saiku/?plugin=true&query=query/open/SAANR_1#query/open/SAANR_1. [Accessed: 04-Jun-2019].

[141] J. Parikh, S. A. Channiwala, and G. K. Ghosal, 'A correlation for calculating elemental composition from proximate analysis of biomass materials', *Fuel*, vol. 86, no. 12, pp. 1710–1719, Aug. 2007.

[142] C.-Y. Yin, 'Prediction of higher heating values of biomass from proximate and ultimate analyses', *Fuel*, vol. 90, no. 3, pp. 1128–1132, Mar. 2011.

[143] P. Adapa, L. Tabil, and G. Schoenau, 'Grinding performance and physical properties of non-treated and steam exploded barley, canola, oat and wheat straw', *Biomass and Bioenergy*, vol. 35, no. 1, pp. 549–561, Jan. 2011.

[144] B. Godin *et al.*, 'Détermination de la cellulose, des hémicelluloses, de la lignine et des cendres dans diverses cultures lignocellulosiques dédiées à la production de bioéthanol de deuxième génération', *Biotechnol. Agron. Soc. Environ.*, Jan. 2010.
[145] E. Frollini, A. Leao, L. H. C. Mattoso, R. Rowell, J. S. Han, and J. S. Rowell, 'Characterization and Factors Effecting Fiber Properties', *Natural Polymers and Agrofibers Composites*, Jan. 2000.
[146] IPCC, 'Forest lands. Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories; Institute for Global Environmental Strategies (IGES);Volume 4 (2006) https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html'. .
[147] S. Thomas and A. Martin, 'Carbon Content of Tree Tissues: A Synthesis'. 11-Jun-2012.
[148] F. A. Ximenes, C. Björdal, A. Kathuria, M. A. Barlaz, and A. L. Cowie, 'Improving understanding of carbon storage in wood in landfills: Evidence from reactor studies', *Waste Management*, vol. 85, pp. 341–350, Feb. 2019.
[149] T. Gurunathan, S. Mohanty, and S. K. Nayak, 'A review of the recent developments in biocomposites based on natural fibres and their application perspectives', *Composites Part A: Applied Science and Manufacturing*, vol. 77, pp. 1–25, Oct. 2015.
[150] M. Jawaid and H. P. S. Abdul Khalil, 'Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review', *Carbohydrate Polymers*, vol. 86, no. 1, pp. 1–18, Aug. 2011.
[151] Tsoumis, G., 'Science and technology of wood - structure, properties, utilization', *IAWA Journal*, vol. 13, no. 3, pp. 268–268, 1991.
[152] SNMI, 'FDES Mortier d'enduit minéral'. 2015.
[153] SNMI, 'FDES Mortiers d'usage courant pour le montage des éléments de maçonnerie'. 2016.
[154] Saint-Gobain Placoplatre, 'FDES Placoplatre® BA13'. 2015.
[155] FCBA, 'FDES Poutre en I avec des membrures et une âme en bois massif'. 2018.

Appendix

Appendix 1: Literature review of carbon content in bio-sourced materials

1.1 Composition and carbon fraction of different bio-sourced materials

Some values have been calculated from the composition considering 44,4%C for holocellulose, 62%C for lignin and 40%C for potential extractibles. Calculated values are in italic.

Biosourced materials	Holocellulose	Lignin	Extractibles and minerals	Carbone fraction (%mass)	Sources
Cereal straw	43,9%-65,9%	12,7%-22,5%	16,7%-35,1%	45,5% 43% 45,7%-47,2%	[141] [142] [143]–[145]
Soft wood	52%-75%	21%-37%	0%-8,5%	50% 50,6%-51,9% 47%-55% 49,3-50,8% 51,4% 48,5%-51,9%	[19] [141] [146] [147] [148] [145], [149]–[151]
Hard wood	56%-86%	14%-34%	0%-7,5%	47,1% 46%-49% 47,7%-48,8% *47%-50,6%*	[141] [147] [148] [145], [149]–[151]

1.2 Carbone composition and sequestered CO_2 from the atmosphere by different bio-sourced materials

biosourced materials	Mean mass carbon fraction at dry state from the literature review - C%	Mass of captured CO_2 per kg of wood [kg CO_2]	
		Dry state	15% moisture
Wheat straw	**45%**	1.61	1.41
Soft wood	**50.6%**	1.86	1.58
Hard wood	**48%**	1.76	1.50

Appendix 2: Calculus details of biogenic carbon emission during end-of-life of bio-sourced materials

Column "kg(gas)/kg of wet wood/straw" is the one whose values have modified outputs of Ecoinvent processes. Wet wood and straw have 15% moisture.

GHG emissions landfilled wood - EoL scenarios					
		mass (kg)	impact factor at 100 years	GWP100 (kgCO2e)	kg(gas)/kg of wet wood
carbon mass/FU	17,3%	0,906			
carbon which is degraded after 100 years	15%	0,136			
CO_2 - IPCC default	50%	0,249	1	0,25	0,1169
CH_4 - IPCC default	50%	0,091	29,7	2,69	0,04250
total IPCC default				**2,94**	
CO_2 - IPCC managed SWDS	77,5%	0,386	1	0,39	0,1833
CH_4 - IPCC managed SWDS	22,5%	0,041	29,7	1,21	0,01935
total IPCC managed SWDS				**1,60**	

GHG emissions composted straw - EoL scenarios					
		mass (kg)	impact factor at 100 years	GWP100 from decay (kgCO2e)	kg(gas)/kg of wet straw
carbon mass (straw 100% composted)/FU		14,15			
which is degraded after 100 years	90,5%	12,808			
CO2 - max	97,45%	45,767	1	45,77	1,2369
CH_4 max	2,55%	0,435	29,7	12,92	0,0118
N_2O - max		0,000787	264,8	0,21	0,000787
total max (Hermann)				**58,89**	
CO_2 min	99,79%	46,866	1	46,87	1,2667
CH4 min	0,21%	0,035	29,7	1,04	0,00095
N2O min		0,0006	264,8	0,16	0,0006
total min (ADEME)				**48,07**	

Appendix 3 : Climate change impact (GWP adjusted at a 100-year time horizon) for the time shift of 1 kgCO2 (from [27])

		capture year											
		1	11	21	31	41	51	61	71	81	91	101	Never
emission year	1	0	0,079	0,160	0,244	0,331	0,422	0,517	0,619	0,728	0,849	1	1
	11	-0,079	0	0,081	0,165	0,252	0,343	0,438	0,540	0,649	0,769	0,921	0,921
	21	-0,160	-0,081	0	0,084	0,171	0,261	0,357	0,458	0,568	0,688	0,840	0,840
	31	-0,244	-0,165	-0,084	0	0,087	0,178	0,273	0,375	0,484	0,604	0,756	0,756
	41	-0,331	-0,252	-0,171	-0,087	0	0,091	0,186	0,288	0,397	0,517	0,669	0,669
	51	-0,422	-0,343	-0,261	-0,178	-0,091	0	0,095	0,197	0,306	0,427	0,578	0,578
	61	-0,517	-0,438	-0,357	-0,273	-0,186	-0,095	0	0,101	0,211	0,331	0,483	0,483
	71	-0,619	-0,54	-0,458	-0,375	-0,288	-0,197	-0,101	0	0,109	0,230	0,381	0,381
	81	-0,728	-0,649	-0,568	-0,484	-0,397	-0,306	-0,211	-0,109	0	0,121	0,272	0,272
	91	-0,849	-0,769	-0,688	-0,604	-0,517	-0,427	-0,331	-0,23	-0,121	0	0,151	0,151
	101	-1	-0,921	-0,84	-0,756	-0,669	-0,578	-0,483	-0,381	-0,272	-0,151	0	0
	Never	-1	-0,921	-0,84	-0,756	-0,669	-0,578	-0,483	-0,381	-0,272	-0,151	0	0

Storage   differed capture

Appendix 4 : Ecoinvent processes used for conventional and biobased walls – production, use and end of life inventory

Changed Ecoinvent processes are highlighted in yellow and described below.

Conventional production:

- Concrete production 35MPa :
    - "Market for sand": sand process changed from RoW to CH
    - "Market for cement, Portland" changed from US to Europe without Switzerland
    - "Market group for tap water" changed from GLO to Europe without Switzerland
    - "Market for electricity, medium voltage" changed from GLO to FR
    - Addition of "blast furnace slag" – 74kg/m3 (process changed with "Electricity market FR")

Biobased

- Treatment of biowaste (compost & incineration)
    - see Appendix 6
- Treatment of waster wood (incineration & landfill)
    - see Appendix 6

4.1 Production

Ref.	Material description	Ecoinvent materials/process	Amount	Unit
Conventional				
1	Paint	alkyd paint, white, without water, in 60% solution state | cut-off, U - RER	0,35	kg
		market group for tap water | tap water | cut-off, U - RER	0,035	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,175	t*km
2	Cement Render	cement mortar production | cement mortar | cut-off, U	30	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	1,5	t*km
3	OPC Concrete blocks	concrete production 35MPa, RNA only | concrete, 35MPa | cut-off, U	0,0872	m^3
		diesel, burned in building machine | diesel, burned in building machine | cut-off, U - GLO	19	MJ
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	38,4	t*km
4	Cement mortar	cement mortar production | cement mortar | cut-off, U - CH	33	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	1,65	t*km
5	Glass wool	glass wool mat production, Saint-Gobain ISOVER SA | glass wool mat | cut-off, U - CH	6	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,3	t*km
6	Gypsum plasterboard	gypsum plasterboard production | gypsum plasterboard | cut-off, U - CH	10	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,05	t*km

Ref.	Material description	Ecoinvent materials/process	Amount	Unit
Biobased				
1	lime render - 1 kg (there are 28kg/FU) from clay plaster process	market for silica sand | silica sand | cut-off, U - GLO	0,7	kg
		lime, hydrated, packed | lime production, hydrated, packed | cut-off, U - CH	0,12	kg
		market for tap water | tap water | cut-off, U - CH	0,18	kg
		market for conveyor belt | conveyor belt | cut-off, U - GLO	3,33E-08	m
		market for industrial machine, heavy, unspecified | cut-off, U - GLO	6,67E-06	kg
		electricity, medium voltage | market for electricity, medium voltage | cut-off, U - CH	0,0278	kWh
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,085	t*km
2	Straw bale - 1kg (there are 37kg/FU)	Carbon dioxide, fossil	1,4025	kg
		Soft wheat grain, conventional, national average, at farm gate - FR	0,00052	7,1 t
		potassium sulfate, as K2O | potassium sulfate production | cut-off, U - RER	0,0123	kg
		phosphate fertiliser, as P2O5 | ammonium nitrate phosphate production | cut-off, U - RER	0,0017	kg
		urea, as N | urea production, as N | cut-off, U - RER	0,0073	kg
		market for diesel | diesel | cut-off, U - Europe without Switzerland	0,00778	kg
		transport, tractor and trailer, agricultural | cut-off, U - CH	0,005	t*km
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,028	t*km
3	Wood battens	Carbon dioxide, fossil	2,25	kg
		lath, softwood, raw, air drying to u=20% | sawnwood, lath, softwood, raw, dried (u=20%) | cut-off, U - CH	0,00259	m^3
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,284	t*km
4	Timber beam	Carbon dioxide, fossil	17,217	kg
		planing, beam, softwood, u=20% | sawnwood, beam, softwood, dried (u=20%), planed | cut-off, U - CH	0,02	m^3
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	2,2	t*km
5	Clay plaster	clay plaster production | clay plaster | cut-off, U - CH	54	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	2,9	t*km

4.2 Use

Ref.	Material description	Ecoinvent materials/process	Amount	Unit
Conventional				
1	Paint	alkyd paint, white, without water, in 60% solution state | cut-off, U - RER	1,4	kg
		market group for tap water | tap water | cut-off, U - RER	0,14	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,7	t*km
2	Cement Render	cement mortar production | cement mortar | cut-off, U	60	kg
		Carbon dioxide, fossil	8,5	kg
		inert waste, for final disposal | treatment of inert waste, inert material landfill | cut-off, U - CH	-60	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	4,8	t*km
3	OPC Concrete blocks			
4	Cement mortar	Carbon dioxide, fossil	2,4	kg
5	Glass wool	glass wool mat production, Saint-Gobain ISOVER SA | glass wool mat | cut-off, U - CH	6	kg
		treatment of inert waste, sanitary landfill | inert waste | cut-off, U - CH	-6	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,48	t*km
6	Gypsum plasterboard	gypsum plasterboard production | gypsum plasterboard | cut-off, U - CH	10	kg
		treatment of waste gypsum, inert material landfill | waste gypsum | cut-off, U - CH	-10	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,08	t*km

Biobased				
1	lime render - 1 kg (there are 56kg/FU) from clay plaster process	market for silica sand | silica sand | cut-off, U - GLO	0,7	kg
		lime, hydrated, packed | lime production, hydrated, packed | cut-off, U - CH	0,12	kg
		market for tap water | tap water | cut-off, U - CH	0,18	kg
		market for conveyor belt | conveyor belt | cut-off, U - GLO	3,33E-08	m
		market for industrial machine, heavy, unspecified | cut-off, U - GLO	6,67E-06	kg
		market for electricity, medium voltage | electricity, medium voltage | cut-off, U - CH	0,0278	kWh
		Carbon dioxide, fossil	0,055	kg
		treatment of inert waste, inert material landfill | inert waste, for final disposal | cut-off, U - CH	-1	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,09	t*km
2	Straw bale (for 1 kg)	Carbon dioxide, fossil	1,4025	kg
		Soft wheat grain, conventional, national average, at farm gate - FR	0,00052	7,1 t
		potassium sulfate, as K2O | potassium sulfate production | cut-off, U - RER	0,0123	kg
		phosphate fertiliser, as P2O5 | ammonium nitrate phosphate production | cut-off, U - RER	0,0017	kg
		urea, as N | urea production, as N | cut-off, U - RER	0,0073	kg
		market for diesel | diesel | cut-off, U - Europe without Switzerland	0,00778	kg
		treatment of biowaste, composting | biowaste | cut-off, U - CH	0 or -1	kg
		treatment of biowaste, municipal incineration with fly ash extraction | cut-off, U - CH	0 or -1	kg
		transport, tractor and trailer, agricultural | cut-off, U - CH	0,005	t*km
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,058	t*km
3	Wood battens	Carbon dioxide, fossil	2,25	kg
		lath, softwood, raw, air drying to u=20% | sawnwood, lath, softwood, raw, dried (u=20%) - CH	0,00259	m^3
		treatment of waste wood, untreated, municipal incineration | waste wood, untreated | U - CH	-0,3635	kg
		treatment of waste wood, untreated, sanitary landfill | waste wood, untreated | cut-off,U - CH	-0,2466	kg
		treatment of waste wood, post-consumer, sorting and shredding | wood chips, from post-consumer wood, measured as dry mass | cut-off, U - CH	0,74416	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,284	t*km
4	Timber beam			
5	Clay plaster	clay plaster production | clay plaster | cut-off, U - CH	108	kg
		treatment of inert waste, inert material landfill | inert waste, for final disposal | cut-off, U - CH	-108	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	8,64	t*km

4.3 End of life

Ref.	Material description	Ecoinvent materials/process	Amount	Unit
Conventional				
		machine operation, diesel, >= 74.57 kW, high load factor |cut-off, U - GLO	1	min
1	Paint			
	Cement Render	treatment of waste concrete, inert material landfill | waste concrete | cut-off, U - CH	-30	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	2,33	t*km
3	OPC Concrete blocks	treatment of waste concrete, inert material landfill | waste concrete | cut-off, U - CH	61,4	kg
		rock crushing | rock crushing | cut-off, U - RER	130,6	kg
		Carbon dioxide, fossil	7,46	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	14,9	t*km
4	Cement mortar	treatment of waste concrete, inert material landfill | waste concrete | cut-off, U - CH	9,6	kg
		rock crushing | rock crushing | cut-off, U - RER	20,4	kg
		Carbon dioxide, fossil	0,8	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	2,33	t*km
5	Glass wool	treatment of inert waste, sanitary landfill | inert waste | cut-off, U - CH	-6	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,18	t*km
6	Gypsum plasterboard	treatment of waste gypsum, inert material landfill | waste gypsum | cut-off, U - CH	-10	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,03	t*km

Biobased				
		power sawing, without catalytic converter | cut-off, U - RER		h
1	lime render	treatment of inert waste, inert material landfill | inert waste, for final disposal | cut-off, U - CH	-28	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,14	t*km
2	Straw bale (for 1 kg)	treatment of biowaste, composting | biowaste | cut-off, U - CH	0 or -1	kg
		treatment of biowaste, municipal incineration with fly ash extraction | cut-off, U - CH	0 or -1	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	0,01	t*km
3+4	Wood battens Timber beam	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | U - CH	-3,14	kg
		treatment of waste wood, untreated, sanitary landfill | waste wood, untreated | cut-off, U - CH	-2,13	kg
		treatment of waste wood, post-consumer, sorting and shredding | wood chips, from post-consumer wood, measured as dry mass | cut-off, U - CH	7,05	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	1,084	t*km
5	Clay plaster	treatment of inert waste, inert material landfill | inert waste, for final disposal | cut-off, U - CH	-54	kg
		transport, freight, lorry 16-32 metric ton, EURO4 | cut-off, U - RER	1,62	t*km

Appendix 5 : Materials inventory for the two types of wall according to French EPDs - EPD scenario

Note that EPD neglect low R values materials thermal performance (renders, gypsum plasterboard…), which is acceptable in the present case since it represents less than 1% of the wall thermal resistance.

Cod.	Material	FU	R m².K/W	Mass Kg/FU	Lifespan Year	Waste treatment	EPD source
conventional - Concrete with internal thermal insulation							
1	Cement render	Cover 1m² with features described in NF EN 998-1	-	24	50	landfilled	FDES SNMI [152]
2	hollow concrete blocks	1m² of bearing wall	1.12	200	100	70% recycled 30% landfilled	FDES Confort City [74]
3	Cement mortar	link masonry components for a 1m² wall	-	24.7	100	landfilled	FDES SNMI [153]
4	Glass wool	Insulate from the inside 1m² of wall	6.25	4.6	50	landfilled	FDES URSA [82]
5	Gypsum plasterboard	Ensure facing for a 1m² wall	-	9.3	50	95% landfilled 5% recycled	FDES St-Gobain [154]
6	Paint	cover and protect a 1m² wall	-	0.5	15	landfilled	FDES SIPEV [87]
biosourced - timber and wheat straw bale							
1	lime render	Cover 1m² with features described in NF EN 998-1	-	24	50	landfilled	FDES SNMI [152]
2	Straw	insulate 1m² of wall with non-bearing straw	7.1	37	50	landfilled	FDES CEREMA [39]
3	Wood battens	-	-	1.27	50	landfilled, incinerated, recycled	FDES CEREMA
4	Timber beam	1m² of bearing wall	-	11.4	100	landfilled, incinerated, recycled	FDES FCBA [155]
5	Clay plaster		-	54	25	landfilled	Ecoinvent 3.2

Appendix 6 : ***Modification of Ecoinvent data for bio-based materials EoL treatment***

Since the IPCC 2013 impact method considers that biogenic CO_2 has no impact on the GWP100, data were modified to include CO_2 emissions due to decay and then to balance these emissions with captured biogenic CO_2 counted as negative in the production stage:

- wood which is landfilled is modelled by the process “treatment of waste wood, untreated, sanitary landfill {CH}” originally worth 0.077 kgCO_2 per kg of wood. Biogenic CO2 is changed into fossil CO_2. Moreover, this process considers a 1.5% overall degradability of wood in 100 years. CO_2, CO and CH_4 are multiplied by 10. Overall, GWP100 of landfilled wood now equals 0.77 (min) or 1.39 (max) kgCO_2eq/kg of wood.

- Incinerated wood is described by “treatment of waste wood, untreated, municipal incineration {CH}”. Its original impact is very low (0.01885 kgCO2e/kg of wood) since during combustion, oxidized carbon is counted as biogenic CO_2. As the impacts of energy valorisation are mostly linked to wood combustion [99], biogenic emissions are converted into fossil emissions. The impact is now 1.47 kgCO_2e/kg of wood.

- Wheat straw disposal is modelled by the process “treatment of biowaste, composting {CH}”. Biogenic CO_2 is converted into fossil CO_2. CO_2, CH_4 and N_2O emissions are increased. The impact of the process was originally 0.21 kgCO_2e/kg and now equals 1.46 kgCO_2e/kg (min) or 1.80 kgCO_2e/kg (max).

- Incinerated straw is modelled by “Biowaste, incineration”. Biogenic CO_2 is converted into fossil CO_2. The value is increased from 0.55 kgCO_2e/kg to 1.44 kgCO_2e/kg since the carbon content of straw is higher than the carbon content decided specified in the process.

Recycled wood is not changed because its impacts are linked to transport and wood crushing which is well described by Ecoinvent 3.2.