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Impact of GHGs temporal dynamics on the GWP assessment of building materials: A case study on bio-based and non-bio-based walls

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ABSTRACT

In a static Life Cycle Assessment (LCA), the global warming potential (GWP) is calculated assuming Green House Gas (GHG) impact to be independent of their emission or uptake timing.This study investigates if this approach is adequate to fully capture the global warming impact (GWI) of building materials. Static LCA (sLCA) was compared to dynamic LCA (dLCA) on two case studies, a conventional wall made of concrete and mineral wool, and a bio-based wall made of wood and straw.

The main results are:

●sLCA do not allow to evaluate the real GWI of building materials. This might mislead the comparison of building materials.

●GWP indicator might be estimated at 100- and 500-year-TH to better support mitigation in the building sector;

●The relative metric in kgCO_2 equivalent misleads conclusions. Absolute global warming indicators calculated with dLCA might be fairer to compare building materials' GWI;

●sLCA with at 100 years GWP indicator and a relative metric in kgCO_2e, which is the approach currently used in the French building sector, disadvantages bio-based solutions compared to conventional ones;

●dLCA applied to an alternative functional unit — maintaining a housing function during several centuries — demonstrates that temporary carbon storage induced by bio-based materials do not lead to dramatic carbon release for future generations.

1. Introduction

Today, efforts are focused to reduce the energy consumption of building during their use phase and to choose less impacting building materials and processes. Construction materials GWI need to be assessed. The most commonly used methodology is static Life Cycle Assessment (sLCA). It calculates the global warming potential (GWP) by summing up GHG emissions and uptakes linked to a production, independently of their timing. sLCA is problematic for several reasons. First, it is physically incorrect to add non-simultaneous emissions. Indeed, during the offset between them, the fraction of the first emission will have decreased due to interactions between the lower atmosphere and forests, biomass, soils and ocean. Moreover, this methodology rises some questions regarding how to consider the contribution of biogenic CO_2 included in bio-based materials. Ref. [1] analysed 101 peer-reviewed LCAs of forestry products and found that 87% of studies considered biogenic carbon as neutral. It is either counted for "0" or "-1/+1", i.e. there is a balance between carbon sequestration and re-emission at the EoL [2,3]. But such a sLCA leads to biases in the 'true' values based on a complete inventory [4] and fails in taking into account the effect of temporary storage of carbon. Another approach is the dynamic LCA (dLCA) method [5–8], which consists in accounting for the timing of carbon storage and emissions on a year-by-year basis. Several authors recently applied this dynamic LCA approach to building materials [9–11].

In both methods, the time horizon at which a global warming indicator is calculated is critical. This aspect has been discussed in Ref. [12]. They recommend diverse metrics to compare the impact of different technical solutions on climate change (CC). However, the most common metric in LCA remains the GWP, that can be applied usually in 20, 100

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and 500 years [13]. In the building context, GWP is usually calculated at 100 years (GWP100).

Building regulations are on the way to require the use of sLCA to evaluate the GWP100 of buildings, such as the French one called "RE2020"[103]. Thus, there is a crucial need to evaluate if a GWP100 calculated this way is accurate enough to decide which are the building methods to promote. This is the aim of this study. This leads to highlight the fundamental difference between sLCa and dLCA on global warming estimations on two case studies: a conventional wall made of concrete and mineral wool, and a bio-based wall made of wood and straw. Different scenarios are explored by changing the building lifetime and the bio-based material end of life. To sum up, the main contribution of this paper is to investigate the impact of some key methodological aspects regarding LCA studies in the building context, to evaluate if the actual LCA method used for material in the French building sector (sLCA, 100 year horizon, global warming expressed in relative metric kgCO2) enables a fair comparison between bio-based and non bio-based practices.

Furthermore, this paper presents three others contributions regarding:

- the question raised about the need to promote fast growing crop rather than forestry to mitigate CC. This topic was first tackled by Ref. [9]. This is linked to an essential point in dynamic LCA methodology: the definition of the eco-system equilibrium that allows to state if a resource is renewable or not. This question is tackled by taking metropolitan France as a case study.
- The appropriate unit for the GWP indicator, which is usually the relative metric "equivalent kgCO_2". Results from static and dynamic LCA at different TH, for conventional and bio-based walls are compared to analyse if equivalent CO2 really capture the effective radiative forcing.
- The question "does temporary carbon storage in bio-based materials is a risk for future generations" ? This question is addressed with dynamic LCA and an alternative functional unit, defined as a service which is "maintaining a housing for inhabitant for several centuries" rather than a building lifetime.

2. Method

2.1. Static Life Cycle Assessment (LCA)

Standard LCA is based on the ISO standards 14040:2006 [14] and 14044:2006 [15]. In the present study, only the climate change is evaluated. As a consequence, the inventory only concerns the greenhouse gases (GHG) related to the process.

Currently, the most common CC metric is radiative forcing: each GHG has its own radiative efficiency per unit mass, a_{GHG}. Since 1990 and the first IPCC report regarding assessment [16], the most widely used metric is the GWP. It is a cumulative and relative metric. It integrates the instantaneous global warming impact (GWI_{inst}) over a period of time up to a TH, to calculate the absolute global warming potential (AGWP) due to a given mass increase of a GHG atmospheric concentration (Eq. (1) and Eq. (2)).

The instantaneous radiative forcing, RF_{GHG}, caused by an increase in GHG atmospheric concentration depends on its radiative efficiency, a_{GHG} and on the lifetime of the given gas. It can be calculated with equations Eq. (1) or more complex ones, in particular for carbon dioxide [17]. This instantaneous radiative forcing of a GHG always decreases with time, due to its decay in the atmosphere by its reaction with oceans and earth soils which act as carbon sinks.

$$RF_{GHG}(t) = a_{GHG}e^{-t/\tau}\ \left[\mathrm{W.m^{-2}.kg^{-1}}\right] \tag{1}$$

The absolute global warming potential, $AGWP_{GHG}$, can be calculated as the sum of instantaneous radiative forcing up to a given time horizon, TH (Eq. (2))

$$AGWP_{GHG}(TH) = \int_0^{TH} RF_{GHG}(t)dt\ \left[\mathrm{W.yr.m^{-2}.kg^{-1}}\right] \tag{2}$$

The GWP is also a relative metric, as it normalises the AGWP due to a new emission of a given GHG by the AGWP of 1 kg of CO_2 (Eq. (3))

$$GWP_{GHG}(TH) = \frac{AGWP_{GHG}(TH)}{AGWP_{CO_2}(TH)}\ \left[\mathrm{kgCO_2e.\ kg^{-1}}\right] \tag{3}$$

Multiplying each mass of GHG by its GWP calculates its GWI, in kgCO_2e, for a given process or product. The TH can be 20, 100 or 500 years after the IPCC [18], but it is usually 100 years. The overall impact is the sum of the GWP of each GHG. This approach does not consider the instant of a gas emission or uptake, and is then called "static" approach. Two main criticisms can be made about this approach: 1/the GWP is relative to the AGWP of CO_2, that introduces a complexity related to the real knowledge of the atmospheric CO_2 concentration, as well as the fact that the climate effect due to gas changes over time, with its overall concentration in the atmosphere [17]; 2/as seen in Eq. (1), the amount of gas in the atmosphere decreases with time. Then if a same gas is emitted at two different times, the amount of gas in the atmosphere will be less than their sum.

2.2. Dynamic LCA (dLCA)

sLCA results are usually evaluated at TH of 100 years, beyond which further impacts are no longer taken into consideration [5]. Changing this TH will modify the GWP since greenhouse gases have different intrinsic decay times: CH_4 stays 12.4 years, N_2O 121 years. Carbon dioxide does not decay like other gases: models consider that between 20% and 40% of emitted anthropogenic CO_2 remains in the atmosphere at a 500-year-timescale [17,18]. Thus, the cumulative effective GWI due to a process that emits carbon will always increase well beyond 100 years.

The dynamic LCA approach was firstly proposed by Ref. [19]. They calculated the benefits implied by a delayed emission depending on the TH. This method was criticized because it still needs a TH and delaying emissions has no real advantage as it simply postpones the problem [20]. Levasseur and her co-workers (2011, 2012) extended the approach by calculating the radiative forcing and the GWP year by year. The time-dependent curves of the impacts on global warming are simply calculated by adapting Eq. (1) and Eq. (2) with the approach of [6]:

The instantaneous global warming impact GWI_{inst} in W.m^{-2} calculated with Eq. (4) and Eq. (5):

$$DCF_{GHG}(t) = \int_{t-1}^{t} a_{GHG}C_{GHG}(t)dt\ \left[\mathrm{W.m^{-2}.kg^{-1}}\right] \tag{4}$$

$$GWI_{inst}(t) = \sum_{GHG}\sum_{i=0}^{t} g_{GHG}(i)^{*}DCF_{GHG}(t-i)\ \left[\mathrm{W.m^{-2}}\right] \tag{5}$$

where:

- $DCF_{GHG}(t)$ 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 global warming impact GWI_{cum} in W.year.m^{-2} is calculated with Eq. (6).

$$GWI_{cum}(t) = \sum_{i=0}^{t} GWI_{inst}(i)\ [\mathrm{W.year.m^{-2}}] \tag{6}$$

The GWI_{cum} represents an absolute GWI. It is converted into a "dynamic" GWP by comparing the GWI_{cum} of the gas with the AGWP of 1 kg of CO_2 emitted in year 1. Then this dynamic GWP represents a relative radiative forcing in $kgCO_2e$, as seen in section 2.1.

Levasseur and coworkers [12,21] also propose a dynamic score, DLCA, close to the static GWP100 definition, by dividing the GWI_{cum} by the cumulative radiative forcing of 1 kg of CO_2 emitted at time zero to a given TH (Eq. (7)):

$$DLCA_{GHG}(TH) = \frac{GWI_{cum,GHG}(TH)}{AGWP_{1kg,CO_2}(TH)} \tag{7}$$

The major interest of a dynamic approach (dLCA) is to take into account the carbon sequestration, and the sequencing of GHG uptake/release due to a practice. With this approach, depending on the fixed endpoint in time (Time Horizon - TH), emissions occurring later have less impact, compared to similar emissions occurring earlier [22].

2.3. How to account for timber and forestry in dynamic LCA?

In dLCA, it is essential to evaluate whether a resource is renewable or not, which depends on the resource growing duration and human practices. In the case of bio-based construction, the rate of carbon uptake has to be compared to the building lifespan, correlated to the forestry rotation time or the crop growth duration. This point has been recently focused by Ref. [9]. The case of annual crop products is quite simple as plants generally grow in one year or less: crops happen one year before the building construction. The case of timber is more complex as its growth lasts from 20 years to several centuries depending on species and forestry management.

A critical point is the carbon uptake timing: should we consider the uptake during the tree growth used for building, i.e before the construction? Or does the uptake occur during growth of the replacing tree, i.e. few years after the construction? [21,23] Carried out a dLCA on wood used in Canadian buildings. They consider a landscape level: a large area where a small proportion of trees is harvested every year, plus a variable age distribution of trees. Assuming a sustainable forest management, the authors consider the carbon uptake in wood in year 0 (harvest year). They also evaluated the ecosystem carbon costs (ECC): the act of harvesting wood has a carbon cost depending on the management context, such as the forest size and the beginning of sustainable management. The ECC in Canadian Forests computed by Ref. [21] mainly shows a negative impact for a TH of 100 years. Thus by considering 100 years of historical forest management for 12 species, the authors take a negative pulse emission at year 0, adding the carbon uptake of wood and the ECC.

Can one also consider French timber products as sustainable? In Europe, timber harvesting is not correlated with deforestation: forest areas have increased in recent decades, even if part of the forest biomass is used as softwood lumber, paper, furniture or for energy. According to the [24]; forest areas in France have increased at a rate of 0.7% per year since 1987, that is between 25 and 36 million m^3 per year [24,25], even if 38.3 million tons of wood have been harvested in 2017 [26] and of that only 32% of French forests are certified [27,28]. Sales of certified timber account only for 56% of total sales [26] but up to 92% of the sales are to the building sector [29]. Thus, it is reasonable to consider a carbon balance in French forests providing wood for the building sector: the forest is able to replace the volume of harvested timber in one year. That is why in the present study, the carbon uptake by wood was considered over one year.

From a broader viewpoint, recommendations are to maintain older, longer-rotation forests, to protect old-growth forests and to optimize forest management to fulfil different objectives: wood production, climate change mitigation and prevention of biodiversity loss [30]. Furthermore, the extension of sustainably managed forests may prevent land use change, a major source of GHG emissions, and may encourage afforestation of unproductive agricultural lands. Nevertheless, care must be taken with sustainable managed forests, since loss of biodiversity, monoculture, chemical inputs, degraded forest soil, and clearcutting can also be observed in some places. The closer the origin of the wood used or assessed, the more the harvesting practices of this renewable resource are known.

Table 1 summarizes data on timber and wheat production in France. Carbon sequestration from annual crop and timber are in the same order of magnitude and resources are not scarce. Thus, there is no need to promote further annual crop production such as straw or long-term production such as wood.

2.4. Which lifespan to consider for building and building materials?

Building lifespan is considered as a major factor in LCA results [35–38]. Currently, a 50-year-building-lifespan is chosen as a standard for LCA, without clear justifications. However, there is no consensus on buildings lifespan and other values are also found in literature, from 40 years to 100 years [39]. Building lifespans are hardly estimated, since they do not only depend on the ageing of the structure but also on social, regulation or aesthetic considerations.

Data from the French building context are compiled in appendix A.1. They show that the building stock will be completely renewed in 95 years, which could be considered as representative of the lifespan of a residential building. This theoretical calculus does not take into account neither future renovation regulations, nor coming methods and building processes. However, it also shows that 50 years is a short and arbitrary lifespan value. Another way to estimate the building in-service life is a durability approach. For example, [39] used a statistical approach on reinforced concrete structures and estimated a lifespan of 94 ± 21 years. Also, two studies conducted in Norway found a lifespan between 40 years and 300 years, a median value of 100 years and a mean of 125 years [40,41]. Furthermore, the average age of existing buildings is about 50 years in France [42–44]. It supports that the average lifespan of current French buildings is clearly more than 50 years.

Hence, in this study, three building lifespans will be used in assessments to cover the sensitivity due to service life duration: 50 years (usual value), 75 years (more than 80% of current buildings after [40] and 100 years (median value of [40]).

During a building's lifetime, its materials are changed depending on their functions, i.e., building materials have their own in-service life. Several authors [35,45,46] proposed different order of magnitude of materials lifespans, depending on their functions:

- Structure (foundation and load-bearing elements): 30–300 years;
- Skin (exterior surfaces): 35 years for conventional exterior rendering, and 30 years for glass wool outside insulation; 25 years for windows and 40 years for roof tiles.

Table 1
Yield per hectare and carbon storage in bio-based materials used for construction in France.

Material	Biomass production	Quantity of carbon permanently stored in the field or forest	Area in France	Sources
Timber	5 m3/ha, being around 3 t/ha (and 3 m3/ha harvested)	165 tC/ha (standing trees ~ 85 tC/ha Litter ~ 10 tC/ha Soil ~ 70 tC/ha)	17.106 ha	[25,26, 31–33]
Wheat	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: 9.3.106 ha (50.5% of arable land)	[31,34]

- Space plan (interior facings and non-load-bearing partitions): 40–50 years for inside gypsum plaster boards, 10 years for carpets and paints

The lifespan of the component materials used in the walls studied here are inspired by these studies. The lifespans of each layer were defined as follows:

- Lifespan of the structure is the same as the building (concrete or timber beam);
- 50 years for the insulation as well as for interior gypsum plasterboards;
- 25 years for renders made of cement, lime or earth;
- 5 years for the paint.

These values are a combination of site feedbacks and literature review. They remain arbitrary and can be very variable from one building to another.

2.5. Software and databases

LCAs are based on life cycle inventory data (LCI) from the Ecoinvent 3.2 database analysed using OpenLCA 1.5 software. Standard LCA focuses on GWP values of GHG relative to CO2 for a lifetime horizon of 100 years (i.e. GWP100) based on the [13] impact assessment method [47]. In construction and building, the main gases emitted are carbon dioxide (CO_2), methane (CH_4) and dinitrogen monoxide (N_2O) with GWP100 values of 1, 28 and 264.8 $kgCO_2e$ respectively [18]. To make data as consistent with local practices as possible, the Ecoinvent 3.2 dataset was sometimes modified to fit the French or European context.

3. Description of the case studies: A conventional and a bio-based walls

3.1. Functional unit

The two exterior walls have the same functional unit (FU), in accordance with NF EN 15804 and NF EN 16783 [48,49]:

- 1 m^2 of wall whose main function is to form a load-bearing structure;
- Thermal resistance value (R) 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 50, 75 or 100 years.

The *conventional* wall is composed of materials commonly used in France (Table 2). It is compared to a *bio-based* wall consisting of a structural timber frame filled with straw bales (Fig. 1).

Insulator thicknesses were defined by looking for the closest wall performance between the two construction types using products available on the market. Considering the superficial convection resistances of inside (Rsi) and outside surfaces (Rse) as 0.13 and 0.04 m^2 $K.W^{-1}$, the R values are 7.36 m^2 $K.W^{-1}$ for the *conventional* wall and 7.33 m^2 $K.W^{-1}$ for the *bio-based* wall.

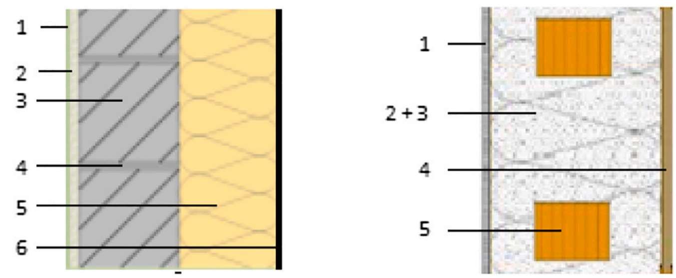

Fig. 1. Composition of the walls referred to in Table 2; *conventional* wall (left), *bio-based* wall (right).

3.2. System boundaries

The approach is from cradle to grave, i.e. from the extraction and supply of raw materials to the end of life treatment passing through construction and usa stages (modules A, B and C). Benefits due to the reuse of materials (energy production, reuse, recycling) are not considered. LCI also includes biogenic to photosynthesis of bio-based materials, accounted for in module A (A1: raw materials), and carbon uptake due to carbonation of cementitious materials. Cement and lime carbonation are included in the use phase (B1: use in building) and in module C for concrete. Detailed LCI and corresponding Ecoinvent processes are provided in Appendix B and C in the supplementary material.

In dynamic LCA, the production stage accounts for year 0 for bio-based materials grown before the construction. When a material is synthetic (glass wool, concrete block, render, paint …) it is assumed to be manufactured in the year of the construction (year 1). For bio-based products, a temporary carbon storage is considered up to their EoL. A partial or total release of the stored carbon is assumed depending on the EoL scenario.

To resume, the construction stage accounts for year 1, the usage is accounted for between year 1 and year 75, and end of life from year 76 (Fig. 2).

3.3. Production and construction impacts

The impact of cement was cross-checked since it has a large influence on the impact of concrete (Table 3 and Appendix D). The impact of growing the wheat straw was allocated assuming that straw represents 10% of the income from the sale of wheat [50]. Hence, the impact of wheat straw is 10% of the “soft wheat grain”, a process included in the French AGRIBALYSE database [51]. For the production of baled straw, a process was created comprising pressing, gathering and storage using

Table 2
Inventory of the materials used for the two types of wall.

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 potential
3	OPC concrete blocks	1000	200	1	192	100	Recycling potential
4	Cement mortar	1900	–	1.2	33.8	100	Recycling potential
5	Glass wool	25	240	0.035	6	50	Landfilled
6	Gypsum plasterboard	770	12.5	0.3	10	50	Landfilled
Bio-based - 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, incinerated, recycled
4	Timber beam	550	–	0.14	10.9	100	
5	Clay plaster	1800	30	0.8	54	25	Landfilled

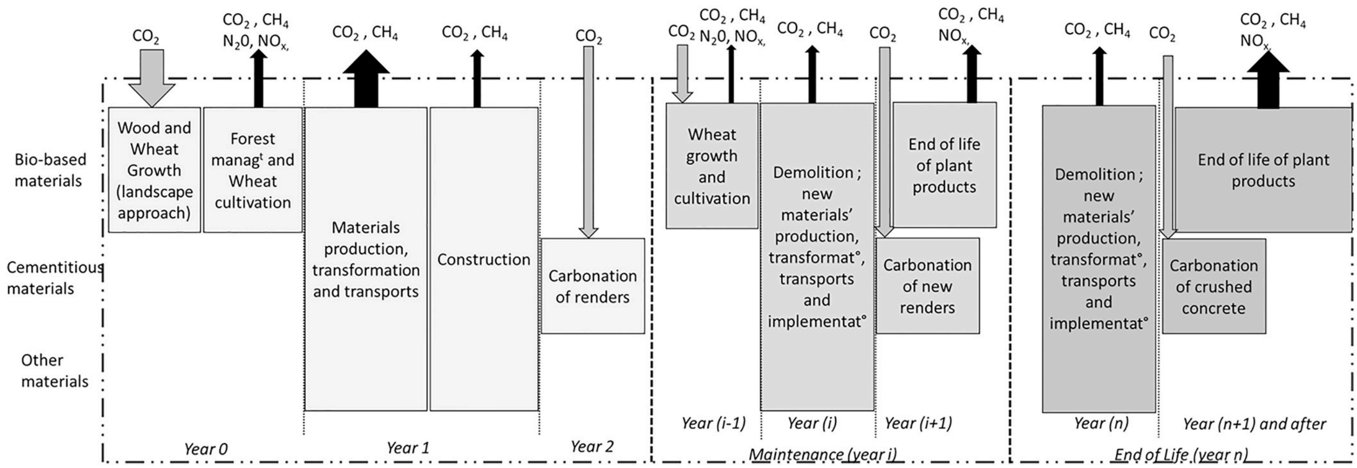

Fig. 2. System boundaries, with the main carbon sinks (grey arrows) and GHG emissions (black arrows), depending on the material type and on material life cycle step.

Table 3
Summary of used Ecoinvent data compared to data from the literature.

Material (unit)	GWP100 of process in Ecoinvent 3.2 ($kgCO_2e$/unit)	Average GWP100 from literature review ($kgCO_2e$/unit)	Standard deviation on literature data	Literature sources
Cement (t)	–	838.2	60.9	[54–64]
Aggregates (t)	–	2.87	0.52	[63,65,66]; Ecoinvent 3.2 'Quarry operation, gravel, crushed-round/sand CH
Water (kg)	–	3×10^{-4}	–	Ecoinvent 3.2, 'tap water production, conventional treatment EUR'
OPC Concrete (m^3)	314.0	332.5	27.6	[55,63,66]
Cement mortar (t)	198.6	201.7	37.2	[67–69]
Glass wool (kg)	1.4	1.33	0.13	[70,71] Ecoinvent 3.2, 'glass wool production CH'
Gypsum plasterboard (kg)	0.19	0.26	0.03	[72–74]
15%moisture wood - CO2 uptake ($kgCO_2$/kg of wood)	–	−1.56	0.064	Sup. doc. - Appendix E
Process of timber beam/timber battens (m^3)	44.1/31.7	36.6/31.6	16.4/11.4	[64,73]
15% moisture straw - CO_2 uptake ($kgCO_2$/kg of straw)	–	−1.40	0.047	Sup. doc. - Appendix E
Straw baling process (kg)	0.149	0.127	0.063	[52,75,76]
Lime render (kg)	0.142	0.16	0.07	[77]; Pretot et al., 2014
Earth plaster (kg)	0.029	0.04	–	[77]

diesel powered baling machines and included fertilisers to model nutrient losses from the field caused by exported straw. These losses are 7 kg nitrogen (N), 1.2 kg phosphorous (P_2O_5) and 12.3 potassium (K_2O) per ton of exported straw [52]. Finally, wheat straw absorbs carbon dioxide (CO_2) during plant growth due to photosynthesis. Literature data regarding straw's carbon storage are summarized in Appendix E. Here, a carbon content of 45% by mass of dry matter is considered. With 15% moisture [53], this leads to a carbon storage of 1.40 $kgCO_2$ per kg of wet straw.

After a literature review (Appendix E), the carbon content of wood is about 50.6%, and so the carbon storage is 1.86 $kgCO_2$/kg of dry wood.

For each type of wall, a 16–32 metric ton truck, EURO4, is used for transport. For the *conventional* wall, transport involves the delivery of concrete blocks from the ready-mix plant to the construction site (200 km) [78] and cement mortar transported from the packing facility to the construction site, which is assumed to be 50 km [9]. Plasterboard and wool insulation are also transported over a distance of 50 km. For the *bio-based* wall, the reference distance for French Douglas fir wood is 200 km [79]. Earth is assumed to be locally available, the conservative assumption that it is transported within 50 km is made. Lime is assumed to be transported over a distance of 500 km [80]. The shipping of straw is: 50% of the straw is assumed to be transported 10 km by tractor, 40% 40 km by truck and 10% 80 km by truck [50,52]. The electricity consumed at the building site and for the transport of the workers is not included. Details on GHG emissions (CO_2, CH_4, N_2O …) released during the production of materials are provided in Appendix F.

3.4. Use phase impacts

The carbon uptake due to cement and lime carbonation and the impact of replacement materials influence the use phase. We considered that cement and lime renders carbonate in 2 years and mortar joints carbonate at a rate of 2 mm/year [81]. Carbonation reactions are detailed in Appendix H.

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. 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 is 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 [82].

3.5. End of life impacts

Demolition of the *conventional* wall is performed by a high load diesel machine (e.g. a Volvo EC 300DL 170 kW). A 100-m^2-house with 4-m-high walls, e.g. 160 m^2 walls, takes 3–4 h to demolish. Thus a 1-min-operation is attributed to the FU demolition and the sorting of materials. For both construction types, waste transport is the same as in 3.3.

Glass wool is disposed of at landfill sites [43,83,84] along with painted gypsum plasterboard [84,85]. In France, 68% of concrete blocks are recycled and 32% are landfilled [86]. 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 does 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 during the use phase, it is 10.9 kgCO_2e.

For the *bio-based* wall, lime carbonation is 1.56 kgCO_2 and is attributed to the use phase. The demolition is performed by a diesel power saw for 0.1 h/m^2 [50]. 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 the French timber building sector [87]: 17.3% is disposed of at solid waste disposal sites, 25.5% is incinerated and 57.2% is reused as raw material by wood chip panel plants. Wheat straw can be incinerated or composted as biowaste [52]. Thus, there are two EoL scenarios for the *bio-based* wall:

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

Decomposition of organic material derived from biomass sources is the primary source of CO_2 released from waste [88]. A literature review was thus undertaken to assess the real impacts of biogenic carbon decay.

Concerning timbers’ EoL in landfill, the literature study [87–90] leads to the following ranges of values:

- a 15% fraction of degradable carbon;
- a carbon decomposition into the air as CO_2 (50%–77.5% of the carbon) and as CH_4 (22.5%–50%);
- a negligible emission of N_2O.

Concerning composted straw, 79% of the carbon is degraded during the first year to form humus. The humus degradation rate is thus set at 0.8% per year for the 100-year horizon [90]. As a result, 9.5% of the carbon content of straw remains permanently in the soil.

Based upon literature [64,89,90], 97.5%–99.9% of the degradable carbon is decomposed as CO_2 and 0.1–2.5% as CH_4. And 0.600–0.787 g of N_2O per kg of dry waste is also emitted during the first year of composting.

Hence, two emission 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 (Table 4).

3.6. Sensitive study

A quantitative fair comparison between these two walls would have took into account as precisely as possible all the uncertainties. This is a quite difficult exercise, especially regarding the effective building lifetime and the EoL scenarios, since human-based systems evolve rapidly, are hard to predict in the coming decades. This might be tackled by sensitivity studies and a probabilistic approach [38].

Based on Table 3, Ecoinvent processes were assumed to be representative enough to highlight the fundamental difference between static and dynamic LCA on global warming estimations at different TH. Only the two EoL scenarios for *biobased* are specified because of a lack of literature data. As an indication, a sensitivity study made from standard deviation figures in Table 3 gives an uncertainty on conventional walls’ GWP equal to 8.3%. The calculus is presented in Appendix G.

Table 4
CO_2, CH_4 and N_2O emission scenarios (min and max) for composted straw and landfilled wood, both with a 15% moisture content. Further details are in Appendix I and modified Ecoinvent processes are presented in appendix C.

	Min		Max	
	Wood	Straw	Wood	Straw
g(CO_2)/kg	116.9	1236.9	183.3	1266.6
g(CH_4)/kg	42.5	11.75	19.35	0.95
g(N_2O)/kg	0.63	0.6	0.63	0.787

4. Results

4.1. Comparison between static and dynamic LCA

The overall LCA results and impacts of materials at each stage of their life cycle are shown in Fig. 3. *Conventional* LCA results give a GWP100 of 79.8 kgCO_2e. For the *bio-based* wall, GWP100 is 26.3 kgCO_2e.

The material with the most impact in the *conventional* wall is concrete, which accounts for 35% of the overall impact, transport and carbonation included. Builders can mitigate it by choosing aerated, porous concrete blocks with optimized cement content. In our case, by selecting the 25-MPa-concrete process instead of the 35-MPa-concrete, the concrete impact in the FU drops by 15%. Nonetheless, concrete remains a source of carbon emissions higher than using wood as an alternative structural material. Glass wool and paint have a rather high impact compared to their mass in the FU.

In the *bio-based* wall, wheat straw drives both carbon uptake and carbon release and wood plays a smaller role in both scenarios (Table 5). This is specific to straw which is a rather heavy insulation material compared to other bio-based insulation materials.

Half of the lime render’s impact is due to its transport. The impact of clay plaster seems overestimated. Since clay plaster might be made with local materials and needs almost no processing, the process in the Ecoinvent database is a conservative one.

Dynamic LCA comparison of the two types of construction is presented in Fig. 4. The instantaneous impact curve shows the effects of radiative forcing on replacing materials.

Bio-based instantaneous radiative forcing curves go through negative and positive values, whereas *conventional* curve are directly positive. The cumulative impact clearly distinguishes between the two types of construction: the *conventional* wall contributes to climate change from the first year, whereas the *bio-based* wall has a cooling effect for several decades. Such information is not available from sLCA approaches.

Furthermore, the longer the TH, the greater the difference in the cumulative impact between the two types of construction. The min and max curves depend on the value taken for landfill and compost processes (Table 4). When straw is 100% composted, there is a significant influence of the min and max scenario. Interestingly, the instantaneous radiative impact shows that composting straw has a bigger impact than incinerating it, due to the significant emission of methane. However, the cumulative impact shows that composting has a higher impact in the short term but a lower impact in the long term. The long-term slope shows this difference keeps on increasing with time. This highlights the specific behaviour of carbon dioxide compared to other GHG: it does not disintegrate but interacts with the carbon cycle and remains for long time in the atmosphere whilst for example methane decay is rather fast. When carbon is emitted at year 1, estimations indicates 20% of the initially emitted carbon remains in the atmosphere after 1000 years [91].

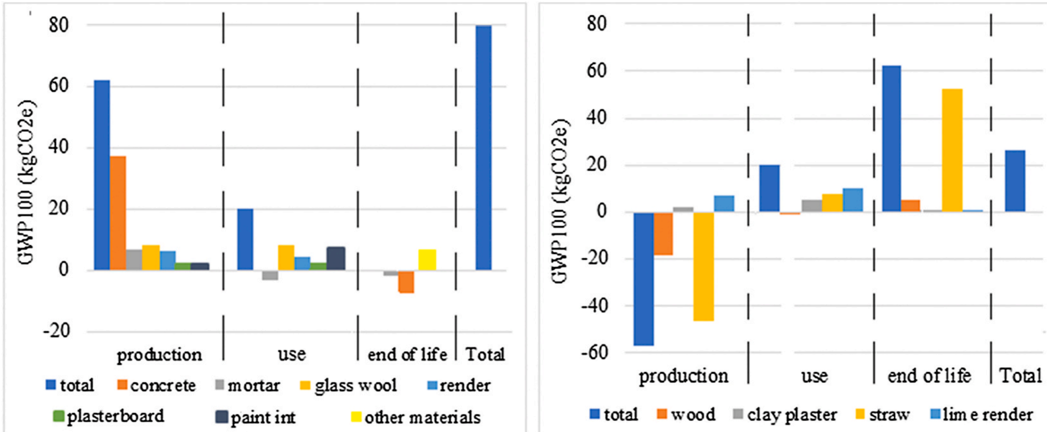

Fig. 3. SLCA results for a *conventional* wall (left) and a *bio-based* wall (right) with details of materials processes impacts (for *bio-based*: straw is 50% composted-50% incinerated).

Table 5
Outcome of wood and straw biogenic carbon sequestration and emission for the FU.

	Uptake ($kgCO_2$/FU)	Emissions ($kgCO_2e$)/FU			Biogenic carbon assessment (sum) ($kgCO_2e$)/FU
		Landfilled or composted (17% for wood and a 100% scenario for straw)	Incinerated (25% for wood and a 100% scenario for straw)	Recycled (57% for wood)	
Wood (12.3 kg)	−19.5	min: 1.6 max: 3.0	4.8	0	**min: 13.1 max: 11.7**
Straw (37 kg)	−51.9	min: 53.8 max: 66.4	51.9	–	**100% compost: [1.9; 14.5]** **100% incineration: 0**

Table 6 shows the effect of the chosen TH on the relative GWP results. Values for the *conventional* wall keep the same order of magnitude, regardless of the TH and the method (static or dynamic). This is due to the high proportion of GHG emitted during the first year of the life cycle. For the *bio-based* wall, the “dynamic” GWP100 is lower than the “static” GWP100, and “dynamic” GWP will converge towards the “static” one over a very long TH (more than 2000 years). Bio-based solutions are penalized when using static method with a TH of 100 years if temporary carbon storage is not taken into account.

From now on, based on the cumulative impact curves, “*bio-based* min” will be the lower curve of “*bio-based* - composted”, and “*bio-based* max” will be the higher curve of “*bio-based* - incinerated”.

4.2. The drawbacks of using a relative metric equivalent CO_2 to evaluate the GWP

Interestingly, dynamic GWP100 and GWP500 of the conventional wall are similar, which suggests that GWP saturates. However, due to carbon dioxide remaining in the atmosphere, the cumulative impact induced by conventional walls keeps increasing over time in terms of radiative forcing (Fig. 4).

This is an essential result: the drawback of using a relative impact indicator such as GWP in kgCO2e instead of GWI_{cum} does not allow the evaluation of the real effect of GHG on global warming. The real construction impacts on global warming are highly dependent on the time scale regardless of the materials used.

4.3. The impact of a longer functional unit on climate change assessment

In a systemic approach, the FU needs to continue providing housing for present and future citizens. Thus, a new FU is defined, as “maintaining 1 m^2 of wall (R = 7.3 m^2 $K.W^{-1}$) for housing during a period of 300 years” (the 300-year value is arbitrarily defined to draw long-term trends). First, a wall is built. At the end of its lifespan, either 50 years or 100 years, the building is destroyed according to its EoL scenario. Then a new wall is built, and so on, for up to 300 years. Results are displayed in Fig. 5.

Unsurprisingly, the longer the *conventional* wall lasts, the lower the impact. Looking at these *conventional* wall results, the instantaneous impact significantly increases every 50 years, due to the demolition and to the construction of a new house (50-year and 100-year lifespan), or due to the maintenance (100-year lifespan). As the GHG supplementary emissions due to the previous building have not totally decayed in the atmosphere, the peak due to the new construction or maintenance is higher than the previous one. In the case of a *bio-based* wall, the uptake of bio-based materials (straw and wood) for the new building will compensate the emissions due to the EoL of the previous materials. Furthermore, in the present study wood stores more carbon than it releases, because its storage in landfill and its recycling corresponds to a permanent carbon sequestration (section 3.4). Thus, by increasing the use of timber beams, the impact is reduced. That’s why, contrary to the *conventional* wall, a *bio-based* wall with a 50-year lifespan has less impact than a *bio-based* wall with a 100-year lifespan, which seems paradoxical. In fact, another study noticed a similar phenomenon [92]: the thicker a bio-based wall, the bigger the carbon storage. In both cases, even if using a lot of biogenic materials is advantageous in terms of short-term mitigation, it is likely that long-term impacts will be increased by an increased use of materials. In addition, a broader view on environmental impacts drive a more prudent use of available resources as a key to sustainability. Thus, from a global environmental standpoint, material consumption should always be optimized to requirements, and the lifespan of the material should be as long as possible.

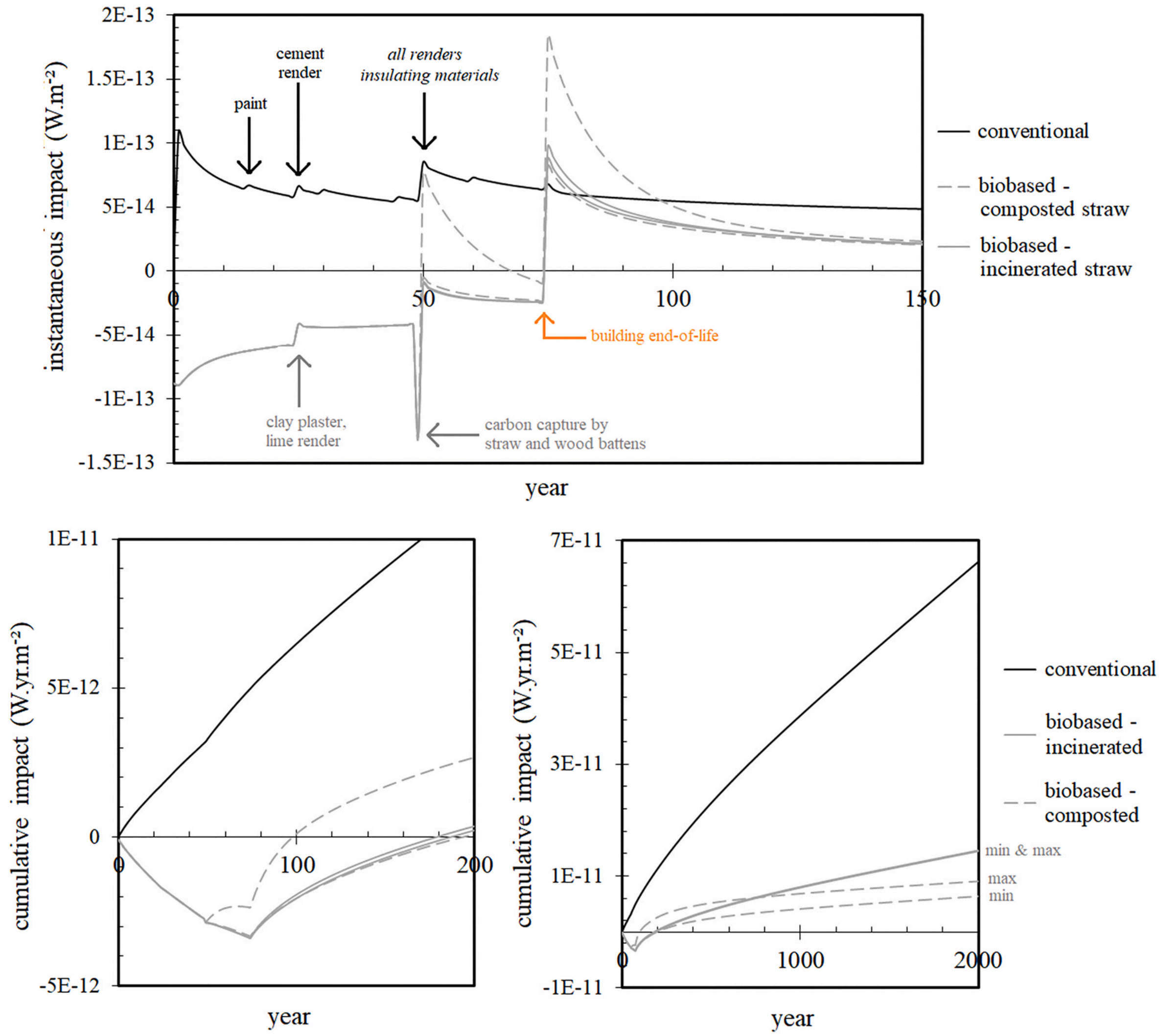

Fig. 4. dLCA of bio-based and conventional scenarios from the FU.

Table 6
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).

	Conventional $kgCO_2e/FU$	*Bio-based* $kgCO_2e/FU$
« static » GWP100	79.8	26.3
	GHG	GHG (min/max)
« dynamic » DLCA 20	60.0	−56.5
« dynamic » DLCA 100	70.8	−22.2/−9.8
« dynamic » DLCA 500	71.8	9.8/14.3
« dynamic » DLCA 1000	71.2	11.1/13.7

5. Discussion

5.1. Is it fair to use static LCA with a 100-year-time-horizon and relative metrics to compare building materials?

In the case studies of this paper, *conventional* constructions have higher GWI than constructions made with bio-based materials. *Bio-based* constructions even have a cooling effect for several decades. A similar comparison was made by Ref. [9]. Their cumulative impacts on the 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 GWI_{cum} 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. [9]also studied a wall composed of light clay straw with a timber frame. Except for one scenario, these authors found a negative GWI_{cum} [-9 to −3]x10^{-12} W yr.m^{-2} at 100 years. In this study, *bio-based* results are [-2.1 to 0.1]x10^{-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 amounts of biodegradable matter and emitted CO_2, CH_4 and N_2O during EoL differ. The present study underlines that results are sensitive to data used for compost, landfill and incineration processes of bio-based materials.

Regarding the TH, the cumulative impact at a 100 years TH (Fig. 4) and the relative GWP100 (expressed in $kgCO_2eq$) are not sufficient to well understand and to compare “carbon emitters” and “carbon sinks”. The time at which the cumulated radiative forcing becomes positive with the very low-tech bio-based wall considered in the present study is between 300 and 400 years with a systemic FU. It suggests that a 500 years TH indicator might be useful to complement the 100 years one. This long-term indicator is useful to promote best practices at long term. A short-term TH is useful as well to lower the uncertainty level on the studied system and to evaluate the short-term impact of environmental policies.

Finally, our results highlight that the bias induced by a static approach and a GWP evaluated at 100 years does not have a similar

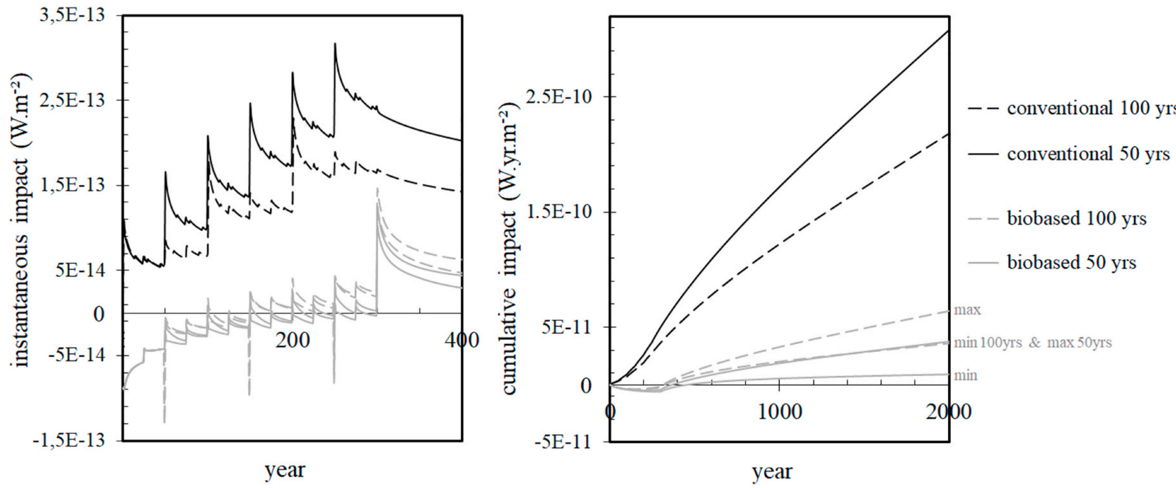

Fig. 5. Comparison of construction and demolition at one site of *bio-based* and *conventional* housing with a 50- or 100-year lifespan over a 300-year time period.

impact on different material. sLCA is especially inappropriate when storage and emission of GHGs occur. This confirms the interest of dLCA for building assessments [93], especially to address the biogenic carbon issue when bio-based materials are used [92,94,95]. In addition, bio-based materials are more disadvantaged than conventional materials with a relative global warming metric.

5.2. Does carbon temporary storage in bio-based materials is a risk for future generations?

To tackle this point, a systemic approach is used, thanks to the FU "maintaining 1 m^2 of wall (R = 7.3 m^2 K.W-1) for housing during a period of 300 years".

Fig. 6 presents the instantaneous impacts for *conventional* and *bio-based* walls which have been linearized, showing the difference between the two curves. It illustrates three essential results.

- First, only maintaining the existing housing stock increases the radiative forcing year by year, even when using bio-based materials. At long terms, sobriety in building needs and design is the best lever to mitigate climate changes, followed by material reemployment and likely very low carbon geo-based materials such as clay-based construction methods and low-tech bio-based materials. The slope of radiative forcing increase is steeper with conventional materials.
- Then, the savings made through the use of *bio-based* walls instead of *conventional* ones increase over time.
- Finally, it demonstrates that temporary carbon storage does not consist in delaying the global warming issue to future generations. On the contrary, conventional building methods induce a higher climate change whatever the timescale and thus induce a higher risk for future generations.

Interestingly, the conclusion that savings made by the use of bio-based building materials instead of conventional ones increase with time (Fig. 6-right) was also obtained with the former FU when using the radiative forcing, but not when using results expressed with the relative indicator in CO_2e (Table 7a). With the new FU based on a systemic approach, the conclusion is valid for both indicators (Table 7b). However, the difference is higher with the relative metric than with the absolute metric. Once again, an absolute metric should be preferred to provide meaningful interpretations on differences between bio-based and conventional materials.

This analysis by changing the FU highlights the importance of scale: national and international policies might consider a systemic LCA approach in order to set up meaningful indicators that promote good practices.

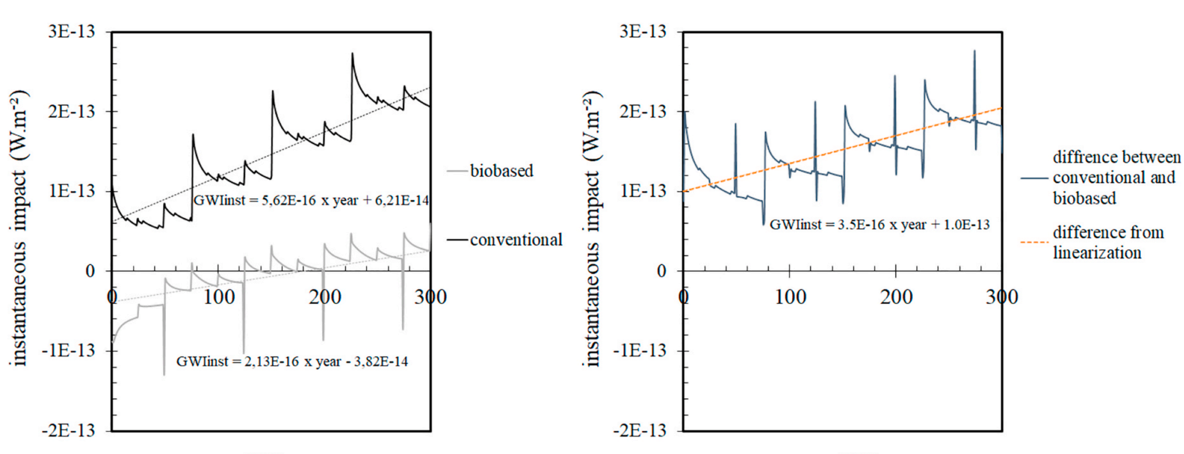

Fig. 6. Instantaneous radiative forcing for *conventional* and *bio-based* walls and their linearization, over a period of 300 years (left), and the difference between the two impacts (right).

Table 7
Impact of *conventional* and *bio-based* construction in radiative forcing and in CO_2e.

a) FU described in part 3.1 (data from Table 6)						
	Absolute impact - GWI_{inst} ($W/m^2/FU$)			Relative impact - dyn GWP (CO_2e/FU)		
	Bio-based (mean)	Conventional	Difference	Bio-based (mean)	Conventional	Difference
at 100 years	-1.7×10^{-14}	1.2×10^{-13}	1.35×10^{-13}	−16	71	87
at 500 years	6.8×10^{-14}	3.4×10^{-13}	2.7×10^{-13}	12	72	60
b) new FU						
	Absolute impact - GWI_{inst} ($W/m^2/FU$)			Relative impact - dyn GWP (CO_2e/FU)		
	Bio-based (mean)	Conventional	Difference	Bio-based (mean)	Conventional	Difference
at 100 years7	-5.7×10^{-15}	1.1×10^{-13}	1.1×10^{-13}	−41	89	130
at 500 years	3.4×10^{-14}	1.6×10^{-13}	1.3×10^{-13}	21	243	222

5.3. Impact of French building sector shift towards bio-based buildings

To assess the effect of a change of practice in the building sector on a country-level a current overview of the housing stock and practices must be done. Indeed, furthest the actual situation from the generalization of a "carbon sink", the more significant the benefits. For example, houses in North-America are mainly built in timber, whereas conventional building materials in Western and Southern Europe are mainly minerals. Some attempts summarized in Fig. 7 were made to evaluate the effect of a change of practice. One can apply it on building: first, the building carbon stock will rapidly grow up and affect the radiative forcing of the earth atmosphere. After a given time, the carbon sink will tend towards a plateau, here, when the whole building stock will have changed.

An analysis of the French building sector has been made and is provided in supplementary material, Appendix A. Currently in France, the use of bio-based building materials is limited: in terms of structure, wood construction only accounts for 9% of new individual houses and 4% of new collective housing [97]; in terms of types of insulation, only 7% are bio-based while 50% are mineral wool and 40% are plastic foam. Then a massive change in practice towards bio-based materials, if better in terms of GWP, would have a significant effect in France.

The following calculus aims to get an order of magnitude due to a change towards of bio-based materials in France. The FU defined in part 3.1 is used.

Assuming that all the residential and tertiary buildings move to a *bio-based* solution, the savings at 100 years are about $2{,}873 \times 10^6$ m^2 (floor surface from Appendix A, Table 1) x 1.15 (floor to wall surface conversion) x 1.35×10^{-13} $W\ m^{-2}$ (difference at 100 years, Table 7a) = 0.45 mW $m^{-2.}$ Global radiative forcing estimations range from 1.1 to 3.3 W m^{-2}, with an average value of 2.3 W m^{-2} [18]. In 2015, France was responsible for 1% of the world's GHG radiative forcing [98,99], thus about 23 mW m^{-2}. The building sector producing about 22% of French emissions [100], this leads to 5.3 mW m^{-2}.

Thus, the order of magnitude of the radiative forcing savings made by changing just the walls from a 100% *conventional* solution to a *bio-based* one is about 8% of the building sector and 2% of the French overall contribution. This is optimistic since it is based on a 100% move to *bio-based* buildings. However, our analysis is limited to walls, but ecological practices can also be included for the whole building such as the floors, ceilings or roofs. This seems to be a small contribution in percentage due to the actual rather low energy efficiency of buildings. In 2009, carbon emissions due to house heating systems were about 20 $kgCO_2/m^2/yr$ in France [101]. By dividing energy consumption by five (250–50 $kWh/m^2/yr$), due to thermal renovation and better equipment would achieve 4 $kgCO_2/m^2/yr$. In this case, the RF savings at 100 years are about 1.5×10^{-12} $W\ m^{-2}$, which is about ten times higher than the shift from *conventional* to *bio-based* walls.

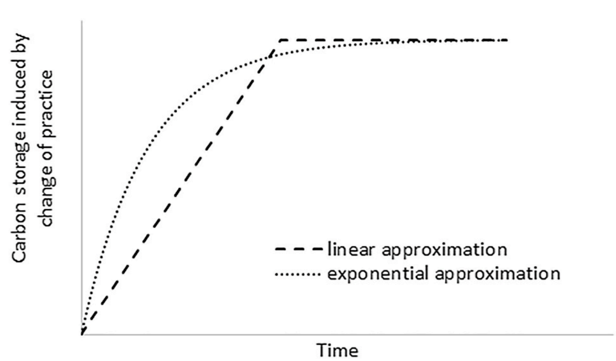

Fig. 7. Theoretical evolution of carbon storage due to a change of practice (in crop, transport, building etc.) [13,96].

This put figures on an already known conclusion: improving the energy efficiency of existing buildings is the very first action to undertake. Bio-based materials would add a benefit, but it should not be detrimental to the performance. For new well-insulated buildings, reducing the radiative forcing due to material production is nevertheless a major source of savings [102].

Assuming that the French housing stock moved to 100% bio-based walls, it would induce about a 2%-reduction of the global French radiative forcing (about 6–8% of RF is due to the construction sector). This preliminary simplified analysis is only based on walls and is not enough to consider the impact of a shift towards ecological practices in all aspects of the construction sector. Further studies could be focused on complete buildings (floors, walls, roof and equipment), taking into account their use (heating, cooling, lighting, equipment), eventually other ecological practices (per capita living space, heating temperature, bioclimatic conception at building and district level) and different scale (district, cities …).

6. Conclusion

The combination of static LCA, fixed time horizon at 100 years and relative carbon dioxide global warming potential indicator lead to misleading comparison between different building methods. Bio-based material are especially disadvantaged by not taking into account the temporary carbon storage, which has a real physical impact at a 100 years-time horizon. Moreover, considering that the functional unit is not limited to the building's lifespan, but it is to maintain the housing function on a site for several centuries, this temporary cooling effect lasts for around three centuries.

It was found that dynamic LCA provides more realistic results, since all Greenhouse Gases emissions and uptakes are taken into account with their timing. Global warming potential indicator can be expressed with absolute indicators at any time horizon.

This results also demonstrates that bio-based materials development does not induce an unmanageable transfer of a temporary stored carbon stock to future generations. On the contrary, conventional materials are riskier for future generations since just maintaining a conventional housing stock is a significant source of GHG emissions. The bio-based solution considered here is always better than the conventional one in terms of global warming potential, whatever the timescale.

On a public policy point of view, our study lead to three recommendations:

1. There is a need for a more robust and reliable methodology than static LCA to calculate building materials impact on global warming. Dynamic LCA constitute a fairer approach to account for the real impact of all materials, bio-based or not bio-based.
2. The time horizon of 100 years appears to not be sufficient to well understand and compare "carbon emitters" and "carbon sinks". Considering both 100 and a more long-term time horizon, like 500 years, is necessary.
3. The global warming potential should be analysed in absolute metrics, (here in W/m^2 or $W/yr/m^2$), rather than with relative metrics such as the equivalent CO_2. It would prevent from misleading interpretations, in particular at long terms, where relative metrics do not indicate the dramatic impact of carbon dioxide due to its long residence time in the atmosphere.

Practically, dynamic LCA can be easily applied to building materials and buildings with the data already collected to perform static LCA.

Another result is that it may not be necessary to promote fast growing crop rather slow growing forest to mitigate climate change, especially in countries where both resources are not scarce. Such a conclusion assumes to maintain eco-systems equilibrium which is key for a sustainable development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.buildenv.2020.107210.

Nomenclature

CaO	Calcium oxide
CC	Climate change
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
dLCA	Dynamic life cycle assessment
DLCA	Dynamic score
DOCf	Degradable organic carbon fraction
ECC	Ecosystem carbon costs
EoL	End of life
EPS	Expandable polystyrene
FU	Functional unit
GHG	Greenhouse gases
GWI_{inst}	Instantaneous global warming impact
GWI_{cum}	Cumulative global warming impact
GWP	Global warming potential
GWP100	Global warming potential at the 100-year time horizon
LCA	Life cycle assessment
LCI	Life cycle inventory data
N_2O	Dinitrogen oxide
R	Thermal resistance
RF	Radiative forcing
SF_6	Sulphur hexafluoride
TH	Time horizon

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