IOP Conference Series: Earth and Environmental Science

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To cite this article: V Göswein *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **588** 042054

Dynamic life cycle assessment of straw-based renovation: A case study from a Portuguese neighbourhood

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Abstract. Action is needed to mitigate climate change. As the building sector is one of the main contributors to energy consumption, renovation of existing buildings is a key strategy. However, for a drastic greenhouse gas emissions (GHG) reduction, sensible material solutions are required. Bio-based products seem to be a promising alternative thanks to carbon sequestration in the new biomass, which needs to be regrown for substitution. The conventional life cycle assessment (LCA) framework seems unsuited to model temporal emissions and carbon uptake of such solutions. Dynamic LCA (DLCA), which models temporal aspects, is more appropriate to evaluate the environmental performance of bio-based products. Moreover, the different dynamic drivers of urban building stocks should be included to allow for informed material choices. A new methodology is proposed, integrating DLCA with material flow analysis (MFA) considering a dynamic renovation rate. The global warming potential over time of the thermal retrofit of a Lisbon neighbourhood with a straw-based technology is assessed. The results highlight the importance of the end of life scenario, greatly influencing the results in the mid- to long term. Increased renovation rates can yield higher carbon storage benefits. However, if accompanied by technological solutions that rely on carbon intensive materials, e.g. finishing, this can lead to increased embodied carbon emissions in the transition period.

1. Introduction

Climate change confronts our building stocks with two major problems: on the one hand, changing temperatures require a constructive adaptation of existing buildings characterized by their current bad thermal performance in order to minimize the operational energy demand. In Portugal, for example, about 70% of the buildings were built in a time when the national standard defining the minimum requirements for thermal performance of new construction did not exist yet (it was legislated in 1990) [1], resulting in a particular high need for building stock renovation. On the other hand, any new construction or thermal retrofit results in emissions, therefore contributing to climate change. [2]. This seeming dilemma can only be answered through the use of smart material choices [3]. In this context, bio-based construction materials seem promising to tackle both challenges simultaneously. Constructive solutions made with for example wood, straw, hemp, or cork are readily available on the market. Moreover, when used for thermal insulation, such bio-based solutions, if properly designed and manufactured, reach thermal conductivity values comparable to those of conventional solutions (e.g. 0.035 W/mK for extruded polystyrene vs. 0.04 W/mK for insulation cork board [4,5]).

During the plant's growth carbon is sequestered that, once harvested and manufactured into a construction product, is captured in the building for an increased lifetime. At the end of life (EoL) of the building material, the sequestered carbon is released back to the atmosphere [6]. Assuming a continuous agriculture or sustainably managed forests, the harvested biomass is regrown in nature. In this sense, the biogenic carbon cycle is generally considered neutral [7]. However, various studies have shown that the timing does play a role in the accounting of CO_2 [8–11]. Therefore, traditional life cycle assessment (LCA), by ignoring the temporal dynamics, can be misleading. Levasseur *et al.* [12,13] proposed a dynamic LCA (DLCA) approach and showed that the carbon cycle of bio-based products is, in fact, not neutral when considering the carbon uptake and deferred release of greenhouse gas (GHG) emissions. Two main aspects that effect the biogenic carbon balance are the EoL scenario [14] and the rotation period of the biomass species [10]. Fast-growing species are advantageous compared to slow-growing species (i.e. trees) since they offer increased carbon sequestration potential thanks to their short rotation periods. Crops, such as wheat and rice, usually have rotation periods of less than a year and are, therefore, particularly promising. However, the consequences of large-scale construction interventions with bio-based materials are not yet well understood since most studies that analyse bio-based construction either stay at the material scale or use constant parameters for building stock parameters such as renovation rate. The various dynamics of bio-based materials and their emission profiles in relation to building stock needs over time need to be better understood to provide construction practitioners with information on smart material choices and policy makers with renovation strategies. The objective of this study is to integrate DLCA, as presented in Pittau *et al.* [10,11], with a dynamic building stock model to uncover the opportunities and threats of using fast-growing bio-based material for thermal retrofit. The results contribute to an informed material choice, considering the dynamics of urban building stocks, which is crucial on the way to achieving the UN's sustainable development goals (SDG) 9, 11, 12.

2. Data and Methods

The proposed methodology links the outputs of a dynamic material flow analysis (MFA), in terms of material requirements over time, with a tailored life cycle impact assessment (LCIA) to separately account for GHG carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO) and nitrous oxide (N_2O). Three different emission types are considered to contribute to GHG emissions: fossil, biogenic, and land transformation emissions.

In line with EN 15804 [15] the considered life cycle (LC) stages were: A1 raw material supply, A2 transport to the manufacturer, A3 manufacturing, A4 transport to construction site, A5 construction and installation processes, B1 use, B4 replacement, C1 demolition, C2 transport to waste treatment, C3 waste processing, C4 disposal, as well as module D to include avoided emissions from avoided energy production and virgin materials supply. The carbon benefits of bio-based construction products do not actually occur in the building systems, but in the natural system through the regrowth of plants, e.g. in the forest. The standard does not specify in which LC stage to account for this process. However, the carbonation of cement products, which describes the direct capture of CO_2 in the building, is accounted for in LC stage B1. Even though concrete carbonation and biogenic carbon capture are different processes, they both relate to carbon capture. Thus, the present study allocated negative emissions arising from the use of bio-based products in LC stage B1.

Three different disposal scenarios (DS) were considered for the EoL stage C depending on the waste category of the material: DS1 – landfill, DS2 – incineration with energy recovery, DS3 – material recycling. DS2 accounts for the benefits of substituting energy from the grid, at a constant present value (no adaptation for transition of energy grid). Material waste without any energy or material recovery potential has to be landfilled. Fast-decomposing biogenic material (in this case: straw) can end up in sanitary landfill or be treated in composting facilities where the methane is captured and stored. Wood can be either brought to sanitary landfill, or can be incinerated, in which case substitution of electricity production can be accounted for, or can be recycled. An overview of the DS can be seen in Table 1.

Table 1. End of life scenarios for the different waste categories included in the material selection

	Disposal scenarios		
Material waste category	**DS1** **Landfill**	**DS2** **Incineration with energy recovery**	**DS3** **Material recycling**
No potential	Inert landfill	Inert landfill	Inert landfill
Fast composing	Sanitary landfill	Composting facility	Composting facility
Wood	Sanitary landfill	Municipal incineration	Recycling facility

The calculation of the instantaneous and cumulative GWI relied on a flexible instantaneous dynamic characterization factor per GHG, accounting for the decay of the GHGs over time, and on a dynamic inventory result, considering the temporal evolution of GHGs. The resulting impacts were aggregated and ordered by moment of emission/uptake in a time-dependent matrix. The matrix was then used as an input for the dynamic impact assessment as proposed by Levasseur *et al.* [12,13] to model the timing of carbon uptake and GHG emissions. 200 years were chosen as a time horizon to model effects until the crucial year 2050 and beyond that the long-term effects.

The methodology is tested for a renovation technology made with straw for the thermal retrofit of a specific archetype in the "SusCity" area. The SusCity project[1] is a research initiative to improve the data availability and quality of urban building stocks for an agglomeration of neighbourhoods in the north-east of Lisbon. The SusCity area consists of four main Lisbon neighbourhoods: Olivais Velho; Encarnação; Olivais North and South; and Parque das Nações. It is a great source of building stock data that cannot be found easily elsewhere in Portugal. The selected archetype represents a multi-family dwelling type with 6 floors, constructed between 1961 and 1990 (thus before the introduction of thermal codes in Portugal), and with a U-value of 1.4 W/m^{2}K for exterior walls. 669 buildings belonging to this archetype were identified in the SusCity area. Thanks to the data provided in geoinformation systems (GIS) it was possible to obtain the exposed exterior wall surface of the selected archetype, which corresponds to the declared unit of this study. The selected renovation technology is based on the façade renovation method "TES", a prefabricated timber-based renovation module, proposed by an ERA-NET funded research consortium [16]. The system can be directly applied to an existing wall, without further preconditioning of the wall, since straw is blown into the gap between the wall and the TES module. For this study, the system was adapted for the Portuguese context as detailed in Figure 1 and in Table 2, using injected straw as insulation. The resulting U-value is 0.15 W/m^{2}K, which is in line with the passive house requirements [17,18]. Table 3 shows the emission inventory for the system's elements and LC stages, as well as the global warming potential (GWP) calculated with the IPCC method for 100 years.

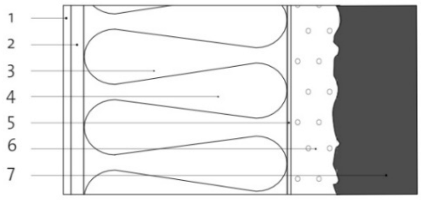

Figure 1. Vertical section of the studied wall retrofit system.

Table 2. Materials inventory of the studied wall retrofit system. For the numbering of materials please refer to Figure 1.

No.	Material	Thickness [mm]	Density [kg/m^3]	λ [W/mK]	Mass [kg/m^2]	Service life [years]	Waste treatment category
1	Fibre cement facing tile	9	1'250	0.55	11	30	No potential
2	Gypsum fibre board	15	950	0.30	14	30	No potential
3	Straw	240	105	0.043	25	60	Fast composing
4	Timber i-joist stud	80/240	--	--	3	60	Wood
5	OSB	4	650	0.13	3	60	Wood
6	Straw blown in gap	30-60	105	0.043	5	60	Fast composing
7	Existing wall	--	--	--	--	--	--

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[1] Refer to the project website http://groups.ist.utl.pt/suscity-project/home/

The benefits from carbon sequestration of re-growing biomass are considered in LC stage B1, assuming that straw is re-grown within one year, while timber from Nordic pine has a rotation period of 75 years. These differences are accounted for in the DLCA. The carbon content of straw is assumed to be 0.4 kg of C per kg of material [19], and for timber 0.5 kg of C per kg of material [20]. Since the expected service life of the cladding and the gypsum fibre board is shorter (30 years) than the service life of the overall wall system (60 years), these two components need to be replaced once during the service life of the element, which is accounted for in LC stage B4.

Two different renovation rates are compared: the business as usual (BAU) scenario assumes a constant 1% annual renovation of residential buildings, which is in line with past figures. An increased dynamic renovation rate, which could be induced by a political incentive or legislation to renovate [21], starting in 2020 peaks after a decade at 8% annual renovation and then follows the service life expectance of the proposed system through a cyclic repetition of the renovation function that is damped over time [22].

Table 3. Emission inventory for the renovation technology, per m^2 of retrofitted wall. GWP values reflect results obtained with IPCC 100 years.

Process	kg CO$_2$	kg CO	kg CH$_4$	kg N$_2$O	GWP [kg of CO$_2$ eq.]
A1 Straw blown in gap	0.2521	0.0022	0.0005	0.0008	0.4666
A1 Fibre cement facing tile	14.9797	0.0262	0.0275	0.0005	15.0236
A1 Gypsum fibre board	18.8899	0.0411	0.0622	0.0013	20.0875
A1 OSB	2.4140	0.0064	0.0041	0.0001	1.0553
A1 Straw insulation	1.3516	0.0118	0.0026	0.0042	2.5019
A1 Timber i-joist stud	20.3667	0.0524	0.0058	0.0003	22.6408
A2 Transport to the manufacturer	4.2480	0.0067	0.0022	0.0000	4.3154
A3 Manufacturing	1.3941	0.0008	0.0041	0.0000	1.3207
A4 Transport to construction site	1.6017	0.0034	0.0015	0.0000	1.6413
A5 Construction / Installation	0.0101	0.0000	0.0000	0.0000	0.0096
B1 Regrow biomass straw	-43.8900	0.0000	0.0000	0.0000	-43.8900
B1 Regrow biomass timber	-75.7570	0.0000	0.0000	0.0000	-75.7570
B4 Replacement Cladding + Gypsum board	37.6870	0.0754	0.0933	0.0018	39.0226
DS1 - Landfill	36.2284	0.1028	2.2729	0.0007	148.8767
DS2 - Energy recovery	-3.4328	-0.0066	-0.3704	-0.0053	-81.6780
DS3 - Material recycling	-2.0347	-0.0874	-0.3286	-0.0044	-22.9724

3. Results

Radiative forcing describes the difference between the energy irradiated by the sun and absorbed by the earth and the energy radiated back into space. It defines our planet's radiative balance, with an imbalance leading to an increase or decrease in temperatures [11]. Figure 2 shows the instantaneous time-depending radiative forcing for the declared unit and studied system, caused by the GHG release for the different renovation rates and EoL scenarios. Even though straw, with a one-year rotation period, is the main insulation material, the radiative forcing stays positive in the beginning since the impacts arising during LC stage A1-A5 outweigh the carbon benefits of those arising during B1. The high renovation rate requires significantly more material than BAU, leading to high radiated forcing caused by LC stage A1-A5. After 30 years, the cladding and fibre cement board are replaced and landfilled. The production and replacement leads to a slight increase in the radiative forcing. The EoL of the first generation of renovation elements (around 2080), leads to a turn into negative radiative forcing for DS2 – energy recovery and DS3 – material recycling. While DS1 – landfill induces a high positive radiative forcing because biogenic materials release methane in landfill. Figure 3 shows the cumulative radiative forcing to highlight the effects of released emissions over time. The most promising is DS2 – energy recovery, in combination with a high renovation rate, while the high renovation rate combined with DS1 – landfill represents the worst scenario. This is because the former refers to a beneficial scenario in which the effects of GHG emissions are minimized, while the latter induces increased methane release from straw.

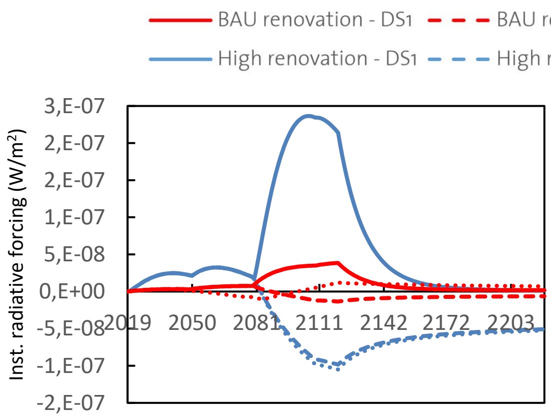

Figure 2. Instantaneous radiative forcing for all end of life scenarios, comparing the business as usual (BAU) with the high renovation rate.

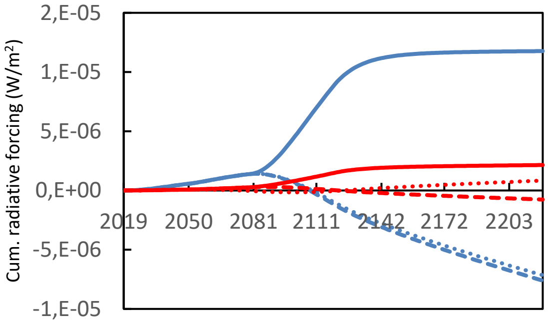

Figure 3. Cumulative radiative forcing for all end of life scenarios, comparing the business as usual (BAU) with the high renovation rate.

The cumulative radiative forcing values were then transformed according to the IPCC method to obtain the carbon emissions and removals in terms of CO_2 eq., which is a more common parameter to measure GWP. The results are shown in Figure 4. Only after the year 2107 the GWP becomes negative.

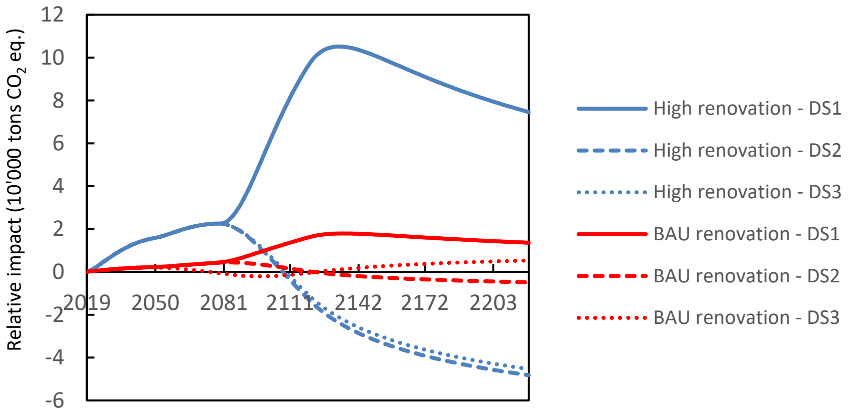

Figure 4. Dynamic GWP for the two different renovation rates (high renovation vs. business as usual "BAU"), for the three different end of life scenarios landfill ("DS1"), energy recovery ("DS2"), and material recovery ("DS3").

4. Discussion

4.1 Comparison of conventional and dynamic LCA

Figure 5 shows a comparison of the obtained values after 100 years (refer to Figure 4) with the values obtained from performing a conventional LCA with the IPCC 2013 method for a 100 year time horizon. In the IPCC method, carbon storage is not included, except for when it is accounted for separately as negative emission according to ISO 14040, which was not done here. The differences between the two approaches become clear in Figure 5: thanks to the carbon storage in the TES module and simultaneous fast regrowth of straw sequestering carbon (accounted for during LC stage B1), the impacts calculated with the DLCA are much lower than with conventional, static LCA. Conventional LCA does not include timing of GWP and all the emissions along the life cycle are shifted to time zero, while the effects of delayed emissions and carbon uptake in the different EoL scenarios are not included.

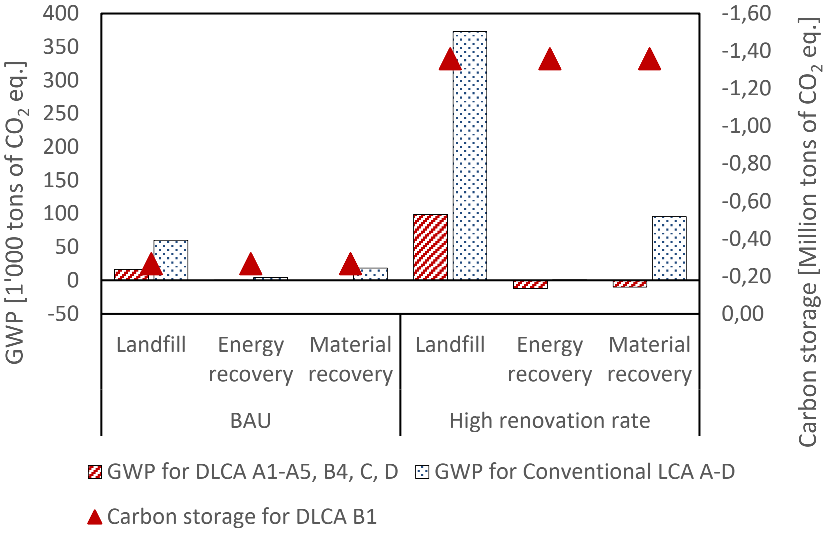

Figure 5. Comparison of dynamic LCA (DLCA) with conventional LCA after 100 years. Please note the opposite signs on the vertical axes: the carbon storage benefits, estimated with DLCA during LC stage B1, are shown on the secondary axis with negative values.

4.2 Bio-based construction systems for climate neutrality

The assumed renovation rate is the main driver of emissions. Therefore, this parameter should be further studied. Clearly, the business as usual renovation rate of 1% per annum is not sufficient to update our buildings and mitigate climate change. A recent EU report [23] states that there are five types of barriers that hinder increased renovation activity: financial; technical; process; regulatory; and awareness barriers. Studies, such as this one, add to the knowledge of technical solutions, which is one part of the problem. However, the other obstacles, specifically financial and regulatory barriers can only be overcome with government intervention. This can be achieved through different policy options. Specifically regulatory mechanisms such as tightened building codes or financial and fiscal instruments such as subsidies and tax incentives are promising [23].

In any case, it is crucial to incorporate life cycle thinking and the EoL of materials when designing construction technologies. Otherwise, as shown in this study, GWP is significantly increased if landfill is not avoided and biogases not captured. Real carbon benefits at the urban scale can only be achieved when combining higher renovation activity with prudent EoL scenarios.

This study builds on previous work done by Pittau *et al.* [10,11] that compared various material solutions for new construction and renovation of buildings. The authors found that particularly fast-growing materials are promising and can lead to a negative radiative forcing starting from year 1. However, this study showed that this is not always true. The material design and assembly of the construction technology is very important: the present study analysed a wall retrofit system with 240 mm of straw insulation plus additional straw between the existing wall and added retrofit system. However, the use of the conventional construction products, such as gypsum fibre board and fibre cement facing tile, leads to production impacts that outweigh the benefits of carbon capture of the fast-growing biomass straw. This means that only full bio-based construction technologies are potentially able to show negative emissions immediately after construction and contribute to remove the fossil carbon emitted in the past during the transition period by 2050. Therefore, it should be considered to replace the finishing with alternative low-carbon or even full bio-based components, such as reed mats and light lime plaster (refer to Pittau *et al.* [10]).

4.3 Existing market barriers of bio-based construction

As discussed and shown in this study, partly bio-based construction materials cannot achieve the desired carbon benefits that are needed for a carbon neutral building stock. The benefits of carbon capture of a fully bio-based construction technology, however, are undeniable as was shown in other studies [10,11]. There is more and more research that underlines that the right manufacturing and installation of the bio-based product, which requires a specific know-how, can ensure that even straw bale construction is durable [24]. Yet, these material-based solutions might still be seen sceptical and architects and homeowners might not be inclined to use them for fear of decreased durability and fire resistance. In order to gain more trust in these materials, reliable and shared technical data, to be used for the design process, are needed [25]. Moreover, construction projects of new public buildings could be used to provide good examples of bio-based construction. In this way, municipalities can positively reinforce sensible construction practices.

5. Conclusion

This paper advances the understanding of bio-based construction material at the urban scale. Three EoL scenarios and two renovation rates were compared. The results show that increased renovation activity yields increased carbon storage (100 years from today, for the landfill EoL scenario, the high renovation rate yields -1’359 tons of CO_2 eq. vs. -266 tons for the BAU renovation rate). However, when the renovation is based on a technology that is partly made with carbon-intensive material, as is the presented case study, this also causes significantly higher total impacts (97’462 tons of CO_2 eq. for higher renovation vs 16’306 tons for BAU, both for the landfill EoL scenario). This suggests that only full bio-based construction can yield the needed short-term carbon benefits. The EoL scenario is crucial for the total impacts, which range, for the BAU renovation rate, from 16’306 tons for the landfill scenario, to 185 tons for the energy recovery scenario, to -401 tons of CO_2 eq. for the material recovery scenario. The proposed integration of dynamic MFA with dynamic LCA is a useful methodology that can be applied to other construction technologies and contexts as well. Future research should include cost and an in-depth analysis of renovation dynamics.

Acknowledgements

The authors would like to thank Cláudia Monteiro for providing her dataset of the SusCity project. The authors acknowledge the support of the CERIS Research Centre, Instituto Superior Técnico, Universidade de Lisboa to this research, and also of FCT (Foundation for Science and Technology) that supports the PhD work of the first author with the PD/BD/127854/2016 scholarship.

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