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Decarbonization possibilities for affordable wood-framed houses in the south of the US. Comparison of conventional, circular, and regenerative options

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Decarbonization possibilities for affordable wood-framed houses in the south of the US. Comparison of conventional, circular, and regenerative options

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Abstract. The transition to more circular practices in the construction sector offers an alternative path to the predominant linear, high-polluting, and wasteful processes. To better understand the full impact of building materials and buildings over their lifespan and beyond, life cycle assessment (LCA) studies have been a field of interest and a growing body of knowledge over the past three decades. Moreover, recent studies stress the critical relevance of the end-of-life (EoL) scenario, particularly for wood-based construction, highlighting its potential for further decarbonization through circular strategies such as design for adaptability, disassembly, and reuse. However, there is a significant knowledge gap in the LCA literature related to environmental impact mitigation strategies specific to affordable housing options, despite the pressing and undeniable need for these typologies. This study contributes to filling this gap by performing a detailed whole-building LCA of an affordable single-family house prototype built in the south of the USA using a standard light wood frame construction method. Besides the standard as-built scenario, this study developed five hypothetical scenarios that evaluated the influence of different EoL options (recycling or energy recovery), increased circular strategies (reuse), and substitution of non-renewable materials with regenerative materials for insulation (wood fiber) and finishing (clay plaster), aiming to identify further possibilities and limitations for decarbonization of such typology and construction method. The results of this study consistently pointed out that priorities should be to (1) guarantee proper end-of-life of metals and wood-based materials. (2) To replace non-renewable materials with regenerative wood or earth-based ones. (3) To improve material reuse and construction waste diversion rates. The results of this study support the development and implementation of policies and regulations for affordable housing, aiming toward increased environmental justice and a more equitable and sustainable built environment for all.

1. Introduction

The construction sector is accountable for the primary portion of greenhouse gas (GHG) emissions, constituting 37% of all emissions [1]. This is due to the energy-intensive procedures of material extraction, transportation, construction, and energy consumption to operate buildings. Building construction activities solely contribute 10% of all emissions [1]. Consequently, these high emissions exacerbate global warming and contribute to the climate crisis. Furthermore, the construction industry accounts for 40% of global resource consumption [2] and is a major contributor to the production of solid waste from the manufacturing, construction, and demolition of buildings [3]. In the US, the EPA

(Environmental Protection Agency) estimates that a staggering 600 million tonnes of construction and demolition waste will be generated in 2018, with the majority (94%) coming from demolition activities[4]. As a result, a significant portion of emission-intensive building materials made from finite resources ultimately end up in landfills.

Given the significant influence of the construction sector and the goal of better understanding and evaluating the complete impact building materials and structures have over their service lives, life cycle assessment (LCA) research has become a field of increasing interest and knowledge over the last three decades [5], [6]. Throughout this time, studies have demonstrated significant disparities between widely-used building materials like steel, concrete, and wood [6], and emphasized the essential role that energy recovery of wood products plays in end-of-life (EoL) for impact mitigation. Previous studies [7], [8], [9] conducted by the author of this paper also endorse the crucial role of End-of-Life (EoL) strategies in reducing the environmental impact of construction.

Understanding the embodied emissions of building materials is crucial in mitigating the impacts of the construction sector [10], as it can contribute between 10% and 50% of total life cycle GHG emissions, depending on the energy efficiency of a building [11]. Despite its relevance, Cai [12] warns that the number of studies reporting embodied impacts at the material level is still limited, which may lead to underestimation. Furthermore, current research emphasizes the crucial importance of materials' end-of-life scenario and its potential for impact mitigation by extending building lifespans and service times of materials through circular strategies such as designing for adaptability, disassembly, and reuse [13], [14].

However, Bahramian [15] conducted a comprehensive review of LCA literature over the last two decades, analyzing over 230 published papers, and revealed a tendency for LCA to concentrate on low-rise commercial buildings in the USA, with only one study examining a low-rise house. Furthermore, the literature review reveals an almost complete lack of studies on affordable/social housing, with only two papers on the topic from Latin America. Despite this noticeable gap in scientific knowledge, there is an undeniable need for more affordable housing in North America. Recent data shows a fast-growing housing shortage in the USA real estate market, estimated at 3.8 million units, which doubled from 2012 to 2019 [16]. One serious consequence of this deficit in a free-market economy such as the USA is that higher-income households compete with lower-income households for the limited housing supply, thus reducing affordability and access to housing [16]. On top of that, the hindered access to a comfortable, safe and affordable housing also profoundly impacts several other vital aspects of society, such as employment rate, health and well-being, and education levels [17].

Therefore, comprehending the embodied environmental impact of building materials and methods appropriate for affordable housing should be a critical subject of scientific research. This study aims to fill the scientific gap in investigating the lifecycle impact of a single-family home for the affordable housing market in the southern United States. This study builds on the initial findings of [9], which identified lightweight wood framing as the most promising option for reducing the environmental impact of single-family homes in the South, by increasing the sample size of such a construction system to seek new insights and verify the results. Thus, it aims to contribute to the field with original information on the environmental performance of affordable housing building options that facilitates decision-making processes, leading to new knowledge that can support the design and construction of lower-embodied-impact affordable single-family homes in the south of the USA.

2. Method

2.1. LCA scope

This study conducted an LCA as per EN-15804 (Table 1) of one affordable single-family house (100.8 m^2) built in 2019 using light wood framing in the southern U.S. The study calculated the global warming potential (GWP) of the as-built house and developed hypothetical scenarios including increased circular strategies and regenerative materials use (item 2.2) to evaluate further possibilities and limitations for impact mitigation.

Table 1. LCA Phases and modules assessed per EN-15804 standard.

Stages	Modules	Assessment
Product	A1 - Raw material supply	Yes
	A2 - Transportation	Yes
	A3 - Manufacturing	Yes
Construction	A4 - Transportation	Yes
	A5 - Construction	Yes
Use	B1 - Installed product in use	No
	B2 - Maintenance	Yes
	B3 - Repair*	Yes
	B4 - Replacement	Yes
	B5 - Refurbishment	No
	B6 - Operational energy use	No
	B7 - Operational water use	No
End-of-life	C1 - De-construction/ demolition	Yes
	C2 - Transportation	Yes
	C3 - Waste Processing	No
	C4 - Disposal	Yes
Benefits and loads beyond boundary	D- Reuse, Recovery, Recycle	Yes

* According to the repair schedule from [9]

Table 2. Bill of materials (BOM) in kg/m^2.

Role	Material	Waste	Mass
Foundation	RC footings	5%	509.42
Foundation	CMU pier	6%	20.09
Structure / Envelope	Kiln dried softwood	8%	89.63
Structure / Envelope	Subfloor – OSB	5%	9.52
Structure / Envelope	OSB	5%	30.61
Structure / Envelope	Galvanized steel fasteners	3%	1.57
Structure / Envelope	Insulation – Rockwool	5%	15.3
Structure / Envelope	Double Glazing (Hard coat, Air fill)	0%	53.52
Structure / Envelope	Door Panel – Plywood	0%	0.51
Structure / Envelope	Window frame - aluminum	0%	0.53
Finishing	Airtight membrane	2%	1.24
Finishing	Water-poof bituminous membrane	2%	0.72
Finishing	Galvalume corrugated roof sheet	5%	9.11
Finishing	Gypsum plasterboard	10%	48.23
Finishing	Fiber cement board	10%	9.93
Finishing`	Paint - Latex	2%	9.52
Finishing	Paint - Acrylic	2%	8.74
Finishing	Ceramic Tiles (wet areas)	10%	11.63

Using the as-built construction documentation of the case-study house, a detailed bill of materials (BOM) was defined (Table 2). Then, lifecycle inventory data for each specified material was gathered from the Athena Sustainable Materials Institute database [18], which provides ISO 14040/14044-

compliant data. The database is geographically adjusted to reflect the industry-wide national average values in the USA and regularly updated to account for the latest manufacturing technology, transportation requirements, and energy mix context, with data less than ten years old. At the time of this writing, three building materials were still unavailable in the database (item 2.2). Nonetheless, the impact data on these three materials was also retrieved from ISO-compliant Type III EPDs. After gathering all LCI data, the Impact Estimator for Buildings software (IE4B v.5.4.0101) was used to obtain the lifecycle impact assessment (LCIA) values for a functional unit of $1m^2$ of construction and a 60-year lifespan.

2.2. LCA scenarios

This study assessed six scenarios to understand the possibilities and limitations for further impact mitigation, described in the sequence. Table 3 presents an outline of each scenario and the assessed variable within each one of them.

Table 3. Description of modified parameters assessed in each scenario.

Scenarios	Condition	Waste	Recycle	Reuse	Replacement
S1 – Standard	Optimistic	Avg.	Yes (1)	No	No
S2 – Standard	Pessimistic	Avg.	50% (1)	No	No
C1 – Circular	Reduce	40%	Yes (1)	No	No
C2 – Circular	Reuse	Avg.	Yes (1)	50% (1)	No
M1 – Regenerative	Envelope	Avg.	Yes (1)	No	Yes (2)
M2 – Regenerative	Finishing	Avg.	Yes (1)	No	Yes (3)

(1) Wood and metals; (2) Insulation; (3) Paints

Standard Scenarios. *S1:* This scenario represents the standard LCA of the as-built case-study. Therefore, it provides a benchmark for the study, with a conventional optimistic view of material recovering and recycling at the end of life. *S2:* This scenario investigates a conceivable pessimist end-of-life fate for sawn wood and metals (aluminum, and galvalume sheathing), typically assumed to be recovered for energy or recycled. This scenario considers that only half of these materials would be soundly recovered or recycled due to the likely challenges of sorting after a conventional demolition process of such buildings [19], [20]. Hence, it estimates the influence of the standard end-of-life fate on the overall LCA results by reducing the benefits obtained in module D. To account for the uncertain effect of different recycling ratios within our scenario, we performed a sensitivity analysis (±50%).

Circular strategies. *C1:* This scenario investigates the effect of reducing construction waste below the national average through off-site prefabrication. According to previous studies [21], [22], off-site prefabrication can reduce construction waste by up to 40% of the on-site values due to a more controlled manufacturing environment. Therefore, we accounted for the potential benefits of construction waste reduction by decreasing the waste amount by a factor of 2.5. To account for the uncertain effect of different waste ratios within our scenario, we performed a sensitivity analysis (±50%). *C2:* This scenario investigates the effect of reusing wood and metal building materials in construction. We assumed a conservative 50% reuse ratio for sawn wood [20], [23] and metals (aluminum, and galvalume sheathing). That allows this scenario to measure the benefits of reuse compared to the conventional EoL fate of energy recovery and recycling in S1. The benefits of reuse were allocated to Module D as the avoided burden of producing new materials from the cradle, as per closed material loop allocation methodology (ISO 14044:2006 section 4.3.4.3.3). To account for the uncertain effect of different reuse ratios within our scenario, we performed a sensitivity analysis (±50%).

Regenerative Materials. *M1:* This scenario evaluated the effect of replacing the two most impactful envelope material in S1 with a functionally equivalent regenerative material. The GWP results per material showed the highest impacts in S1 arise from glass and insulation. The latter material was

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replaced with wood fiber insulation because there is no regenerative option for glass on the market yet. Wood fiber insulation is manufactured in batts such as rock or glass wool insulation. The manufacturing process uses steam and mechanical treatment to break down coniferous wood species into individual fibers bound together by lignin, eliminating the need for external adhesives [24]. The choice of wood fiber insulation over blown-in cellulose made from recycled newspaper is its greater resistance to moisture, a much-needed specification in the Gulf South.

M2: This scenario evaluated the effect of replacing the most impactful finishing material in S1 with functionally equivalent regenerative materials. The GWP results per material showed the highest impacts arise from the galvalume roof sheathing, and paints. The latter material was replaced with clay plaster applied on the gypsum plasterboard, providing a finished smooth surface, following the specifications of the manufacturer [25], because there is no functionally equivalent regenerative option for galvalume sheathing on the market yet. It is worth noting that in a hurricane-prone area like New Orleans, Galvalume sheathing is the preferred choice for the homes instead of asphalt shingles due to its greater durability and resilience.

3. Results and discussion

3.1. Aggregated LCA results

The combined findings (see Figure 1) indicate that among all the scenarios, S2 has the highest GWP value, whereas M2 has the lowest. These results underscore the importance of considering a pessimistic but realistic EoL scenario for enhancing the environmental sustainability of affordable light wood framing houses. The S1, C1, and M1 scenarios exhibit only slight differences, with a mean of 1.5%. C1 had the least impact among the three, highlighting the importance of minimizing material waste in construction. Furthermore, the high impact of S2 underscores the critical need for appropriate EoL of materials. In contrast, C2 and M1, as the third and fourth most impactful scenarios, respectively, show a more limited mitigation potential of reusing materials and replacing rock wool insulation with wood fiber. However, it is important to note that for reuse (C2), the decrease in mitigation potential results from a lower quantity of wood-based materials in the end-of-life (Eol), thereby leading to a reduction in benefits obtained from energy recovery of wood in comparison to the standard scenario (S1). Therefore, while the circular reuse strategy diminishes the impact of high embodied energy materials like steel, it also diminishes the amount of wood available for recovery and energy conversion at the end of life. As a result, the benefits at module D are reduced, and GWP values increase. This is a methodological drawback of the static LCA's cradle-to-grave approach. Finally, M2 achieved the lowest global warming potential value, indicating the significant environmental impact of a traditional painted finish on light wood framing houses. Clay plaster shows potential as a mitigation alternative.

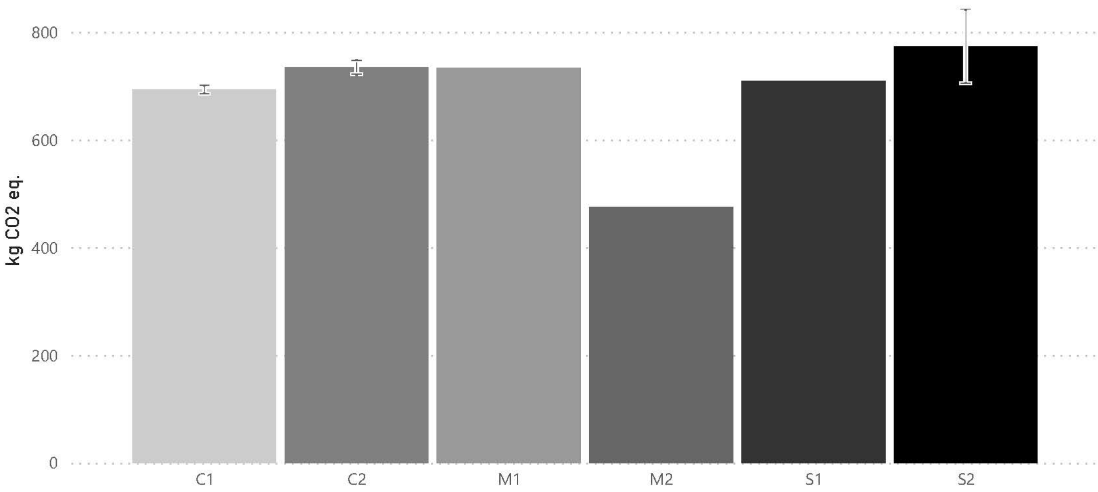

Figure 1. Total embodied Global Warming Potential (GWP) by scenario.

3.2. LCA results by construction role

Figure 2 illustrates that the finishing materials are responsible for the largest share of GWP in all scenarios. Except for S2, the foundations were the second-most impactful element in construction, with the envelope coming in third. The impact of finishing materials remained virtually identical across scenarios S1, S2, M1, and C2. The global warming potential (GWP) of finishing materials in C1 was 2.7% lower compared to the mentioned scenarios, thanks to a reduced rate of construction waste. This reflects the importance, albeit limited, of implementing measures to increase material efficiency during the construction phase. Meanwhile, the GWP of finishing materials in M2 was the lowest, about 84% lower than S1, due to replacing latex and acrylic paint finishing with clay plaster. C1 exhibited a slightly higher GWP values for envelope materials than S1 and M2 (2.5%), demonstrating that reducing construction waste rates has little impact as a mitigation strategy for the case study. Envelope materials in M1 presented a 30% higher GWP value than S1, indicating that using wood fiber insulation instead of rock wool has only a limited potential for mitigation. Finally, the envelope materials used in S2 had the highest GWP with 80% more impact than in S1. That emphasizes the necessity for an appropriate end-of-life solution for materials (S2) and the implementation of measures to improve material efficiency during construction.

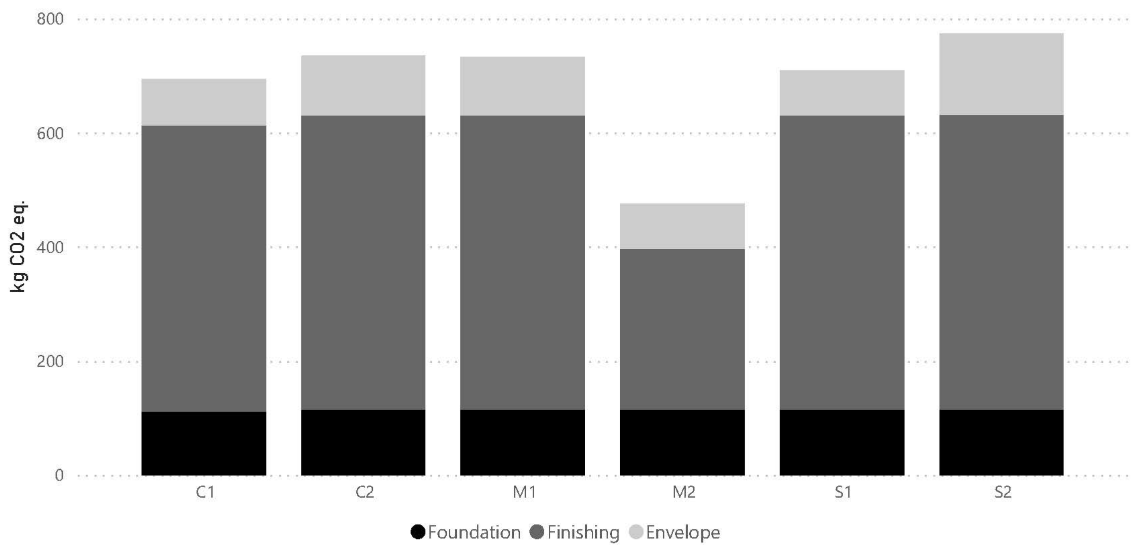

Figure 2. Embodied Global Warming Potential by construction role.

3.3. Limitations of this study

Three materials, namely ceramic tile, wood fiber insulation, and clay plaster, were not yet available in the Athena Sustainable Materials Institute database[18] at the time of this study. Therefore, we obtained the cradle-to-grave, ISO-compliant life cycle impact data for these materials from Type III EPDs. The first is an industry-wide EPD[26], regionally adjusted to the US context, as is the rest of the database utilized for the materials evaluated in this study. However, the EPDs for the latter two materials (wood fiber and clay plaster) [27], [28] were only available for European averages. Arguably, the manufacturing technology in the US and Europe should be equivalent, resulting in minor differences in impacts. Nevertheless, there could be more significant differences in the environmental impact of different energy mixes and possibly transportation distances that could affect the final results and thus introduce uncertainty to the LCIA of these specific materials. Therefore, the values related to wood fiber insulation and clay plaster are best considered to approximate the exact impacts until regionally adapted databases on these materials are available.

Also, this paper developed an LCA of a single house, which means that the results still lack the sampling robustness to be considered directly applicable to the general field of affordable housing in the South. Nevertheless, they provide solid indications of neglected issues that need to be addressed when dealing with light wood frame construction. However, further studies should increase the sample size of houses and building assemblies to validate the results presented in this study and deepen the investigation on perceived areas of interest such as the impact of latex paints vs. clay plasters, aiming to provide more general guidelines that consider also the larger field of affordable housing in the South and in the US.

4. Conclusions

The objective of this study was to examine the global warming potential (GWP) of an affordable single-family house constructed in the southern region of the United States in 2019, utilizing light wood framing. The as-built house's GWP was calculated, and five hypothetical scenarios, which incorporated circular strategies and regenerative material usage, were also developed.

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The results of the Standard Scenarios demonstrated that appropriate end-of-life (EoL) materials handling, specifically the recycling of metals and recovery of wood-based materials, significantly mitigates the GWP of the case study. This mitigation impact is noteworthy in comparison to the pessimistic scenario wherein only 50% of these materials are recycled or recovered due to the potential challenges of material sorting after a conventional demolition process of such a predominantly nailed connection-based construction system. The first circular scenario of reducing construction waste below the national average showed a small but certain potential to reduce GWP; the second circular scenario of reusing metals and wood-based materials increased the impact compared to the baseline scenario due to the reduced availability of wood to be recovered and converted to energy at end of life, thus reducing the benefits in Module D. In addition, replacing mineral wool with wood fiber insulation in the first regenerative scenario showed a limited mitigation potential. However, replacing latex and acrylic paints with clay plaster significantly reduced the global warming potential (GWP) of the case study, emphasizing the environment's high costs associated with a traditional painted finish on light wood framing homes.

It should be emphasised that the recent push for circularity poses a methodological challenge in the field of LCA, defined as a cradle-to-grave method, where there is an ongoing debate on the appropriate modelling procedures for multi-cycle LCA and the calculation of the benefits and impacts of extended service life of wood-based materials. There is still no consensus on the preferred modelling approaches, such as attributional or consequential, biogenic carbon accounting and its cut-off time, and the method of allocation of loads and benefits (0/100, 100/0 or 50/50) [29]·[30], [31]·. This is particularly critical for the C2 scenario in this paper. Given the static nature of this LCA study, a 100/0 allocation method for the benefits and loads of using wood-based materials was chosen. A different choice of 0/100 or 50/50 would result in a more favorable assessment of C2, as the benefits of biogenic carbon could be transferred to the second life-cycle. In any case, the critical point is that the lack of consensus on appropriate LCA modelling procedures for assessing the benefits of circular strategies hinders a more coordinated and replicable assessment of these strategies. Increasing the body of knowledge on the subject could lead to a more widespread, consensual methodology, which in turn could help to strengthen the findings and coherence of individual studies and the push for implementation of circular strategies such as reuse.

In conclusion, the findings indicate that the incorporation of circular strategies and regenerative materials presents additional potential for reducing carbon emissions in the affordable single-family case study. Throughout this study, the findings suggest the necessity of prioritizing three key areas: (1) ensuring proper disposal of metal and wood materials, (2) substituting renewable wood or earth-based materials for non-renewable ones, and (3) enhancing rates of construction waste diversion. This work built upon [9] by employing the same methodology to validate the results through a more robust sampling size. Furthermore, it explored the possibilities and limitations of lightweight wood framing as the most promising option for reducing the environmental impact of single-family homes in the South. This study represents an intermediate step in an ongoing investigation. Subsequent analyses will address topics that are currently outside the scope of this study. 1) Further increase of sampling size through additional case studies under comparable circumstances. 2) Conducting LCA studies to evaluate a wider variety of regenerative materials for use in structural applications (mass timber products), insulating applications (other types of fiber-based insulation), and finishing applications in affordable housing. 3) An analysis of the financial implications of incorporating innovative regenerative materials into affordable single-family homes constructed using lightweight construction methods.

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CRediT author statement

Rafael Novais Passarelli 1 (1st author, corresponding author): Conceptualization, Methodology, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.