WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

THE ROLE OF TIMBER BUILDINGS IN CIRCULAR BIO-BASED CITIES

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ABSTRACT: Humanity's demand for ecological resources exceeds the planet's regenerative capacity. Decoupling environmental benefits from economic stagnation is necessary to transition towards more resource-efficient economic models and sustainable lifestyles. A circular city is a vision aimed at achieving growth without exceeding planetary boundaries, but defining and implementing circular cities remains a subject of debate. We argue that a broader definition of circularity is needed to include the use of timber as a building material. Timber is well-accepted as a renewable construction material if sourced from sustainably managed forests. However, traditional definitions of circularity focus on materials that can be recycled, a criterion that construction timber often does not meet. The goal of this presentation is to stimulate international discussion and strategic implementation of circular cities that go beyond the concepts of reuse, refurbishment, and recycling. We propose the concept of the "Circular Bio-based City," which aims to minimize environmental degradation by combining circularity and the use of bio-based materials (with timber as a main player) to create global regenerative loops. The goal is to foster harmonious relationships between cities and natural ecosystems, moving towards fully integrated regenerative urban systems.

KEYWORDS: Timber buildings, circular cities, sustainable bio-based materials, greenhouse gas emissions

1 – INTRODUCTION

The global consumption of ecological resources exceeds Earth's ability to regenerate them, posing a significant challenge to sustainability and jeopardizing the long-term well-being and prosperity of humanity [1-4]. Decoupling economic growth from the consumption of natural resources is widely regarded as a critical step toward adopting resource-efficient economic models and promoting sustainable consumption patterns [5].

The concept of circular cities envisions economic prosperity while remaining within the limits of planetary boundaries [6]. It holds the potential to advance the United Nations' (UN) sustainable development goals while mitigating human-induced environmental impacts and reducing the depletion of natural resources [7-8].

The definition and implementation of circular cities remain active areas of discussion. This complexity arises because circular cities are not merely facilitators of a circular economy; they also serve as hubs for fostering environmental sustainability, cultural enrichment, and economic resilience. An illustrative example is the joint declaration signed by 72 cities across Europe, which characterizes a circular city as "*one that promotes the transition from a linear to a circular economy in an integrated way across all its functions, in collaboration with citizens, businesses, and the research community* [9]."

A circular economy, in contrast, represents an economic model that seeks to sustain material and energy flows within closed-loop systems [10-12]. This approach is engineered to reduce reliance on virgin resources and

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https://doi.org/10.52202/080513-0115

energy while minimizing waste generation and environmental pollution within economic processes [13].

Often described as the antithesis of a linear economy [13-15], a circular economy challenges the traditional extract-use-dispose paradigm, where materials and energy are drawn from the environment, converted into consumer goods, and ultimately discarded as waste after their functional lifespan.

In a previous study [16], we explored the concept of "circular bio-based cities" as a transformative approach to mitigating environmental degradation. This framework integrates the reuse and regeneration of resources to minimize the need for raw materials and energy inputs, coupled with the implementation of clean technologies that curtail waste and pollution. Additionally, the incorporation of bio-based materials and carbon storage mechanisms aims to offset the impacts of greenhouse gas emissions.

However, our study [16] rejects the notion that minimizing urban inputs and outputs is the solution for achieving circular cities. Rather, we believe that encouraging the exchange of materials, energy, and manufactured goods between cities and nations is essential for fostering economic prosperity in an increasingly interconnected global economy. We argue that to realize global circularity, it is imperative that we reduce to zero those inputs linked to unsustainable resource depletion, and outputs associated with waste accumulation, pollution, and greenhouse gas emissions.

The objective of this paper is to underscore the advantages of utilizing timber as a building material within the framework of global circularity, highlighting its potential role in achieving more sustainable urban infrastructures.

2 – BACKGROUND

Ellen Macarthur Foundation's "butterfly diagram" (Figure 1) is probably the most well know representation of materials flow in a circular economy [17]. Since its introduction in 2013, the diagram has been widely used by governments, academics, businesses, and NGOs to explain circular economy principles. The diagram is divided into two primary cycles: the technical cycle and the biological cycle. In the technical cycle, products and materials remain in continuous circulation through strategies like reuse, repair, remanufacturing, and recycling. Meanwhile, in the biological cycle, nutrients from biodegradable materials are reintegrated into the environment, facilitating the regeneration of natural systems.

Since materials and energy are exchanged across cities, regions, and nations, a truly closed-loop circular economy - like the one illustrated in the butterfly diagram - can only be achieved on a global scale. This necessitates establishing a criterion for classifying whether materials and energy are within the economic loops or external to them. In our previous study [16], we proposed a classification system for the inputs and outputs of a circular economy, focusing on their potential negative impacts on the biosphere, including human health and cultural values. Specifically, materials and energy are categorized as inputs if their production relies on non-renewable natural resources that cannot be restored to their original state. Conversely, they are classified as outputs when their disposal at the end-of-life results in harmful or undesirable consequences for both people and the environment.

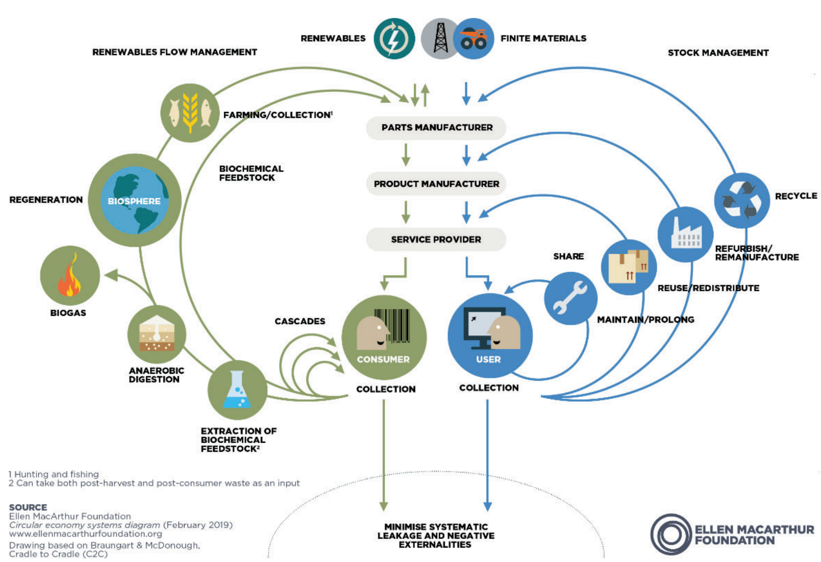

Figure 1. Ellen Macarthur Foundation's "butterfly diagram" of materials flow in a circular economy

A key output of the global economy is the emission of greenhouse gases (GHGs). New findings from the Global Carbon Project [18] reveal that global carbon emissions from fossil fuels hit an all-time high in 2024. Fossil CO_2 emissions will total 37.4 billion tonnes this year, marking a 0.8% increase compared to 2023. Additionally, emissions from land-use changes, such as deforestation, are projected to contribute 4.2 billion tonnes, bringing total CO_2 emissions to 41.6 billion tonnes in 2024, up from 40.6 billion tonnes the previous year.

Approximately half of the greenhouse gas emissions are absorbed by natural carbon sinks, such as vegetation and oceans, while the remainder accumulates in the atmosphere, contributing to climate change. The Global Carbon Atlas project [19] presents a simplified diagram of the Global Carbon Budget, illustrating that roughly 22 billion tonnes of CO_2 are added to the atmosphere annually (Figure 2).

global cement production was estimated to have reached 4.1 billion tonnes [20]. Cement primarily consists of limestone (70 to 80%) and clay, meaning that, on average, each person contributes to the extraction of approximately 0.5 tonnes of limestone and clay annually.

A more pressing concern is the global consumption of sand, which is essential not only in concrete production but also in various infrastructure materials such as asphalt, glass, bricks, and tiles. It is estimated that approximately 50 billion tons of sand are consumed worldwide each year [21], equating to about 6.1 tons per person. The rapid depletion of sand, particularly due to illegal extraction, is contributing to environmental degradation, including coastal loss. The issue has garnered global attention, with significant geopolitical implications, such as conflicts over territorial boundaries and resources [21].

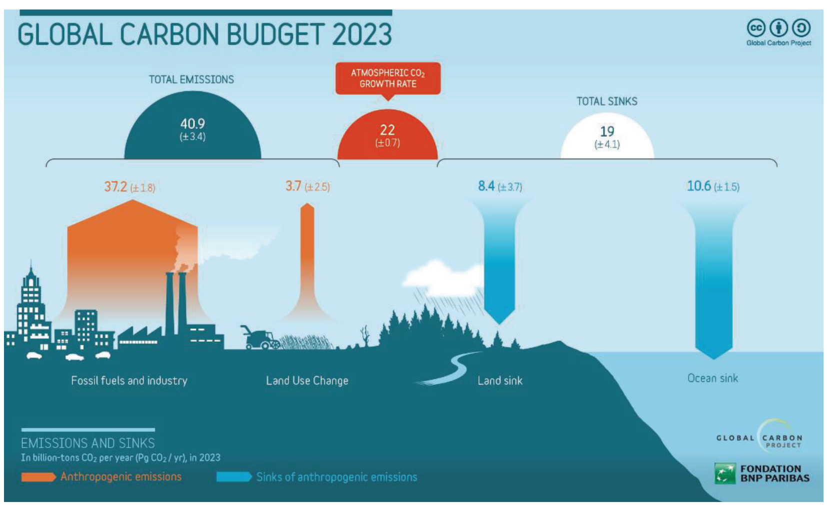

Figure 2. Global carbon cycle diagram based on Friedlingstein et al., Global Carbon Budget 2023, from the Global Carbon Atlas project [19]

With a global population of approximately 8.2 billion people in 2024, this implies that the annual output of CO_2 from the global economy is 2.7 tonnes per person.

Key material inputs for the global economy include minerals acquired from mines, particularly for the construction sector. Sustainably sourced timber is not accounted for as an input in our definition of global circular economy, since it can be regenerated by biological cycles.

The cement industry is characterized by its high energy intensity, with its energy consumption representing nearly 5% of total global industrial energy use. The theoretical energy required to produce 1 kg of Portland clinker is approximately 1.76 megajoules [20]. In 2019,

Steel production is a highly energy and carbon intensive process. In 2020, global steel production reached 1.6 billion tonnes, with each ton requiring an average of 5.17 MWh of primary energy. This resulted in steel manufacturing being responsible for approximately 9% of global anthropogenic CO_2 emissions [22]. Raw materials for steel production, depending on the technology used, typically include iron ore concentrates (55 to 65% iron) [23], implying that, on average, each person is responsible for mining about 0.3 tons of iron ore annually. In addition to mining, several hundred million tons of steel are recycled annually from scrap. Nearly half of the steel produced worldwide being used in the construction of buildings and infrastructure [24].

https://doi.org/10.52202/080513-0115

Timber presents a sustainable option as building material. which we do not categorize as an input to the global economy but rather a renewable biomaterial that can be regenerated through biological cycles.

Several studies compared the greenhouse gas (GHG) emissions of timber buildings with conventional materials including concrete and steel construction [25-27]. The findings of these studies suggested that building with sustainably supplied timber can reduce the GHG emissions of about 20%, achieving in some cases almost 50% reduction [28].

Also considering other environmental impacts assessed by the LCA (Life Cycle Assessment) approach, timber-based structural systems resulted much less impactful than concrete and steel ones in terms of eutrophication and fossil fuel depletion with up to 62.5% improvement in both parameters [29].

Furthermore, timber is a suitable building material not only from the environmental point of view, but it is also able to guarantee high stability performance. Timber is indeed a material characterised by low self-weight and high strength. These features make timber particularly recommended in seismic areas [30-31].

According to the Food and Agriculture Organization of the United Nations (FAO) [32], the global annual production of industrial roundwood in 2018 was approximately 2.03 billion m³ (while another 1.9 billion m³ was consumed as fuel). Roughly half of this roundwood is processed into construction materials. FAOSTAT data [33] indicates that global production of logs for timber and veneer reached 1.07 billion m³ in 2023.

Converting log volume to weight presents challenges due to the variability of the resources and moisture content in the wood. Without moisture, the basic density of construction-grade timber typically ranges from 400 to 800 kg/m³. Using a 600 kg/m³ figure, the global annual per capita consumption of industrial roundwood is approximately 0.15 tonnes.

Figure 3 illustrates the estimated three major annual per capita inputs to the global economy - iron ore, sedimentary soil, and sand - and one of the most serious outputs, the excess of CO_2 emissions that is not absorbed by the ecosystem. In contrast, industrial logs are neither considered input nor output in our definition of global circularity, as they can regenerate by biological cycles.

3 – PROJECT DESCRIPTION

This paper highlights the transformative potential of timber buildings in advancing circular urban environments. Through an extensive literature review, we observed that key concepts such as circularity, regeneration, and biomaterials like timber are often explored in separate contexts: circularity in resource efficiency and zero-waste strategies, regeneration in sustainable lifestyle initiatives, and bio-based materials in climate change mitigation. However, we propose that integrating these concepts creates a synergistic impact, surpassing the sum of their individual contributions.

Timber, as a renewable and carbon-storing material, offers a compelling opportunity to reshape the built environment. By incorporating timber in construction, we can simultaneously reduce greenhouse gas emissions and decrease the reliance on non-renewable resources.

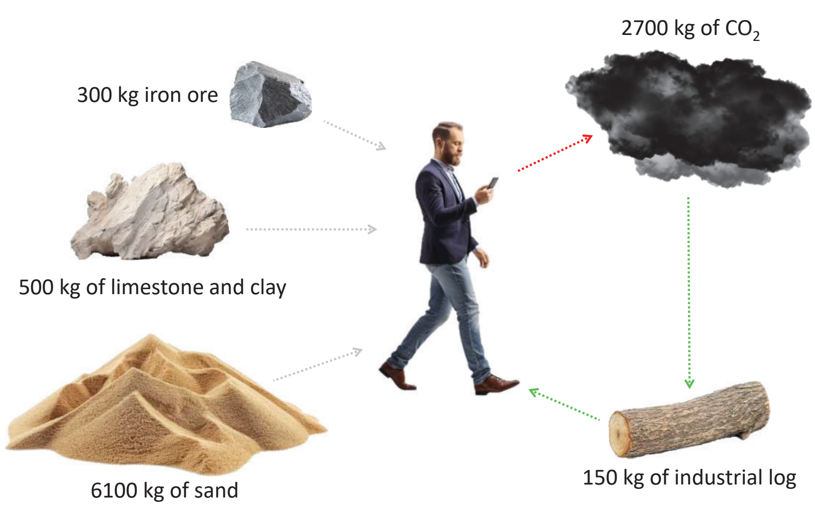

Figure 3: Calculated examples of three major annual per capita inputs to the global economy - iron ore, sedimentary soil, and sand - and one output, the excess of CO_2 emissions. Logs are regenerated through natural biological cycles.

Using data from international material intensity databases and life cycle analyses for construction materials, this study quantifies the environmental benefits of timber buildings. Our findings demonstrate how residential timber buildings can drive meaningful reductions in the inputs and outputs that perpetuate global environmental challenges, offering architects a natural pathway to sustainable design and regenerative urbanism.

4 – EXPERIMENTAL SETUP

The global material intensity of buildings was derived using the RASMI dataset [34], which provides a comprehensive and standardized repository of Material Intensity (MI) values across 32 global regions. This dataset offers a detailed analysis spanning eight construction materials, four dominant structural types, and three functional use categories. Figure 4 illustrates an example of material intensity distribution in residential buildings across the European Union (17 countries) [34] for single- and multi-family homes constructed with steel, timber, masonry, and concrete. For each building type, the dataset captures the distribution of material intensity (in kg/m²) for concrete, brick, wood, steel, plastics, aluminium, and copper, although the latter three are not shown in the figure.

5 – RESULTS

The resulting global average material intensities for concrete, masonry, steel, and timber residential buildings are presented in Table 1. The source data for the selected countries is provided in the Regional Assessment of Buildings' Material Intensities (RASMI) accompanying the published methodology [34]. Table 1 summarizes the averages based on the populations of the respective countries.

The global warming potential (GWP) of various construction materials was derived from Environmental Product Declarations (EPDs) collected across 27 European countries [35]. To compile that data, the authors conducted a comprehensive literature review, and input was also gathered from at least one expert in each of the EU-27 countries. Table 2 presents a summary of the GWP values for various construction materials, expressed in kilograms of CO_2 equivalent per kg of material, as well as the percentual contribution of the different Life Cycle stages. The source data for the selected materials is segregated in the original study [35] by C = Continental, M = Mediterranean, N = Nordic, and O = Oceanic regions of Europe. Table 2 summarizes the average for the four regions.

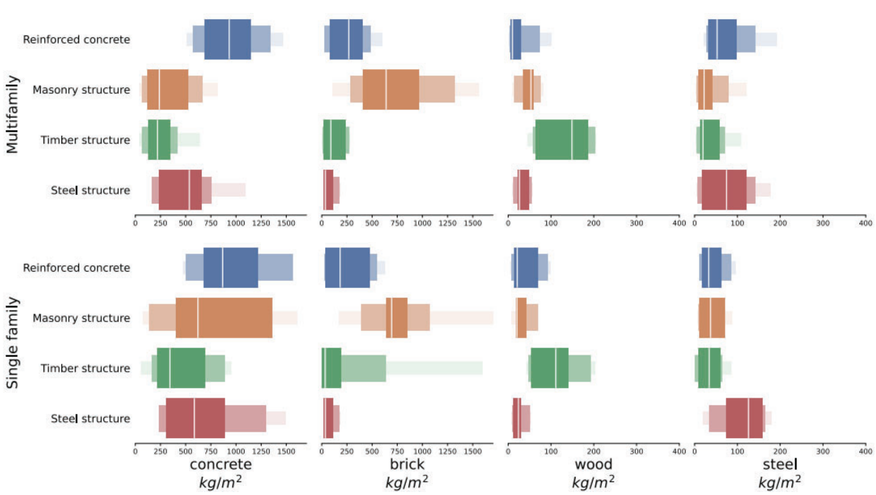

Figure 4: Example of material intensity distribution in the European Union (15 countries) for single and multifamily steel, timber, masonry and concrete residential buildings. Adapted from [34]

The median, representing the 50th percentile, serves as the central benchmark for average material intensity [34]. In this study, population-weighted averages of the 50th percentiles were calculated for China, India, Indonesia, Pakistan, Taiwan, Brazil, Mexico, South Africa, Australia, New Zealand, Canada, the European Union (15 countries), Japan, South Korea, Turkey, the United States, and Russia (representing a population of over 5 billion people).

A key consideration in this study is the carbon storage potential of timber materials. Wood consists primarily of carbon (45–50%), followed by oxygen (40–50%), hydrogen (about 6%), and a small amount of nitrogen (less than 1%) [36]. Given that CO_2 is 27.3% carbon, it can be estimated that for every kilogram of timber, approximately 1.7 to 1.8 kilograms of CO_2 are captured from the atmosphere during the growth of the tree.

https://doi.org/10.52202/080513-0115

The captured carbon remains stored in the wood throughout the building's service life, only being released when the building is deconstructed and the timber either burned or naturally biodegraded. This paper explores a scenario where timber is used to construct new residential buildings instead of other traditional construction techniques. Under this scenario, the new timber building would store carbon throughout its lifespan, and it will be replaced by another timber building after demolition.

The results of this scenario are presented in Table 3, obtained by multiplying the material intensity for each construction technique by the GWP of each material (Table 2), and adding 1.75 kg of CO_2 equivalent per kg of timber material. Table 3 shows the calculated $kgCO_2$-e /m^2 emitted by the different construction techniques, as well as the reduction of emissions for a 100 m^2 building if timber is used instead of other traditional construction techniques.

Table 1: Global average kg/m^2 of different building materials in residential buildings of different contraction techniques

	Concrete	Brick	Wood	Steel	Glass	Plastic	Aluminium	Copper
Multifamily	kg/m^2							
Concrete	1002	220	20	47	2.3	1.2	0.5	0.2
Masonry	861	588	30	18	1.9	1.2	0.5	0.2
Steel	675	91	22	71	2.2	1.2	0.5	0.2
Timber	132	72	82	11	2.2	1.2	0.5	0.2
Single house	kg/m^2							
Concrete	889	287	33	23	2.0	1.2	0.5	0.2
Masonry	708	529	31	22	2.6	1.2	0.5	0.2
Steel	778	91	22	83	2.0	1.2	0.5	0.2
Timber	331	55	76	8	2.6	1.2	0.5	0.2

Table 2: Average global warming (GWP) potential for different construction materials in 27 European countries

	Concrete	Brick	Wood	Steel	Glass	Plastic	Aluminium	Copper
Raw material supply (%)	86.3	67.8	-15.9	88.2	83.4	61.4	91.8	85.1
Transport (%)	1.3	1.1	3.3	1.5	0.7	0.9	0.7	1.5
Manufacturing (%)	1.8	21.4	17.8	4.8	6.5	3.6	1.5	5.2
Transport (%)	4.8	4.7	2.3	1.1	1.7	1.7	0.3	6.1
Construction (%)	2.5	3.0	2.0	1.3	1.4	11.9	0.7	0.3
Use (%)	-1.4	0.0	-0.1	0.0	0.0	0.0	0.0	0.0
Maintenance (%)	0.5	0.0	0.4	1.0	0.3	0.8	0.6	0.0
Repair (%)	0.0	0.0	0.0	0.3	0.1	0.0	0.9	0.0
Deconstruction (%)	0.8	0.3	0.5	0.3	0.3	0.4	0.1	0.0
Transport (%)	1.7	0.8	1.0	0.5	0.5	0.4	0.1	0.2
Waste processing (%)	0.8	0.6	80.4	0.9	3.9	12.9	2.9	1.6
Disposal (%)	1.0	0.3	8.3	0.2	1.3	6.1	0.5	0.1
Total GWP ($kgCO_2$-e/kg)	0.23	0.31	0.97	2.34	2.73	4.68	9.52	3.94

Table 3: Total GWP per m2 emitted from residential construction techniques and GWP differences for the scenario in which a 100m^2 timber building replace other construction techniques.

Multifamily	Total $kgCO_2$-e/m^2	Difference CO_2-e Ton/100m^2
Concrete	414	- 38.3
Masonry	420	- 38.8
Steel	353	- 32.1
Timber	31	
Single house	Total $kgCO_2$-e/m^2	Difference CO_2-e Ton/100m^2
Concrete	342	- 27.1
Masonry	375	- 30.3
Steel	404	- 33.3
Timber	71	
	Average	- 33.3

https://doi.org/10.52202/080513-0115

The results suggest that using timber as the primary construction material for a 100 m² residential building, compared to other traditional construction techniques, can reduce emissions by 27 to 39 tons of CO_2 equivalent. This reduction is comparable to offsetting the climate change contribution of one person for 10 to 14 years.

For further context, we provide a rough estimation of the resource consumption associated with each construction technique. This estimation is based on assumed compositions: 15% cement and 30% sand in concrete; 75% limestone and 20% clay in cement; 60% clay and 30% sand in bricks; 60% iron content in iron ore; 70% sand and 10% limestone in glass; and 45% timber recovery from industrial logs. The average differences in resource consumption between timber and other construction techniques are summarized in Table 4 and the averages represented visually in Figure 5.

6 – CONCLUSION

Building residential houses with sustainably sourced timber, as opposed to other traditional construction materials, offers significant benefits for climate change mitigation and the conservation of planetary resources. Using global average material intensity data for various construction techniques, we estimate that a 100 m² timber residential building can remove between 30 to 39 tonnes of CO_2 equivalent emissions from the atmosphere. Additionally, it prevents the extraction of 1 to 13 tonnes of iron ore, 9 to 41 tonnes of sedimentary soil, and 15 to 37 tonnes of sand.

Table 4: Total resource consumption for residential construction techniques and difference for the scenario in which a 100m² timber building replace other techniques.

	Iron ore	Soil	Sand	logs	Iron ore	Soil	Sand	logs
Multifamily	Total kg/m²				Difference Tons/100m²			
Concrete	78	275	368	45	- 6.0	- 21.3	- 30.5	13.7
Masonry	31	476	436	67	- 1.3	- 41.3	- 37.3	11.4
Steel	119	151	231	49	- 10.1	- 8.8	- 16.8	13.3
Timber	18	63	63	182				
Single house	Total kg/m²				Difference Tons/100m²			
Concrete	39	299	354	73	- 2.6	- 21.9	- 23.7	9.5
Masonry	36	418	373	68	- 2.3	- 33.8	- 25.5	10.1
Steel	139	165	262	48	- 12.6	- 8.5	- 14.5	12.1
Timber	13	80	117	169				
			Average difference		- 5.8	- 22.6	- 24.7	11.7

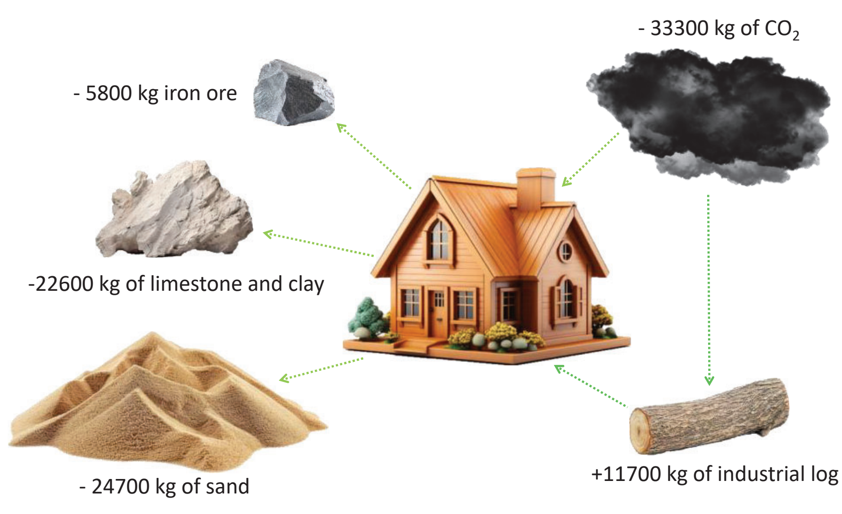

Figure 5: Total average effect in GHG emissions and natural resource consumption from building 100 m² of residential timber building instead of other construction techniques

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At current rates of greenhouse gas (GHG) emissions and resource consumption, this 100 m² timber building offsets 10 to 14 years of a person GHG emissions, while also reducing the need for mining iron ore, sedimentary soil, and sand for an average of 19, 45, and 4 years per person, respectively. Furthermore, the increased demand for industrial logs to construct these buildings supports a sustainable, circular global economy. A 100 m² timber building requires an additional 12 tonnes of industrial logs, equivalent to 84 years of per capita consumption at current levels.

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