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Revising regulations unleashes engineered timber buildings potential for climate mitigation

Fabio Sporchia[a, b], Nicoletta Patrizi[b], Anna Ruini[b, c], Simone Bastianoni[b]
a) Life Cycle Sustainability, Department of Sustainability and Planning, Aalborg University, Aalborg, Denmark
b) Ecodynamics Group, Department of Physical Sciences, Earth and Environment, University of Siena, Italy
c) Department of Science, Technology and Society, University School for Advanced Studies IUSS Pavia, Pavia, Italy

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Abstract: Engineered timber can substitute traditional carbon-intense building materials playing a critical role in climate action thanks to its capacity to store biogenic carbon removed from the atmosphere during forest growth. However, the existing regulations and standards developed in the past along with the development of traditional building practices based on concrete and steel, hinder the possibility to fully exploit the potential of engineered timber within the construction sector. Current standards impose 50 years as reference service life for buildings. While irrelevant for traditional materials, which are not carbon stocks, this imposition belittles this unique feature of timber-based materials. Furthermore, current standards for timber-based materials impose well-defined End-of-Life (EoL) scenarios, each culminating with the incineration of the timber – regardless of any cascading process. However, among the possible EoL scenarios, the possibility of reusing engineered timber materials maintaining the same function is not conceived, although technically feasible. Consequently, LCA of buildings following such standards are forced to neglect the potential positive impact of timber-based buildings possibly providing results that tend to favor traditional over timber-based materials. In this work, we show the potential of timber-based buildings to act as a mean of climate mitigation, calling for an urgent modification of the current standard and linked LCA practices. The case study of a timber-based multi-story building shows that RSL extension and reuse reduce the emission by 13% and 1-2% respectively compared to concrete, except for a RSL of 150 years for which the reduction is marginal.

Introduction

The construction industry is a significant driver of socio-economic growth (UNEP, 2021). However, it accounts for 50% of all raw materials extracted, more than 42 billion tons of material per year (UNEP, 2021). It is linked with one-third of waste generation (UNEP, 2021) and 37% of global energy-related CO_2 emissions (UNEP & Yale, 2023). About 10% of these emissions are due to construction materials (UNEP & Yale, 2023). The choice of building materials is crucial for reducing the embodied emissions of buildings (Pomponi et al., 2020). Mass timber construction products are exceptionally durable and flexible within their use phase (Duan et al., 2022). The use of wood in the construction sector can replace more carbon-intensive, non-renewable materials, contributing to climate change mitigation and resource conservation (Amiri et al., 2020). Timber-based buildings generally have lower Global Warming Potential (GWP) compared to reinforced concrete or steel buildings (Duan et al., 2022).

Wood is a renewable resource sourced from forests that absorb CO_2 as they grow. By using wood to produce durable goods, such as buildings, carbon can be stocked for a long time, generating a large mitigation benefit (Churkina et al., 2020). Buildings become a "second forest" and while they store carbon, further wood generated (Churkina et al., 2020; Garcia et al., 2020). For the sake of simplicity, hereby we refer to the carbon transfer between the atmosphere and the wooden biomass as CO_2 regardless of the carbon oxidation status, instead of referring to CO_2 for the absorption and to carbon for the storage (or stock) in wood.

The standards that currently guide LCA of buildings (EN 15804:2012+A2:2019 and the specific BS EN 16485:2014 for wood materials) present some criticalities when applied to wooden buildings: EN 15804:2012+A2 impedes the selection of "cradle to gate" system boundaries for products containing biogenic carbon as well as the inclusion of biogenic carbon storage. This neglects timber-based materials' climate change mitigation potential. EN 16485:2014 considers four possible End-of-Life (EoL) scenarios for construction wood: landfill (i.e. release of CO_2 stored in wood); energy recovery (i.e. burn); recycling (cut and burn); reuse (chip and burn). Consequently, burning wood is considered as a carbon-neutral activity regardless of where and especially when the CO_2 is absorbed or released. The relevance of considering carbon storage in products is highlighted by the recent establishment of the EU certification framework for permanent carbon removals, carbon farming and carbon storage in products (European Parliament, 2024)

The Reference Service Life (RSL) is defined as the expected service life of a component or assembly in a well-defined set of conditions (Sandak et al., 2019). ISO standard 15686-1 (ISO, 2011) defines the RSL of materials according to their accessibility. Therefore, inaccessible, irreplaceable, or structural materials should have the same reference service life as the building. The other materials with progressively shorter reference service lives should be layered around the inaccessible ones so that materials with shorter reference service lives can be replaced without removing the inaccessible ones (Marsh, 2017). The RSL of a building is defined according to different categories, i.e., technical, functional, economic, and aesthetic lifetime (Haugbølle et al., 2021). However, at a practical level, it is often assessed as the technical RSL, and it is considered as the duration in which the building meets the functions for which it was established. ISO standard 15686-1 defines the factorial method to be used to estimate the RSL of a building and it is the most frequently used in recent years (Silva & De Brito, 2021). The RSL is calculated according to various factors associated with different usage conditions. For LCA purposes, RSL is an important parameter to determine the environmental impacts of a building. This parameter becomes more critical for timber buildings because a longer service life allows for a more extended carbon storage period – thus larger climate change mitigation potential. RSL can strongly influence environmental impacts in LCA studies (Hosamo et al., 2024; Marsh, 2017; Potrč Obrecht et al., 2019; Rauf & Crawford, 2015; Silva & De Brito, 2021). The literature shows significant variability in terms of RSL considered (Anand & Amor, 2017; Andersen et al., 2022; Goulouti et al., 2020; Janjua et al., 2021; Jayalath et al., 2020; Marsh, 2017; Niu et al., 2021; Petrovic et al., 2019; Pittau et al., 2019; Rauf & Crawford, 2015).

This broad variability exists because determining the RSL in LCA of complex systems as buildings is challenging. It depends on many factors, like maintenance, exterior environment, orientation, and material selection (Grant & Ries, 2013). Nevertheless, a building RSL of 50 years is dominant in LCA studies. This is typically justified by reference to previous works (Janjua et al., 2021; Marsh, 2017) and is driven by the application of ISO 15686-1 and BS EN 1990 (Eurocode 0), which assigns a design RSL of 50 years. However, empirical data regarding the current RSL of buildings, together with annual rates of new construction, renovation, and demolition, indicate that an average building lifespan of 100 years or more would be more accurate in sustainability assessments, reflecting the changes that occurred in the existing social, technical, and economic factors (Marsh, 2017). For instance, (Haugbølle et al., 2021) estimated an average reference service life of about 78 years for the Danish context, while for the U.S. context, a statistical analysis of residential buildings determined that the average building reference service life is about 61 years (Aktas & Bilec, 2012).

Against this background, this study explores the potential implications of considering alternative EoL choices as well as RSL other than 50 years, as imposed by the current standards. The implications are studied through the case of a timber-based multi-story residential building. To make sound comparisons, a functionally equivalent concrete and steel building is modeled as well. LCA is performed for both buildings across different scenarios considering different EoL or RSL alternatives.

Methods

The building case study

The product system under assessment is a multi-story residential building with an engineered timber structure. It comprises two building blocks of 4 and 6 stories, respectively, as shown in Figure 1. The height of each story is 3.25 m. The gross internal area of the whole construction is 2,881 m^2. The height of each story is 3.25 m. The gross internal area of the whole construction is 2,881 m^2. The bearing structure is a post-and-beam system, under the Design for Deconstruction and Reuse principles (Cristescu et al., 2020), and both building blocks have a flat roof.

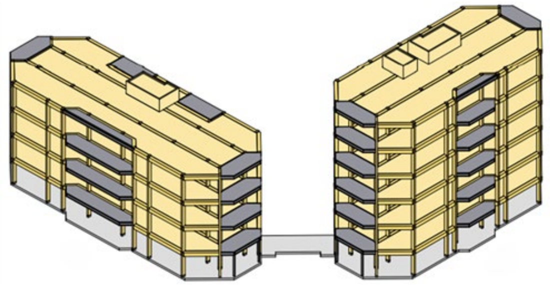

Figure 1. Structural design concept.

The columns and beams are composed of glue-laminated timber (Glulam), and the bearing structure of the floors and roof is made of cross-laminated timber (CLT) panels as well as the technical rooms and staircase shafts (core) and stabilizing wall. The foundation and terrain deck are made of concrete. The façades consist of wood skeleton elements in Laminated Veneer Lumber (LVL) with 2 layers gypsum on the inside, Oriented Strand Boards (OSB) in the middle, mineral wool insulation, and cement-based windbreaking boards on the outside, and a rain shield of tiles. Outdoor balconies are made of steel as bearing structure and fiber cement plates as the bottom of the balconies and as front plates.

Life Cycle Assessment

An attributional LCA was performed. The functional unit is the housing service provided for 150 years by 1 average m^2 of the gross internal area of a timber building.
The study follows a cradle-to-gate approach, thus including modules A1-A3 (e.g., the materials) as defined in EN 15804:2019. Module B4 (materials replacements) is included too as the focus of this study is on materials. This applies for both the engineered timber-based and the concrete-based buildings.

The life cycle inventory represents an average post and beam timber building system that can be ubiquitously implementable across Europe. Reserved primary industrial data have been used together with data retrieved from the literature (Rüter & Diederichs, 2012) for timber building elements manufacturing (i.e., CLT, Glulam, LVL, OSB).
Where data were unavailable, the inventory was based on the Ecoinvent database v. 3.6 (Wernet et al., 2016) and Environmental Product Declarations (EPDs). Ecoinvent 3.6 database was used to integrate the background data.
The assessment excludes minor elements such as furnishing components (e.g., windows, doors, etc.). Balconies and external cladding (i.e., tiles) have been supposed to be replaced every 75 years (Haugbølle et al., 2021).

EN 15804 +A2 Method V1.00 and EF 3.0 normalization and weighting set (Fazio et al., 2018) complying with EN 15804:2019 A2 (EPD International, 2019), and we focus on the global warming potential (GWP_{100}).

An equivalent building (in terms of FU) was modeled based on traditional materials (concrete and steel) to allow a comparison across buildings systems and materials. The bearing structure in this case is made in reinforced concrete, but the functional features (e.g., internal area) are maintained.

Scenarios

To account for the two investigated variables (RSL, and reuse at the End of Life), we defined eight scenarios, to capture all possible combinations (Table 1). The GHG emission related to the EoL phase are not included, but different EoL are modeled to enable performing an LCI over 150 years, as the focus is on material requirements and related emission.

Material	Scenario code	Reuse	RSL (years)		
			50	75	150
Engineered timber	BAU		x		
	RSL75			x	
	RSL150				x
	R50	x	x		
	R75	x		x	
Traditional	BAU		x		
	RSL75			x	
	RSL150				x

Table 1. Scenarios modeling. BAU = Business as usual (50 years RSL, no reuse); RSL75 = 75 years RSL, no reuse; RSL150 = 150 years RSL, no reuse; R50 = 50 years RSL and reuse, R75 = 75 years RSL and reuse.

Each scenario is compared with the results for the equivalent building based on traditional materials.

"Reuse" indicates the reuse of the timber elements deriving from the disassembly of the previous timber building. They are reused in a new, equivalent timber building keeping the same original function. Theoretically all the wood used in the building is protected and not exposed to external or internal weathering, thus falling in use class 1 (EN 335:2013), guaranteeing its durability. However, part of the timber deriving from the disassembly might be unsuitable for reuse (e.g., damaged during disassembly operations). Here, we adopt a highly conservative approach considering low reusability rates for the glulam framework (CLT slab, 50%), for the core (CLT, 50%), and for the façade (LVL 30%). All the timber-based material unsuitable for reuse is sent to incineration following the EoL imposed by EN 16485:2014. The concept of reuse with the same function is illustrated in Figure 2.

Furthermore, to investigate the relevance of accounting for the biogenic carbon and its climate change mitigation potential, on the one hand we tracked the temporal dynamics of the stock of biogenic carbon embodied in timber products. On the other hand, we tracked the carbon absorption through forest regrowth, occurring during the reference service life of the building. For that we assessed forest carbon uptake occurring in a spruce forest in Europe having a rotation period of 75 years. The IPCC Guidelines (IPCC, 2006, 2019) were used to estimate the carbon sink function in the forestry sector. In particular, the forest carbon stock dynamic is tracked over two growing periods, i.e., two fully mature forests were modelled to be generated over 150 years (75 years each). The cumulative carbon stock captured over time through the transfer from the atmosphere to the forest due to tree growth is tracked as well in order to account for the exceeding demand for wood due to the misalignment of the building lifetime and the forest rotation period. This means that when the building lifetime is shorter, a further (extra) stock of carbon in a mature forest will be affected, while when the building lifetime is longer, a further (extra) stock of carbon will be generated in another forest.

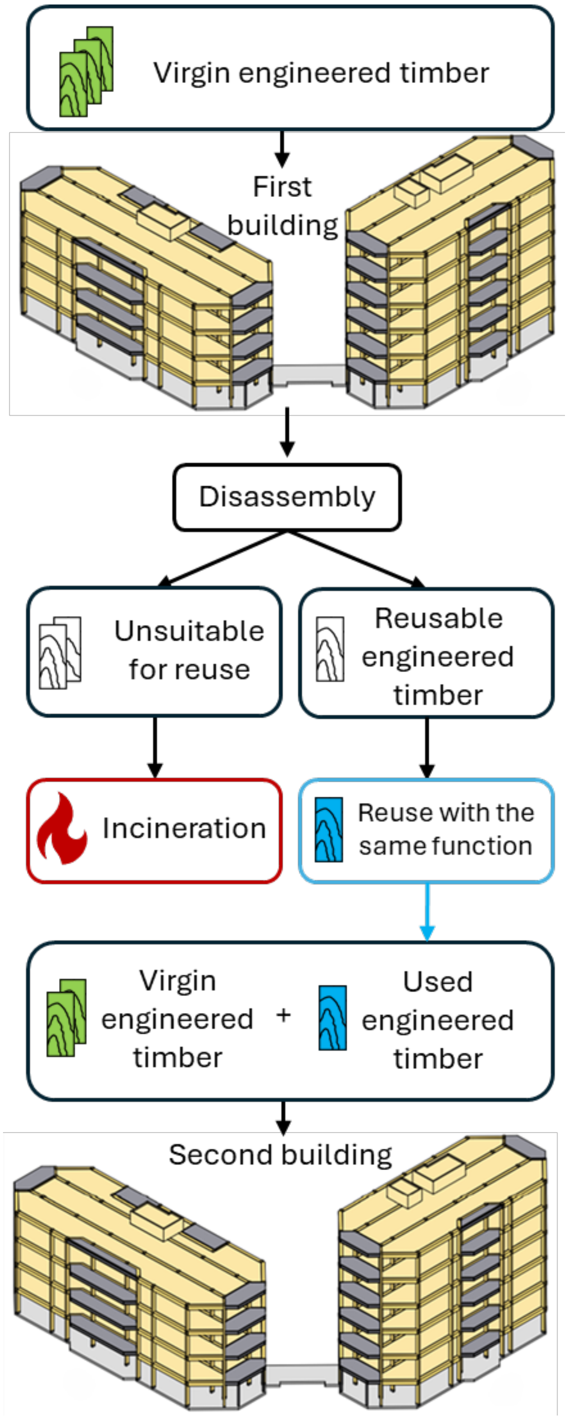

Figure 2. Schematic representation of how engineered timber reuse with the same function is modeled.

The cumulative carbon stock sequestered over time through atmospheric transfer from the atmosphere to the forest, driven by tree growth, is also monitored to account for the increased demand for wood resulting from the misalignment between building lifespan and

forest rotation period. The considered stocks include not only the carbon embodied in the building itself but also the emission generated for its production. The latter include the stock linked with the punctual emission due to the production of the building – product stage emission (A1 to A3) and the emission due to the replacement of ceramic tiles and balconies (B4 assumed to happen after 75 years). Although concrete carbonation could reduce the overall GHG emission, it was excluded for both engineered timber-based and concrete-based buildings due to its marginal significance (<5% (Collins, 2010; Yang et al., 2014) and to the high variability due to environmental conditions (Oyinkanola & Panesar, 2023; Possan et al., 2016).
This second part of the work is purely meant to provide insights into the necessity to consider the carbon dynamics that are significantly different between the two kinds of materials considered. The focus is specifically on timber and the related forest, i.e., what distinguishes it from concrete and steel. Accordingly, while we considered EoL emissions for timber (i.e., incineration) in the dynamic representations we did not include the impact for the EoL of other materials and none for the traditional materials-based building. This is meant to show the actual timber-related carbon flows, hindered by current regulations. Nevertheless, A dynamic and more complete analysis should be implemented to provide accurate results.

Results and discussion

The analysis reveals that either acting on the RSL or implementing a reuse with the same function for engineered timber allows to save GHG emissions, making it a potential mitigation strategy.
In particular, the longer the RSL the larger the mitigation potential (Table 2). Reuse contributes to saving GHG emissions too, but less significantly. A large part of the timber-based building is still made of traditional materials, thus making the reuse only applicable to part of the total materials. Reusable timber is reused with the same function in the second building, but most of the materials have to be sourced from new production. In all scenarios the engineered timber-based building presents lower GWP compared to the equivalent traditional one, although this difference is minimal for the RSL150 scenario (-0,3%).

Material	Scenario code	Overall GWP	GWP per m^2
		t CO_2eq	t CO_2eq/m^2
Engineered timber	BAU	1120.32	0.39
	RSL75	746.88	0.26
	RSL150	442.32	0.15
	R50	1097.91	0.38
	R75	724.47	0.25
Traditional	BAU	1283.85	0.45
	RSL75	855.90	0.30
	RSL150	443.66	0.15

Table 2. Scenarios results are shown for the overall 150-year period and per m^2 as per the functional unit.

The largest improvement is linked with scenario RSL 150 for the engineered timber-based building, resulting in 61% less GWP.
However, it is fundamental to distinguish between the types of materials composing the two modeled buildings, one mostly renewable (wood), and one mostly non-renewable (minerals). This difference becomes evident when considering the upstream processes that underly the (re)generation of wood and thus timber. Figure 3, Figure 4, and Figure 5 show how a dynamic representation of the carbon fluxes involved in the (re)generation of wood over the considered lifetime can better highlight this difference. Year 151 is also shown just to hint at the future dynamics.
While the quantified results in terms of share of GHG reduction are in line with the values found by Hart et al. (2021) (36% - 48%), no publication was found specifically addressing the GHG reduction linked with a normative change in the RSL and re-use and with a comparison between concrete- and engineered timber-based materials.

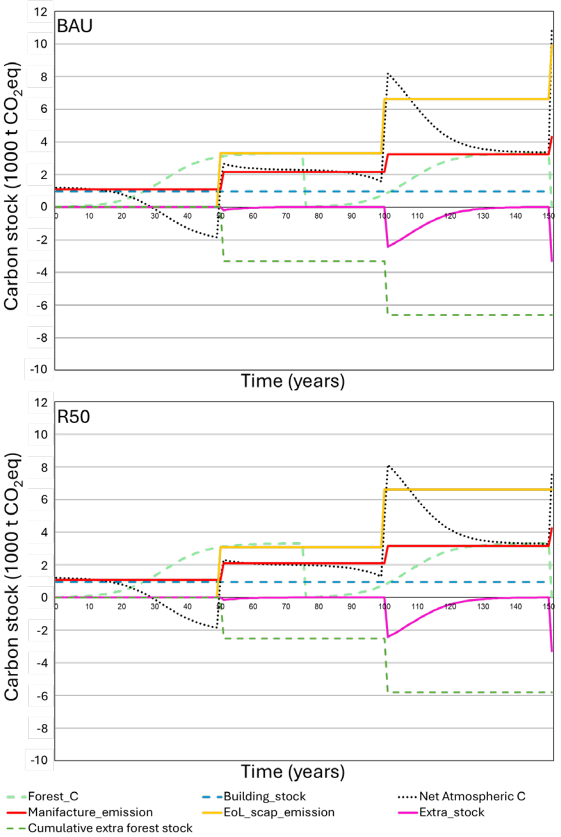

Figure 3. Forest, atmosphere, and building carbon stock and linked cumulative emissions or removals for the scenarios with a 50 years RSL. "Extra stock" indicates the deficit of wood over time.

Figure 3 shows how considering a RSL lower than the time to (re)generate wood (i.e., to bring a forest to maturity), incurs a positive carbon balance considering the GHG emission released into the atmosphere and absorbed by forest. This is due to the necessity to harvest "three forests" to build three times the building, while over the available time only two forests can reach maturity, thus being ready for harvest.

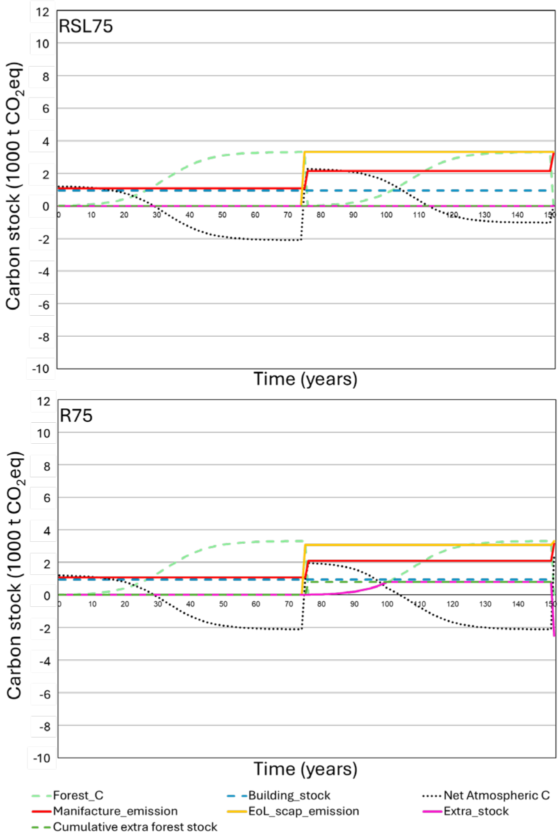

Figure 4. Forest, atmosphere, and building carbon stock and linked cumulative emissions or removals for the scenarios with a 75 years RSL. "Extra stock" indicates the surplus of wood over time.

Figure 4 shows how considering a RSL equal to the time to (re)generate wood (i.e., to bring a forest to maturity), incurs an alternating positive and negative carbon balance due to GHG emission released into the atmosphere and absorbed by forest. Since there is a balance between the carbon absorbed and transferred to timber, and the carbon released when incinerated after the RSL, the GHG emissions that affect the overall long-term growing trend are the ones linked with the manufacturing processes. However, the long-term storage of carbon in the building grants a significant time of lower balance, over which carbon is prevented from contributing to global warming, acting as a mitigating factor.

This becomes even more evident when the RSL is further extended to 150 years (Figure 5). In this case, over the considered temporal boundaries, twice the timber implied is generated. Consequently, the carbon balance becomes negative, even compensating the manufacturing (and replacement) emissions.

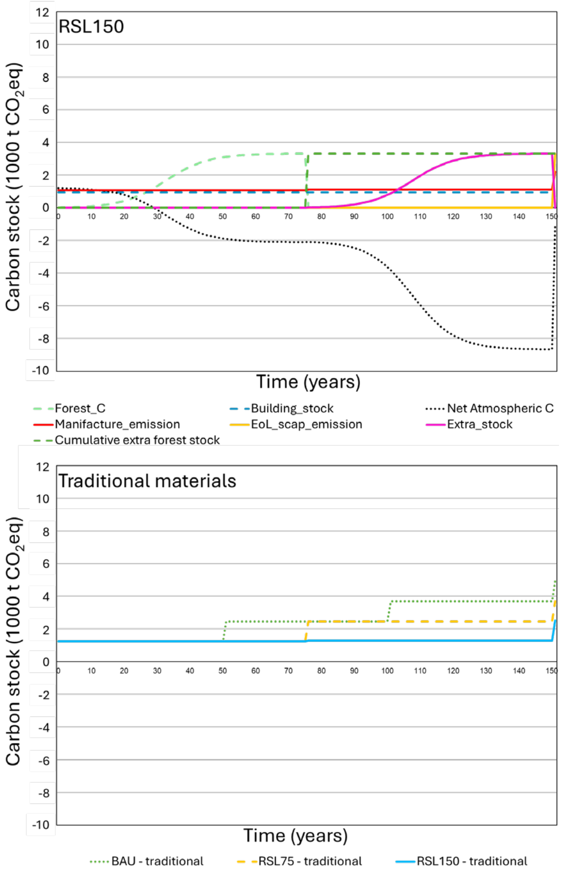

Figure 5. Forest, atmosphere, and building carbon stock and linked cumulative emissions or removals for scenario RLS150 and cumulative GHG emissions for the traditional building scenarios.

Instead, traditional materials-based buildings are linked with emissions that cannot be reabsorbed through the same process that generates the raw materials implied, i.e., what happens for timber.

Conclusions

Current standards and regulations were designed and meant for traditional materials-based buildings. However, the emergence of timber as an alternative, renewable, and more sustainable material requires a revision of such standards, and the linked environmental assessment practice. Our very conservative approach shows that reusing engineered timber with the same function is fit for climate action. Aligning the RSL of timber buildings to wood regeneration time could boost this climate action ensuring a sustainable use of a renewable resource. For this action to be put in place, it is fundamental a change in perspective. While current policies advocate for renewability, current regulations obstacle the needed shift from a fossil- to a renewable-based economy since they overlook the fundamental temporal feature that characterizes renewable resources as, in this case, wood. While the RSL is irrelevant for fossil resources as they are non-renewable by definition – thus linked with extremely long regeneration time – it is fundamental for renewable resources which are defined through a temporal feature.

A generalized systemic change is required to treasure the potential of timber to support climate action. This entails the creation of a market for engineered timber reusable with the same function, a substantial revision of the temporal dimensions of the standards, and a consequent modification of the linked environmental assessment practices.

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