LIFE CYCLE ASSESSMENT

SUSTAINABLE AUTOMATED TIMBER FRAME CONSTRUCTION

AUAR

As the first European venture capital fund, Planet A relies on its own scientific team to assess the environmental and climate impact of an innovation. Prior to an investment, a life cycle assessment, like this one, is conducted and integral part of the investment decision. All assessments as well as the methodology are published for maximum transparency.

Terminology and abbreviations

CCS	Carbon capture and storage
CN	China
CO_2-eq.	Carbon dioxide equivalents
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life Cycle Assessment
MFH	Multi family home
PL	Poland
SFH	Single family home
UK	United Kingdom
US	United States

About AUAR

AUAR (Automated Architecture) is a UK-based company specializing in modular construction and sustainable building solutions. By combining digital fabrication technologies with renewable materials like timber, AUAR focuses on creating adaptable, low-carbon structures that prioritize resource efficiency and minimize waste. AUAR developed a design-to-manufacture software that enables homebuilders to design innovative timber frame buildings. These designs can be manufactured in automated robotic micro-factories. Their modular approach makes sustainable housing universally accessible and enables flexible design and efficient construction processes, supporting sustainable urban development and addressing the evolving needs of the built environment. Through innovation and environmentally conscious practices, AUAR aims to contribute to a more sustainable construction industry.

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Summary

This Life Cycle Assessment (LCA) report analyzes the environmental impact of AUAR assessing the shift from existing building practices to modular construction with timber and digital fabrication. The report is divided into three parts.

Part I identifies the construction industry's significant environmental challenges, including GHG emissions from material production and operations, resource depletion, and waste generation, and discusses mitigation strategies like using timber as a sustainable alternative, highlighting AUAR's role in providing integrated planning and construction using timber frames.

Part II presents an overview on the impacts of using timber by reviewing scientific literature. The systemic view on timber use in construction emphasizes the lower embodied carbon compared to steel and concrete, the carbon storage potential contingent on sustainable forest management, the importance of biodiversity protection in harvesting, and the necessity of policies supporting sustainable timber supply and long-lasting wood products while aligning with biodiversity targets.

Part III provides an assessment of AUAR's environmental impact. We assessed the net avoidance in GHG emissions using a modular approach focusing on climate change for a 50-year building lifespan. The results demonstrate significant GHG emission avoidance by switching to timber frames, utilizing automated construction to reduce waste and commuting, and employing sustainable insulation like cellulose, with variations in quantified impact between the US (efficiency focused) and European (shift to timber) markets.

Switching to AUAR's technology can significantly reduce GHG emissions, notably by substituting high-carbon materials such as concrete and steel. In Europe, average net GHG avoidance is approximately 291 kg CO_2-eq./m^2 for single-family homes (SFH) and 241 kg CO_2-eq./m^2 for multi-family homes (MFH). Conversely, in the US, where timber frames are prevalent, the advantages derive from improved material use, decreased workforce commuting, and promotion of sustainable insulation, leading to average net GHG avoidances of 141 kg CO_2-eq./m^2 for SFH and 135 kg CO_2-eq./m^2 for MFH.

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1. Part I: The challenge - Transforming a hard to decarbonize industry

1.1. Environmental impacts of the construction industry

The future demand for living space is projected to increase on a global scale: Research models indicate a substantial increase in demand for buildings. Estimates project that global demand for new building space will range from 230 billion square meters by 2060 to as much as 400 billion square meters between 2020 and 2050. (Pauliuk et al., 2024; Pomponi et al., 2020). These trends are propelled by an increasing world population, urbanization and increasing per capita living space. Catering the need for living spaces and other built structures with current building materials and techniques will result in numerous negative environmental impacts if it relies on existing materials and practices:

- **Global Warming:** The built environment is responsible for 37% of global GHG emissions (United Nations Environment Programme, 2023). The production of conventional construction materials contributes approximately 9% of global GHG emissions. The remaining 28% stem from direct emissions (operational emissions).
- **Resource depletion:** Residential buildings are the second greatest anthropogenic material stock, second only to roads (Wiedenhofer et al., 2024). The construction industry is a major consumer of raw materials, including aggregates such as sand and gravel, which are mostly used for concrete production. The scale of aggregate extraction is projected to double by 2060, reaching around 55 billion tonnes (Torres et al., 2021). This high demand for resources leads to depletion of natural resources and can have other environmental consequences potentially leading to irreversible damages. For instance, sand mining results in a loss of biodiversity, a decline in protection against extreme events, erosion, lower groundwater tables and GHG emissions (Whiting et al., 2023).
- **Waste generation:** Closely related to the material demand is waste generation. The construction sector is a large producer of waste. Pauliuk et al. estimate that between 2020 and 2050, 100 billion m^2 residential buildings and 35 billion m^2 non-residential buildings will be demolished (Pauliuk et al., 2024). Construction and demolition waste is a significant problem, and current recycling practices are often not sufficient. A large portion of buildings and their components are not built for reuse and recycling. The sector needs to move beyond a linear "take-make-dispose" model toward a circular economy approach.

In conclusion, the current state of the construction industry is unsustainable, leading to significant environmental degradation and resource depletion. The problems of an already unsustainable industry is exacerbated by the projected increase in demand for buildings. There is an urgent need to transition to more sustainable practices, including the adoption of low-carbon materials and the implementation of circular economy principles.

1.2. Transforming the construction industry

To mitigate its environmental impact, a range of innovative materials, design strategies, and technologies have emerged to enhance sustainability in the construction industry and during the life-time of buildings. These innovations aim to reduce GHG emissions, improve energy efficiency, displace toxic and pollution materials, as well as promote circular economy principles. The following section provides an overview of the two most commonly discussed options:

1. Reducing GHG emissions and other environmental impacts of conventional building materials is one of the key strategies to mitigate the climate impact and broader externalities of the construction industry.

- **Cement:** Traditional cement production accounts for around 8% of global CO_2 emissions. Innovations such as carbon-capturing concrete and alternative binders (e.g., geopolymer concrete, magnesium-based cements) reduce emissions. One of the most widely adopted strategies is to lower the quantity of conventional cement in concrete. Cement can be replaced by alternative geopolymers and cementious materials, such as fly ash, flue gas desulphurization gypsum, silica fume, bauxite residue and other ashes. According to Shah et al. (Shah et al., 2022), these waste materials are available in sufficient quantities in many regions of the world to substitute substantial proportions of conventional cement in concrete, providing a high GHG emission reduction potential. Alternatively, magnesium-based cement, such as magnesia oxychloride cement, magnesia silicate cement, magnesia oxysulfate cement and magnesia carbonate cement, can substitute conventional cement (Bernard et al., 2023). Magnesium carbonate cements can be combined with carbon capture and storage (CCS) to maximize benefits in terms of GHG emissions. Combining CCS and the construction industry is an approach followed by other researchers and startups, too, who are working in sequestering CO_2 in concrete via carbonation reactions. So far, the total quantity of CO_2 that can be sequestered in concrete remains low if functional properties of concrete are maintained (X. Fu et al., 2024; Winnefeld et al., 2022). Another option is to improve the operational performance, fuel efficiency and used fuel type. New solutions provide tools to optimize existing cement plants, reducing the environmental impacts and costs (Shahrokhishahraki et al., 2024; Summerbell et al., 2016, 2017).

- **Steel:** There are several options, such as CCS, direct reduction of iron using hydrogen (or other reducing agents) and electrification (electric arc furnace) (Kazmi et al., 2023) to lower the carbon footprint of steel. These solutions require a massive deployment of new technologies and infrastructure, i.e. energy from renewable sources, hydrogen supply and CCS technologies (incl. transport and final disposal of CO_2), entailing high costs and systemic transformations. To date, only a limited number of projects exist globally, and most industry players with net-zero targets aim to achieve them by 2050 or later (Leadership Group for Industry Transition, 2024).

- **Glass:** The main strategies to reduce GHG emissions (and other negative externalities of glass manufacturing) include the use of cleaner heat sources, e.g. oxyfuel combustion or electrification, and electricity from renewable sources (Atzori et al., 2023).

- **Ceramics (bricks, tiles):** The manufacturing of ceramics requires high amounts of energy because of high firing temperatures and heat required for drying. The use of more sustainable heat sources and heat carriers as well as recycled material present the most promising approaches to reduce GHG emissions and other negative impacts (Furszyfer Del Rio et al., 2022).

- **Aluminum:** The Hall-Héroult process, the dominant aluminum smelting method, requires large amounts of electricity. Transitioning from fossil fuel-based grids to hydropower, wind, or solar energy can significantly lower emissions (Saevarsdottir et al., 2020). Another approach is to replace traditional carbon anodes emitting CO_2 in aluminum electrolysis with inert anodes made of ceramic or metal. This eliminates direct GHG emissions by producing only oxygen as a byproduct, enabling nearly carbon-free aluminum production (He et al., 2021). Again, hydrogen can be used as a reducing agent and CCS can be applied to capture CO_2 in conventional aluminum production (Zore, 2024).

2. The second key strategy to reduce the environmental impact of the construction industry is to **replace unsustainable conventional materials with more sustainable materials.** This ranges from using higher shares of waste materials in existing production processes, e.g. in steel, aluminum, glass, concrete and ceramics manufacturing to a full replacement of construction materials by traditional and novel building materials:

    - **Timber:** Timber has been used for millennia as a structural building material. Researchers consider timber to be one of the most promising materials that can help to reduce GHG emissions of the construction industry (Mishra et al., 2022; Tupenaite et al., 2023). While timber frames have been used for a long time, novel building materials made from timber gain popularity due to their structural performance, like cross-laminated timber (CLT), glue laminated timber (glulam) and dowel laminated timber.

    - Other **bio-based materials**: Scientific research shows that conventional mineral and/or fossil-based insulation materials perform worse in terms of environmental impacts than bio-based alternatives (Füchsl et al., 2022). Using more sustainable and better insulation materials can substantially reduce environmental impacts associated with the manufacture of these materials, the emissions associated with the energy use during the building's lifetime as well as the end of life of these materials. Some fossil-based insulation materials contain blowing agents that pose environmental and health hazards (Füchsl et al., 2022; Maury-Micolier et al., 2023; Skleničková et al., 2022).

Many of those solutions discussed above are currently introduced to the market by startups and incumbent players. Yet, the full implementation of these solutions, especially those that transform the industry producing traditional building materials, will take considerable time due to technological challenges to be solved and a very high capital demand. The latter might result in increasing costs of materials. Such a *green premium* is a major barrier preventing a quicker adoption of more sustainable practices. Notably, some solutions can deliver immediate sustainability benefits at no additional cost — such as machine learning-based optimizations of conventional production processes and material substitutions using familiar materials and technologies already known to stakeholders in the construction industry.

1.3. The role of AUAR

AUAR's software and hardware components allow the seamless integration of planning and construction using timber frames. Timber frames are the dominant structural element used in the US and are gaining popularity in Europe. AUAR's software allows architects and designers to translate their visions on-the-fly into a digital twin that uses timber frames ensuring structural integrity and the alignment with building codes. Once the design is completed, the timber frame structure is produced by automated robots. AUAR's tool allows the design and production of open wall panels and closed panels. AUAR's software enables designers and architects to use timber frames in projects that would otherwise require the use of unsustainable mineral building materials or less sustainable engineered timber, such as CLT. Compared with the latter, AUAR'S frame design requires less timber while maintaining the structural performance of buildings. The system furthermore reduces wastes and uses more sustainable insulation materials. We discussed the environmental implications of these aspects in Part II and III of this report. Besides these environmental benefits, AUAR's solution reduces costs and building times. AUAR therefore provides a solution that offers cheaper and more sustainable construction projects at scale.

2. Part II: Systemic view on timber use

The environmental impact of timber use in construction is strongly dependent on the market conditions, design choices and the conditions under which timber is harvested. In the following section, we present a review of scientific literature on the impact of scaling timber use in the construction industry.

2.1. Climate change

The use of timber in construction is emerging as a potential alternative to more emission-intensive materials. Engineered wood products are seen as a "green" alternative, as they store carbon and can displace materials with higher GHG emissions. Table 1 shows an overview of results from review studies. All review studies containing hundreds of datapoints suggest that wood structures have lower embodied carbon emissions than steel other building types.

Table 1 *Overview of GHG emissions reported review studies (ordered by year of publication).*

Review study	N1/N2 [a]	Main results [b]
(Röck et al., 2022)	769/744	• Buildings using wood as the main structural material result in 100 to 200 kg CO_2-eq. less per m^2 • GHG intensity of different buildings ○ Massive concrete: 750 kg CO_2-eq/m^2 (250 to 900 kg CO_2-eq/m^2, outliers up to 1850 kg CO_2-eq/m^2) ○ Steel frame: 700 kg CO_2-eq/m^2 ○ Hybrid timber/concrete: 700 kg CO_2-eq/m^2 ○ Concrete frame: 650 kg CO_2-eq/m^2 (400 to 1200 kg CO_2-eq/m^2) ○ Solid timber construction: 600 kg CO_2-eq/m^2 ○ Timber frame buildings 500 kg CO_2-eq/m^2 (300 to 800 kg CO_2-eq/m^2).
(Duan et al., 2022)	62/?	• Mean GHG intensity of different buildings[c]: ○ Bricks: 242 kg CO_2-eq/m^2 ○ Reinforced concrete: 224 kg CO_2-eq/m^2 ○ Concrete: 224 kg CO_2-eq/m^2 ○ Hybrid mass timber 190 kg CO_2-eq/m^2 ○ Engineered timber: 142 kg CO_2-eq/m^2 ○ Light weight timber: 137 kg CO_2-eq/m^2 ○ Steel: 176 kg CO_2-eq/m^2 ○ Masonry 105 kg CO_2-eq/m^2
(Andersen et al., 2021)	79/229	• Median/average GHG intensity of different buildings[c]: ○ Timber single family: 3.0/4.8 kg CO_2-eq/m^2a_{50} ○ Timber multi family: 2.2/3.9 kg CO_2-eq/m^2a_{50} ○ Timber office: 2.5/4.1 kg CO_2-eq/m^2a_{50} ○ Timber other: 3.2/4.4 kg CO_2-eq/m^2a_{50} ○ Residential (Röck et al., 2022): -/9.0 kg CO_2-eq/m^2a_{50} ○ Office (Röck et al., 2022): -/14.4 kg CO_2-eq/m^2a_{50}
(Leskinen et al., 2018)	51/433	• Using wood in structural construction reduces GHG emissions by -1.4 to 8.7 t CO_2-eq./t wood[d]. The average net reduction is 2.1 t CO_2-eq./t wood. • Using wood in non-structural construction reduces GHG emissions by 0.3 to 7.5 t CO_2-eq./t wood. The average net reduction is 2.6 t CO_2-eq./t wood.

Table 1 *Continued.*

Review study	N1/N2 [a]	Main results [b]
(Sathre & O'Connor, 2010)	21/?	• Using wood in construction reduces GHG emissions by -3.6 to 23.5 t CO_2-eq./t wood[d]. • The average net reduction is 3.3 t CO_2-eq./t wood. The average minimum and maximum net reduction of reviewed studies are 1.3 and 7.2t CO_2-eq./t wood.(Andersen et al., 2021)

[a] N1: Number of studies included in the review (total); N2: Number of individual values included in the review
[b] Minus indicates a net increase
[c] Data extracted with plot digitizer
[d] The study reports a substitution factor using the unit t C/t C in wood used. This factors are converted into CO_2-eq. assuming 50% C content of dry wood and a moisture content of 15% of wood products (Leskinen et al., 2018).

The reviewed literature clearly shows net benefits of using timber over other building materials. With the exception of Andersen (2021), the reviewed studies do not explicitly address the influence of the chosen life cycle assessment (LCA) model. While consequential LCA evaluates the changes in environmental impact resulting from building more or less with timber, attributional LCA simply compares different building types without accounting for systemic shifts in material use. As such, attributional LCA is not suited to answer questions about the broader consequences of increasing timber construction. In contrast, consequential LCA captures systemic effects — such as the environmental impacts of increased timber extraction or the expansion of timber plantations. Andersen (2021) found 218 values of attributional LCA studies and 7 consequential LCA studies, showing that the average and mean GHG emissions of studies assessing systemic change (consequential LCA) are lower than the results of other studies (Figure 1). The values presented in Table 1 and these findings indicate that shifting to timber use in buildings is beneficial in terms of GHG emissions.

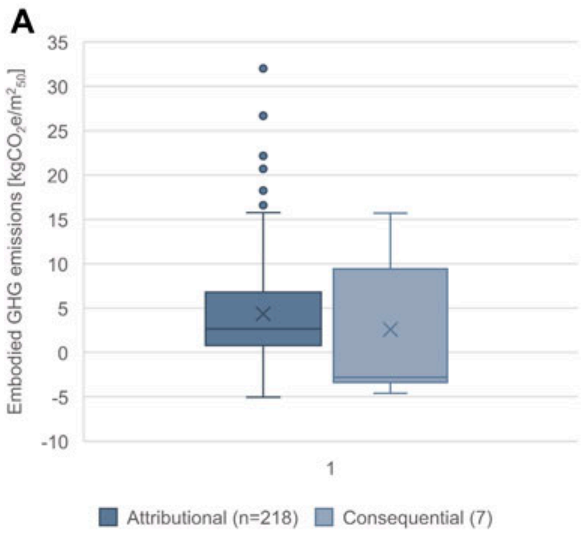

Figure 1 *Embodied GHG emissions distributed on LCA method). The dots in the plot indicate the outliers of the dataset. The boxes and the line within the boxes indicate the quartiles of the dataset (25 percentile, 50 percentile (median) and 75 percentile). The x indicates the average. The error bars outside the boxes indicate the deviation in the data. Provided by Andersen (2021), licensed under a CC BY license.*

Combining economic and forest carbon stock models with LCA can provide insights into the climate impact of using more timber. Increasing wood harvest might lead to a loss in carbon stored in biomass. A comprehensive review shows that for each t carbon contained in wood, an average or median net change in the carbon balance of 1.6 and 1.5 t carbon might happen (Soimakallio et al., 2022). In other words: each t carbon harvested results in an additional loss of 0.6 or 0.5 t carbon stored in the forest, corresponding to 0.8 and 1 kg CO_2-eq. per kg wood product (see footnote of Table 1 for further details on the conversion).

The use of wood in a given application — such as construction — is considered beneficial when the net reduction in emissions from substituting conventional building materials exceeds the GHG emissions associated with the resulting loss in forest carbon stocks. A comparison of these values with values reported in Table 1 indicates a net climate benefit of using wood. Studies combining economic, forest and LCA models show mixed outcomes: some of these studies indicate a reduction in GHG emissions that can be achieved by switching to timber in construction, cf. (Mishra et al., 2022; Moreau et al., 2023; Schulte et al., 2023; Gustavsson et al., 2021), while others report the opposite, cf. (Maierhofer et al., 2024; Hurmekoski et al., 2023). The net impact will depend on many factors, such as the forest ecosystems affected, climate change, global and local market conditions, demand for wood and all other products affecting land-use, forest management practices, trade, policies etc. The capability of models to accurately predict the impact on such a complex level depends on the model quality and data availability (which is a key barrier, projecting the impact of timber use over the next decades to centuries). Management practices and an efficient use of timber use maximize overall benefits and reduces pressures on the environment (Papa et al., 2023; Petersson et al., 2022; Schulte et al., 2023)

2.2. Biodiversity

Land use and land use change (LULUC) are the main drivers of biodiversity loss. In addition to LULUC, forest management practices play an important role in biodiversity loss and protection. Timber harvesting has a complex impact on biodiversity across various forest types, with the degree of impact depending on several factors including the intensity of management, the type of harvesting method used, and the specific characteristics of the forest ecosystem. For instance, timber harvesting changes the age structure and composition of tree species. It can also alter the vertical stratification of the forest, leading to modifications in local temperature, light, moisture, soil and litter conditions (Chaudhary et al., 2016).

The impact on these properties depends mainly on the forest management practices. Chaudhary et al.'s review shows the impact of different forest management practices on alpha diversity. Reduced impact logging, for instance, provides a way to largely maintain alpha biodiversity for most taxonomic groups. In contrast, clear cut, plantations and slash and burn practices result in a loss of alpha biodiversity. Clear-cutting is still a common practice (Fridén et al., 2024). It should be noted that management practices could also enhance biodiversity if managed forests are established on degraded land or unsustainably managed plantations. In general, the magnitude of the impact on biodiversity varies depending on climatic zones, food web structures, and ecosystem properties, causing geographical variability in the impacts of forestry. Different taxonomic groups may respond differently to forestry operations, due to variations in body size, mobility and diet.

2.3. Ensuring sustainable timber use

Scientific literature and other reports underline the importance and challenges of meeting the demand for wood products while maintaining biodiversity and achieving climate change mitigation.

- **Promote sustainable wood supply: Sustainable forest management** accounting for local conditions is key to provide wood resources sustainably (Eyvindson et al., 2018). The potential negative impact on biodiversity can be minimized by managing existing forests sustainably and only using degraded land for wood plantations. Certification of sustainable practices is key. Yet, scientific research indicates that existing certification do not guarantee positive impacts on biodiversity (Matias et al., 2024; Vogt, 2019) although such outcomes can be achieved under certain conditions(Kadam & Dwivedi, 2025; Malhi et al., 2022; Zwerts et al., 2024). Yet, measuring the impact is complex and further research is needed taking local contexts into account ibid. and (Lehtonen et al., 2021).

- **Prioritize sustainable wood use:** Policy needs to **prioritize wood use in long-lasting products** where carbon remains locked while wood serves a function, e.g. in buildings (Beck-O'Brien et al., 2022). Wood used for energy production or pulp and paper is the least preferable use of forest resources. Once the end of life of a building is reached, timber could be reused or recycled, and, if not possible, it could be stored or converted into biochar to maintain carbon locked-up to provide a long-term carbon sink, cf. (Zeng et al., 2024; Zeng & Hausmann, 2022). Implementing circular principles in the wood economy can have very positive impacts on climate change mitigation efforts but requires a fundamental change of current business practices and a revision of policies (Forster et al., 2024). In addition to using wood in long-lasting products and the introduction of circular economy principles, wood and timber must be used in the **most efficient way** possible, e.g. solutions need to be implemented that reduce the amount of wood needed to provide a certain function. AUAR offers a solution that uses timber more efficiently than engineered wood, such as CLT and glulam. AUAR therefore reduces pressure on land-use and land-use change.

- **Aligning biodiversity targets with needs for biogenic materials:** Forest conservation protects important natural habitats. Maintaining primary habitats is key to the survival of many species. Yet, biodiversity protection through forest conservation might lead to a leakage of biodiversity risks to other regions from which timber and other biomass might be sourced (Fischer et al., 2024). In 2022, Europe produced more than 500 million m^3 of roundwood and imported less than 10 million m^3 from extra-EU countries (Eurostat, 2023). Thus, less than 2% of roundwood used in the EU comes from countries outside of the EU, where less strict regulations and enforcement might be in place. Thus, ensuring sustainable timber harvesting in Europe, while protecting biodiversity, should be a key priority for both policies and business practices.

- **Adapt forests to a changing environment:** Forest disturbances have been increasing in Europe and the US (Anderegg et al., 2022; Patacca et al., 2023). Climate change is likely to exacerbate the situation by applying more stress to forest ecosystems (Forzieri et al., 2022). Sustainable long-term forest management practices can help to mitigate adverse effects of climate change (Baldrian et al., 2023; Prichard et al., 2021).

3. Part III: AUAR's environmental impact

This LCA uses a modular approach relying on scientific literature. The assessment uses the environmental impact reported in the scientific studies listed in Part II to build a modularized LCA. This approach was chosen because of the endless number of different building typologies and design choices that could be used to design and build buildings with AUAR's technology. Additionally, the assessment of the environmental impact of different materials depends on geography, data sources, methodology, system boundaries, etc. To account for this variability and ensure broad applicability, we include data covering multiple geographies, building typologies and methodological assumptions.

AUAR's solution results in specific changes in the construction industry (Table 2). The environmental impacts associated with each of the aspects are discussed in 3.2. The methodology and data used for the assessment are detailed in the corresponding subsections. We quantify the overall net environmental impact of introducing AUAR's solution in section 3.3.

3.1. System boundaries, functional unit and indicators

AUAR's tool allows designers, developers and architects to design and build timber frame structures efficiently. It can be used to design and produce open wall panels and closed panels. These panels can be used instead of unsustainable mineral building materials or less sustainable engineered timber, such as CLT.

The assessed system boundaries include all life cycle stages of a building related to *'embodied carbon*' (Figure 2). We include all life cycle stages from A1 to C4, excluding B6 and B7 and D. We excluded these two stages for the following reasons:

- B6 and B7: AUAR mainly affects embodied carbon. To achieve a fair comparison between different building types we assume similar heating systems and energy demand.
- D4: From a systemic perspective, using timber provides additional benefits at the end of life of a building. Timber could be used for other purposes, it could be incinerated to produce energy (potentially replacing other types of energy supply) or it could be stored to create a long-term carbon storage. Those additional benefits are speculative considering the long lifetime of the building. In 50 to 70 years from today, the energy system is (hopefully) running on renewable energy. Thus, producing heat from used timber only has a minor positive impact. Long-term storage in vaults could provide the biggest climate benefit but so far, such systems are not operational yet. We therefore exclude these aspects from the assessment.

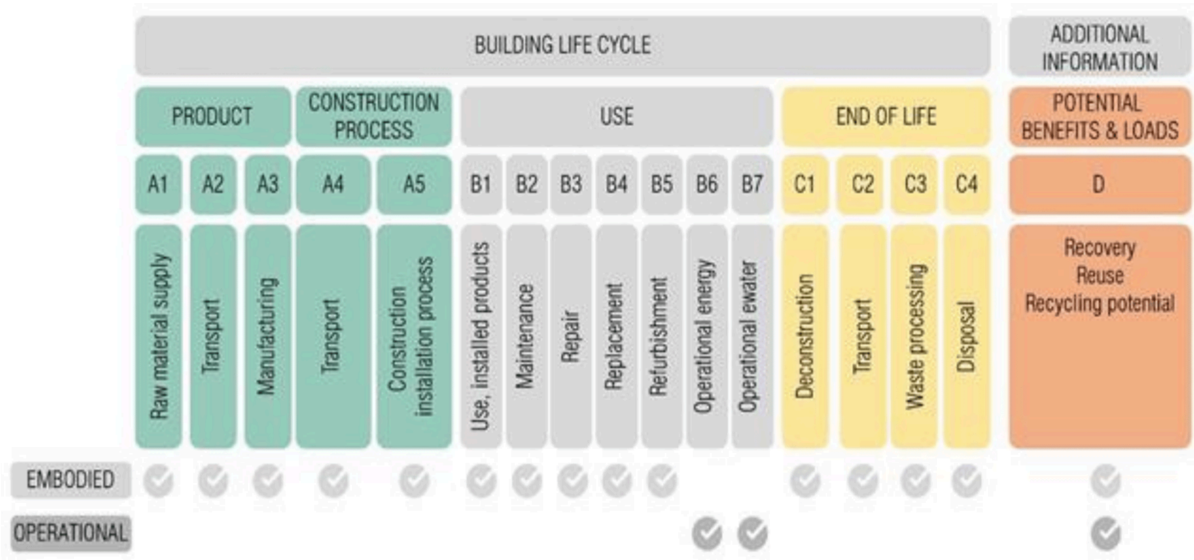

Figure 2 *Life cycle stages of buildings. The system boundaries in this study comprise stages A1 to C4 except for B6 and B7. Image taken from (Giordano et al., 2021), published under a CC BY license.*

AUAR aims at scaling into the EU and US markets. Both markets differ substantially in terms of building typology, materials used, technologies employed as well as structural characteristics and challenges faced by the industry. In the US, timber frames are the dominant building type accounting for more than 90% of new single family homes (J. Fu, 2024). Therefore, the environmental impact of AUAR depends on the market AUAR scales into (Table 2).

Table 2 *Overview of systemic changes triggered by AUAR. Parameters (rightmost column) are explained in sections 3.3.1. and 3.3.2.*

Aspect	**Market**		**Section**	**Parameter**
	EU	**US**		**in Eq. (1) and (2)**
Switch from mineral structural building materials or engineered wood to automated timber frame construction	x		3.2.1.	$aGHG_{timber}$
Switch from manual to automated timber frame construction		x	3.2.2.	GHG_{waste}, $aGHG_{worker\ trans.}$
Incentivising the use of sustainable insulation materials	x	x	3.2.3.	$aGHG_{insulation}$

3.1.1. AUAR's environmental impact in the US market

Timber frame buildings are by far the most common building type in the SFH segment. If AUAR's technology is used in the US, the avoided GHG emissions can be estimated by Eq. (1)

$$aGHG_{total,\,US} = aGHG_{waste} + aGHG_{worker\ trans.} + aGHG_{insulation} \quad \text{Eq. (1)}$$

The total avoided GHG emissions $(aGHG_{total,\,US})$ in kg CO_2-eq./m^2 are the sum of the avoided GHG emissions through more efficient material use ($aGHG_{waste}$), less transportation requirements of work forces ($aGHG_{worker\ trans.}$) and the avoided GHG emissions associated with more sustainable insulation materials ($aGHG_{insulation}$). All parameters are quantified in section 3.2. Due to the lack of data, the change in transportation requirements of materials is excluded as described in section 3.2.2.

All avoidances in GHG emissions in the US market stem from more efficient material use, more efficient construction and the use of more sustainable building materials.

3.1.2. AUAR's environmental impact in the European market

In Europe, timber frame buildings play a minor role. AUAR's technology offers timber frame buildings at competitive prices and therefore could result in a shift to more timber frame buildings. The total avoided GHG emissions in the European market can be estimated by Eq. (2).

$$aGHG_{total,\ EU} = aGHG_{timber} + aGHG_{waste} + aGHG_{worker\ trans.} + aGHG_{insulation} \quad \text{Eq. (2)}$$

The total avoided GHG emissions ($aGHG_{total,\ EU}$) in kg CO_2-eq./m^2 are the sum of the avoided GHG emissions from switching from other structural materials to automated timber frame construction.. The switch to timber construction ($aGHG_{timber}$), as discussed in section 3.2.1. does not include any automation. Thus, $aGHG_{waste} + aGHG_{worker\ trans.}$, representing the more efficient use of timber and less transportation requirements, are additional avoided GHG emissions triggered by AUAR, as discussed in section 3.2.2. Additionally, the more convenient and price competitive use of sustainable insulation materials (i.e. automation favours cellulose, instead of labour-intensive mineral insulation materials), might provoke a shift to the use of such materials ($aGHG_{insulation}$) as discussed in section 3.2.3.

3.1.3. Assessed indicator and functional unit

The system is assessed using the indicator **climate change** (Intergovernmental Panel on Climate Change (IPCC), 2014). The functional is 1 m^2 of a building (single or multi family home) with a lifetime of 50 years.

3.2. Quantification of the environmental impacts of different aspects affected by AUAR

3.2.1. Switch from mineral construction materials to timber frames

We assessed the environmental impact of switching from mineral construction materials to timber frames by using the comprehensive dataset published by Röck et al. (2022) comprising 744 individual buildings typologies. We extracted the harmonized GHG emissions of different single and multi family homes (SFH and MFH) and calculated the average net reduction in GHG emissions from switching from certain structures to timber frames (Table 3). The data harmonization ensures comparability across different studies and literature sources. The harmonization uses a reference study period (building lifetime) of 50 years and ensures consistent scopes and assignment to the different life cycle stages of a building.

The assessment shows that the shift to timber frames can result in a net avoidance of GHG emissions of 82 to 338 kg CO_2-eq. per m^2 in case of SFH and 44 to 153 kg CO_2 per m^2 in case of MFH.

Table 3 *Average life cycle and total GHG emissions of single and multi family houses (SFH and MFH). The rightmost column shows the net avoidance in GHG emissions associated with the use of timber frames instead of other structural components. The data taken from Röck et al. (2022)*.

Structure	Stage							Sum (w./o B67)		Shift to timber frames
	A123	A45	B1234	B5	B67	C12	C34	kg CO_2-eq./m^2/a	kg CO_2-eq./m^2	kg CO_2-eq./m^2
SFH										
Concrete frame	5.4	1.1	1.1		3.4	0.4	3.3	12.4	620	-133
Concrete/wood frame					1.6			16.5	826	-338
Steel frame	4.7	1.1	.01		4.8	0.3	4.4	11.4	570	-82
Wood frame	1.1	0.8	1.7		10.2	0.2	4.1	9.8	488	
Massive brick	6.2	0.8	4.4		7.5	0.2	0.2	12.2	610	-122
Massive concrete	7.8	1.1	0.7		4.1	0.4	3.1	12.1	604	-117
Engineered wood	-8.0	1.1	0.6		5.4	0.4	15.4	11.9	595	-107
MFH										
Concrete frame	6.6	1.2	0.7		6.5	0.3	20.5	12.2	608	-44
Concrete/ wood frame					6.7			12.8	641	-78
Timber frame	6.1	0.6	3.8		22.5	0.2	0.2	11.3	564	
Solid brick	8.2	1	5.1		20.6	0.3	0.3	14.3	717	-153
Solid concrete								14.2	710	-147

3.2.2. Switch from manually to automated timber frame construction

Switching to an automated timber frame construction has three main effects affecting the GHG emissions of a building:

- Increase in material efficiency,
- reduction in waste quantities,
- Less worker commuting needed.

Unused materials and off-cuts are the two most important sources of waste of on-site manual timber constructions (Osmani et al., 2006). Contractors mention offcuts and improper storing space as the two most important sources of construction waste (ibid.) In contrast, prefabricated automated frame building ensures waste minimization through more efficient use of materials and lower losses through improper storing (e.g. less exposure to the environment). Only a few studies quantify the different waste quantities in a comparable setting (Table 4).

Table 3 *Material and waste quantities of on-side manual and prefabricated timber frame buildings in China (Tam et al., 2005) and the US (Kim, 2008). The reported quantities refer to quantities of timber.*

Building type	Unit	Waste quantity	Total material quantity	Waste share	Reduction in waste
Prefabricated, Low waste value	lbs	599.00	20,561.00	2.9%	-54%
Prefabricated, high waste value	lbs	988	20960	4.7%	-26%
On-site manual	lbs	1164	18310	6.4%	
On-site manual	m^2	115000	400000	28.8%	
Prefabricated	m^2	150	2000	7.5%	-74%

To estimate potential avoided GHG emissions, we used wastes shares and waste reductions listed in Table 3 and extracted data on structural timber use and GHG intensities of structural timber production to calculate the net avoidance in GHG emissions arising from less waste (Table 4). We did not account for biogenic carbon contained in the waste because we assumed that it is released back to the atmosphere, i.e. wood waste will be burned. No further displacements (e.g. by producing energy from the wood waste) are considered. We defined a minimum, maximum and base case scenario based on literature values on structural timber use, GHG intensities and waste quantities and reductions (as reported in Table 3). We excluded biogenic carbon uptake to only account to the avoided emissions associated with the production of the material that is wasted (if incinerated, biogenic carbon is released back to the atmosphere). **Our estimates show that increased material efficiency can avoid between 0.1 and 4.8 kg CO_2-eq. per m^2** (Table 4)**.**

Table 4 *Waste share, waste quantity, timber quantity and GHG intensity of structural timber production. Waste share taken from Table 3, structural timber quantities taken from (Eslami et al., 2024; Röck et al., 2022), GHG intensities extracted from the econinvent database and scientific literature (Eslami et al., 2024; Wernet et al., 2016). The timber quantities refer to a SFH. No data on MFH was found in literature. The minimum and maximum values present the minimum and maximum values found in literature. The medium/base case is a hypothetical scenario using the average GHG intensity of structural timber production and structural timber quantities. All other values in this scenario are chosen based on the minimum and maximum values.*

	Unit	Min	Max	Medium/Base case
Waste share on-site	%	6%	29%	10%
Waste reduction	%	24%	74%	50%
Structural timber use	kg/m^2	77.1	164.2	119.4
Waste from structural timber use	kg/m^2	1.2	34.9	6.0
Avoided GHG emissions				
Structural Timber Frames	kg CO_2-eq./m^2	0.1	4.8	0.8

In addition to the reduction in waste materials, automation reduces the amount of material that needs to be transported and the number and/or distances of worker commuting. We evaluated scientific literature assessing the effect of modularization on transport requirements to understand the magnitude of the effect (Table 5). Only two studies assessed timber frame buildings. **The studies show that the prefabricated modules reduce worker commuting (km, pkm or GHG emissions) by 73 to 95%. The net reduction in GHG emissions reported is 8.8 t CO_2-eq./SFH or 101 kg CO_2/m^2 in a study comparing modular and on-site timber construction in the US** (Kouhirostami, 2023). This value compares a modular building and on-site construction. AUAR offers a pre-fabricated approach where frames and walls are pre-assembled in a central location, whereas final assembly and further construction is accomplished on-site. Therefore, the net reduction in worker commuting is likely to be smaller than in the reported values. The studies report on transportation of materials, too. Yet, since most materials (foundation, installations, roof, etc.) will still be transported to the construction site individually, we do not use these values to estimate the net reduction in material transportation needs. Due to the lack of information this is excluded from this study.

Table 5 *Worker commuting and transportation requirements of conventional and pre-fabricated buildings covering studies from Poland (Tavares et al., 2021), the US (Kouhirostami, 2023; Kim, 2008) and China (Du et al., 2019). Note: The impact on transportation requirements is very much case dependent as it depends on the local conditions (location of factories, prefabrication sites, workers commute distances. Table 5 includes concrete buildings, too. These building types are included to show the general trend of effects on transportation needs. Abbr.: CN - China, PT - Poland, US - United States.*

Aspect	Unit		Prefabricated	Conventional	Net reduction	Compared buildings	Geography
Worker commuting	pkm		12833	20167	-36.4%	Prefabricated timber frame vs. on-site concrete	PT
	km		2817	10588	-73.4%	Timber frame; modular vs. on-site	US
	kg CO_2-eq./house		1631	10460	-84.4%	Timber frame; modular vs. on-site	US
	miles	Min	1995	24000	-91.7%	Timber frame; modular vs. on-site	US
	miles	Average	1995	31500	-93.7%	Timber frame; modular vs. on-site	US
	miles	Max	1995	40000	-95.0%	Timber frame; modular vs. on-site	US
Total transportation	kg CO_2eq/m^2	Min	2.69	2.82	-4.3%	Concrete; modular vs. conventional	CN
	kg CO_2eq/m^2	Average	2.76	2.81	-1.8%	Concrete; modular vs. conventional	CN
	kg CO_2eq/m^2	Max	2.85	2.81	1.4%	Concrete; modular vs. conventional	CN

3.2.3. Use of other, more sustainable insulation materials

AUAR's tools and robots allow the design of open and closed panels. Projects developed by AUAR with customers demonstrated that AUAR achieves cost competitiveness while using sustainable insulation materials. AUAR developed a passive house with bio-based insulation materials and achieved a price reduction of ca. 30% per square feet compared with a standard timber frame building with PUR/PS insulation. The use of automated construction systems and increasing pressure on construction companies because of shrinking labour force further increase the attractiveness of insulation materials that require less manual work, e.g. cellulose. In addition to economic aspects, policy and regulation plays an important role in promoting the use of suitable insulation materials. In many US federal states (e.g. California, New York State, Washington State, Massachusetts, Vermin, Oregon and Colorado), as well as on federal level (e.g. US Department of Energy's Zero Energy Ready Home Program), programs and legislation are in place. While the ultimate decision on material selection rests with the project developer, builder or architect, legislation and the cost competitiveness of AUAR's tools are likely to support the transition towards more sustainable insulation materials.

Füchsl et al. (2022) provide a very comprehensive comparison of LCA studies on different insulation materials. The review demonstrates that cellulose insulation generates substantially lower GHG emissions than all fossil-based insulation materials and most other bio-based materials (Figure 3).

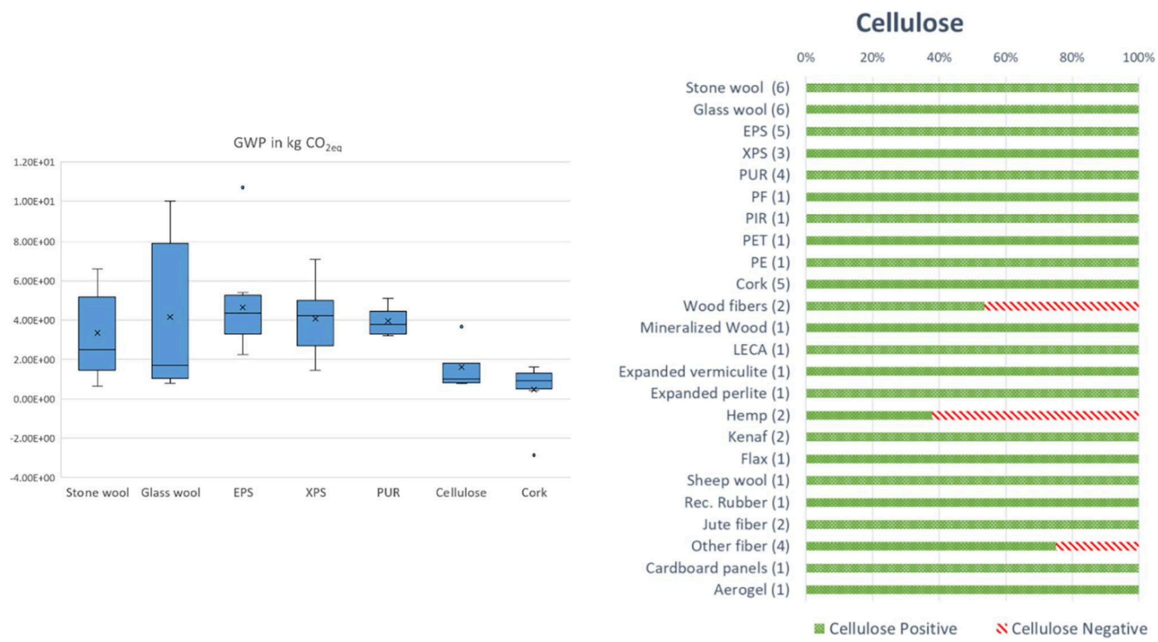

Figure 3 *Left: GHG intensity of different building material in kg CO_2-eq. per mass of insulation in kg to achieve 1 R over 1 m^2, where R is the thermal resistance. Right: comparison of different insulation materials and cellulose. The number in parentheses indicates the number of values compared against cellulose. Provided by Füchsl et al. (2022), licensed under a CC BY license.*

To estimate the net benefit of using cellulose over other insulation materials in accordance - based on the functional unit defined in this study (1 m^2 floor area) - the target heat transfer coefficients (U value) of walls and roofs are set for 0.18 and 0.11, respectively (Stewart, 2023). The resistance (R) is the inverse of U. Additionally, we extracted the wall-to-floor and the roof-to-floor ratios from a sample of 36 European SFH and MFH reflecting typical building typologies in European countries (Table 6). These values reflect the wall and roof areas per m^2 of floor area.

Table 6 *Wall-to-floor and roof-to-floor ratios of SFH and MFH. Data extracted from a sample of 36 representative buildings in Germany, Denmark, Great Britain, Netherlands and Italy. Data extracted from datasets provided by (Loga et al., 2016; EPISCOPE Project, 2016)*

	SFH		MFH	
	wall-to-floor	roof-to-floor	wall-to-floor	roof-to-floor
Min	0.68	0.35	0.26	0.23
Max	1.83	1.31	1.46	0.63
Average	1.08	0.78	0.74	0.40

By multiplying the GHG intensity per mass to achieve 1 R over 1 m^2 (roof or wall area, data extracted from Figure 3 with a plot digitizer (Table A.1 in the Annex)) by the resistance (R) and the wall-to-floor and roof-to-floor area ratios, the resulting GHG emissions for different insulation materials can be estimated per m^2 of floor area. Table 7 shows the net avoidance in GHG emissions by substituting mineral insulation materials with cellulose (wall and roof insulation combined).

Table 7 *Net avoidance in GHG emissions associated with using cellulose insulation (wall + roofs) instead of the listed insulation materials in kg CO_2-eq./m^2 floor area. The minimum and maximum GHG intensities used correspond to the first and third quartile shown in the boxplots in Figure 3. Min. and max. values express the smallest and highest net avoidances in GHG emissions, respectively.*

	SFH			MFH		
Material	**Min**	**Max**	**Average**	**Min**	**Max**	**Average**
Stone wool	-4.3	-73.4	-22.6	-2.2	-34.0	-13.4
Glass wool	-1.7	-134.1	-33.7	-0.8	-62.7	-25.8
EPS	-17.1	-75.6	-39.5	-8.6	-41.4	-25.8
XPS	-12.8	-69.6	-32.0	-6.5	-39.2	-25.8
PUR	-17.1	-57.7	-30.2	-8.6	-41.9	-39.2
All	-1.7	-134.1	-31.6	-0.8	-62.7	-26.0

3.3. Quantification of AUAR's environmental impact in different markets

AUAR is likely to generate various systemic impacts depending on the markets in which AUAR's technology is applied (Table 2, Section 3.1). In the US, where timber frame buildings are the dominant type of buildings, automation has different effects compared to Europe, where timber frame construction is less common. Hence, the net avoided GHG emissions in both geographies differ (Figure 4):

- **In the EU,** the net avoided emissions range from 185 to 590 kg CO_2-eq./m^2 and 146 to 333 kg CO_2-eq./m^2 in case of SFH and MFH, respectively. The average net avoidance is 291 and 241 kg CO_2-eq./m^2 in case of SFH and MFH. Using the average floor area of SFH in the dataset provided by Röck et al. (2022), 152 m^2 (SFH) and 1044 m^2 (MFH, up to 4 storeys above ground), these values translate into net avoidances in GHG emissions of 44 and 252 t CO_2 per SFH or MFH. The major share of avoided GHG emissions of SFH stems from the switch to timber frames replacing other structural materials, such as concrete, steel or bricks (51%). The remainder comes from less transportation of work forces (37%) insulation (11%) and more efficient material use (1%). In the case of MFH, the shift to different materials accounts for 44% of avoided GHG emissions, worker transportation for 45%, insulation for 11% and material efficiency for less than 0.5%.
- **In the US,** the net avoided GHG emissions range from 102 to 252 and from 102 to 181 kg CO_2-eq./m^2 in case of SFH and MFH, respectively. The average net avoided GHG

emissions amount to 141 and 135 kg CO_2-eq./m^2 in case of SFH and MFH. The average SFH measures 218 m^2 in the US (U.S. Census Bureau, 2024). A reasonable MFH[1] built by AUAR is 1472 m^2. Thus, AUAR's technology can avoid on average 31 tonnes of CO_2 per SFH and 200 tonnes per MFH in the US. Without replacement of other structural materials, the largest contribution comes from reducing worker transportation (77% in case of the SFH and 80% in case of the MFH). Insulation accounts for 22 and 19%.

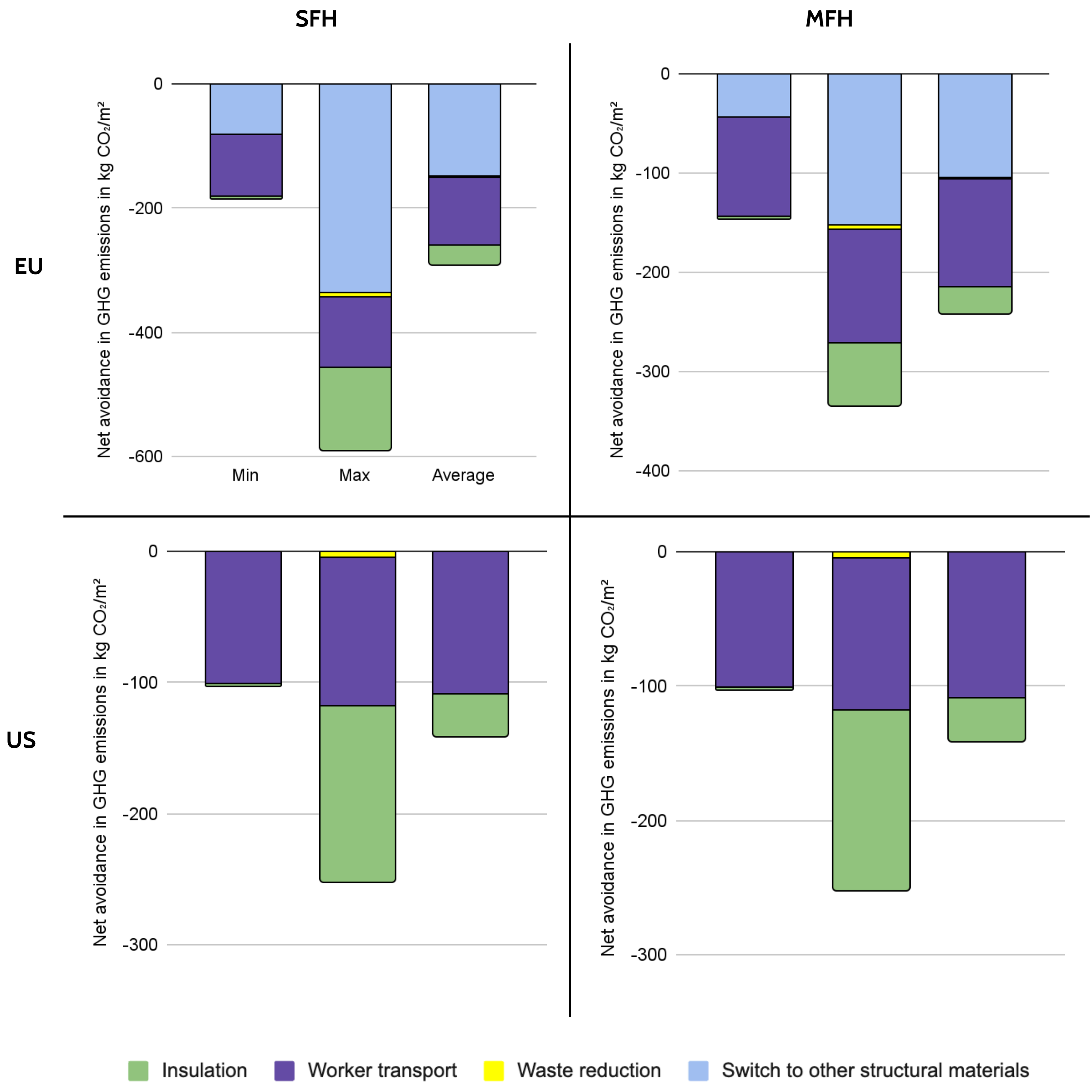

Figure 4 *Net avoided GHG emissions by using AUARs technology in the EU and US.*

[1] No data on the size of MFH in the US was found. Therefore we approximate the size: The average sold housing unit in a US MFH is 92 m^2(U.S. Census Bureau, 2024) . This translates into a size of 1472 m^2 assuming 4 storeys and 4 units per storey.

There are a few important considerations to interpret these results:

- AUAR offers a price competitive alternative to conventional building materials and insulation materials. The decision to choose more sustainable materials is supported by AUAR's offering, a shrinking and ageing workforce, changing regulations and political measures to promote the use of more sustainable materials. Ultimately, the final decision regarding the design and specifics of a building lies with the owner, architects and contractors. They could still choose less sustainable materials, e.g. an AUAR-designed and built timber frame combined with a mineral or fossil-plastic based insulations. In such a case, the avoidance of a change in insulation materials must be omitted.

- We did not include operational GHG emissions and assumed similar insulation properties of buildings to allow a fair comparison. If AUAR offers higher quality insulation at lower costs, buildings constructed using AUAR's approach could potentially achieve further reductions in energy demand.

- AURA-designed buildings use a breathable wall buildup, potentially extending the lifetime of buildings compared with conventional timber frame buildings.

- We did not consider any benefits beyond the system boundaries (section 3.1). Once the end of life of a building is reached, different options arise. Materials could be re-used, incinerated (to produce energy), converted into other products or stored in vaults for long-term carbon storage. Each option brings additional benefits: Material use, conversion or energy production will replace some other materials, avoid the production of such materials or replace a certain type of energy supply. This will be far in the future (assuming a lifetime of at least 50 years). If biobased materials are stored in vaults, long-term carbon storage can be achieved. Such systems are not in place yet. We therefore exclude these effects from the assessment. Including these effects would result in an even higher net avoidance attributable to AUAR.

- The shift from less sustainable to more sustainable building materials is a result of many decisions and activities. Market participants, e.g. insulation material manufacturers, or property owners, architects and others decide which techniques and materials to use. Therefore, all of them collectively drive the transformation in the built environment. AUAR plays a central role in this transformation and provides the core technology to enable automated timber frame constructions at scale. The net avoidance of GHG emissions is the result of the collective and systemic shift to more sustainable building practices.

- These results presented are based on the average values of different structural materials, e.g. the average GHG intensity of steel frame SFH in the dataset provided by Röck et al. (2022). The minimum and maximum scenarios presented in Figure 4 are based on the highest and lowest difference between these average values. The use of the lowest and highest values in the datasets result in much larger net avoidances and net increases. For example, the shifting from steel frames with the highest GHG intensity to timber frames with the lowest GHG intensity avoids 900 kg CO_2-eq./m^2. Likewise, switching from the lowest impact concrete building to the highest impact timber frame building increases emissions by 55 kg CO_2-eq./m^2. These values present extreme outliers in the dataset (see ranges listed in Table 1). To avoid drawing conclusions from extreme outliers, we decided to use the minimum and maximum averages to calculate the minimum and maximum scenarios.

3.4. Carbon dioxide uptake, release and modelling of carbon balances

Biogenic materials, such as timber, sequester carbon dioxide from the atmosphere during their growth. This inherent carbon storage capacity makes them potentially valuable in mitigating climate change when used in construction. However, the carbon balance of these materials is complex and involves several dynamic processes, e.g.:

- Biomass sequesters carbon dioxide from the atmosphere through photosynthesis. The use of bio-based materials converts trees or other biomass into building materials that retain carbon.
- Once the end of life of a building is reached, the carbon stored in the building material might be released back into the atmosphere, if materials are incinerated or decomposed. Alternatively, materials could be stored for centuries to provide a long-term carbon sink (Zeng et al., 2024).
- Timber harvesting can lead to a temporary decrease in forest carbon storage as trees are removed and soil organic carbon might decrease. New trees draw carbon dioxide from the atmosphere to sustain growth. The carbon uptake and quantity of carbon stored depends on the tree age (Figure 5). Litter and deadwood from trees decompose and feed the soil organic carbon pool. Changes in forest management practices and harvesting intensity can significantly impact the balance between carbon sequestration and release, influencing the overall climate benefits of using wood (Part II).

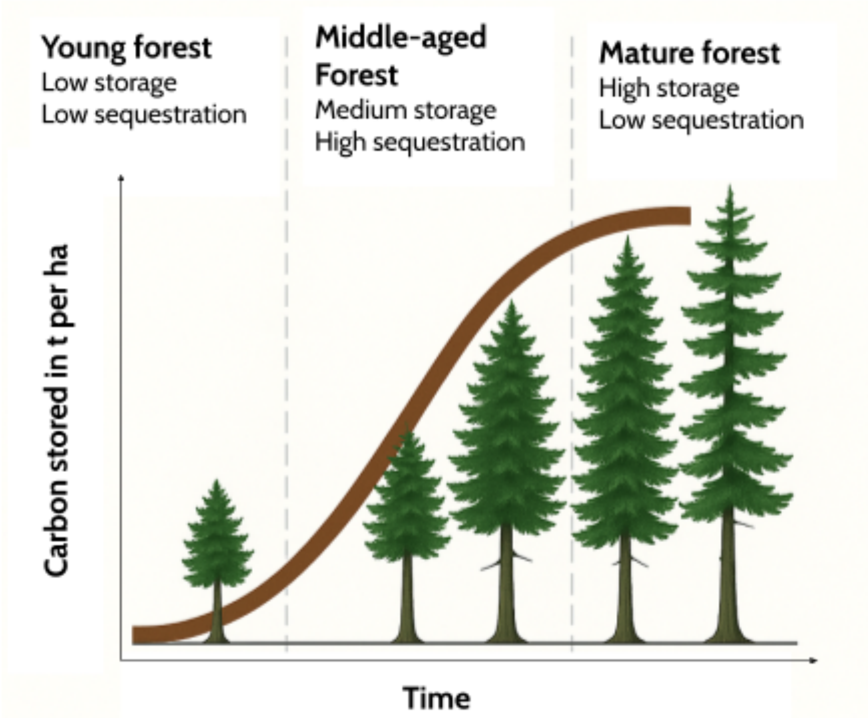

Figure 5 *Schematic depiction of carbon storage in forests.*

Modelling carbon sequestration and temporal carbon storage is a widely discussed topic among LCA practitioners and researchers. There are many different approaches to account for temporal storage. The most simplistic approach is to use a static approach where carbon uptake is considered as - 1 and released carbon dioxide as 1 kg CO_2 per kg CO_2 stored in biomass. This approach does not account for any temporal storage. This is by far the most common approach applied in LCAs and GHG assessments.

Alternatively, dynamic approaches seek to cover the temporal dynamics of carbon sequestration and release, as well as the temporal impact on climate change or GHG emissions. The indicator global warming potential (GWP) includes a time horizon, most commonly 100 years (GWP_{100}). Figure 6 displays the fraction of a pulse emission that remains in the atmosphere over a time horizon of 200 years. After 100 years, about 33% remain in the atmosphere. Therefore, there is a difference in the GWP between annually emitting 1 kg CO_2 over a period of 100 years or a pulse single emission of 100 kg CO_2 in year 1. In the latter case, the climate forcing exerted by the pulse emission is the integral below the graph in Figure 5. In case of annual emissions of 1 kg of CO_2 over a 100 year period, the climate impact over these 100 years is smaller. E.g, the 1 kg CO_2 emitted in year 99 only contributes to 1 year (considering the 100 year time horizon).

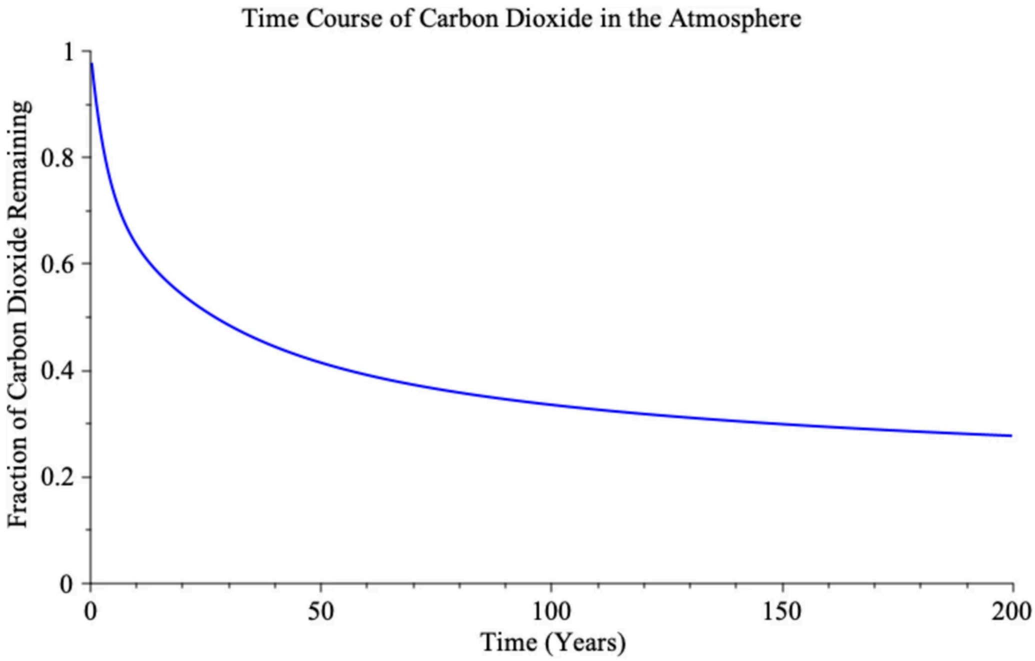

Figure 6 *Fraction of carbon dioxide remaining in the atmosphere after a pulse emission in year 1 according to the Bern Carbon model (Joos et al., 2013). Graph taken from (Marland et al., 2025), published under a CC BY 4.0 license.*

With regards to bio-based building materials, this is relevant because carbon dioxide is stored in a building and then potentially released into the atmosphere after the end of life of a building. Using the most common metric GWP_{100}, the release of carbon dioxide after 50 years contributes less to climate change over the 100 year period starting from the time when the carbon dioxide was stored in the tree or when the building was built (Figure 7). Scientific studies show that taking such temporal dynamics into account lowers the potential climate impact of carbon dioxide, cf. (Marland et al., 2025; Andersen et al., 2024; Buchspies et al., 2020). It should be noted that this temporal benefit might be compensated by changes in carbon dioxide uptake and loss in forests originating from timber extraction (see Part II and literature cited therein).

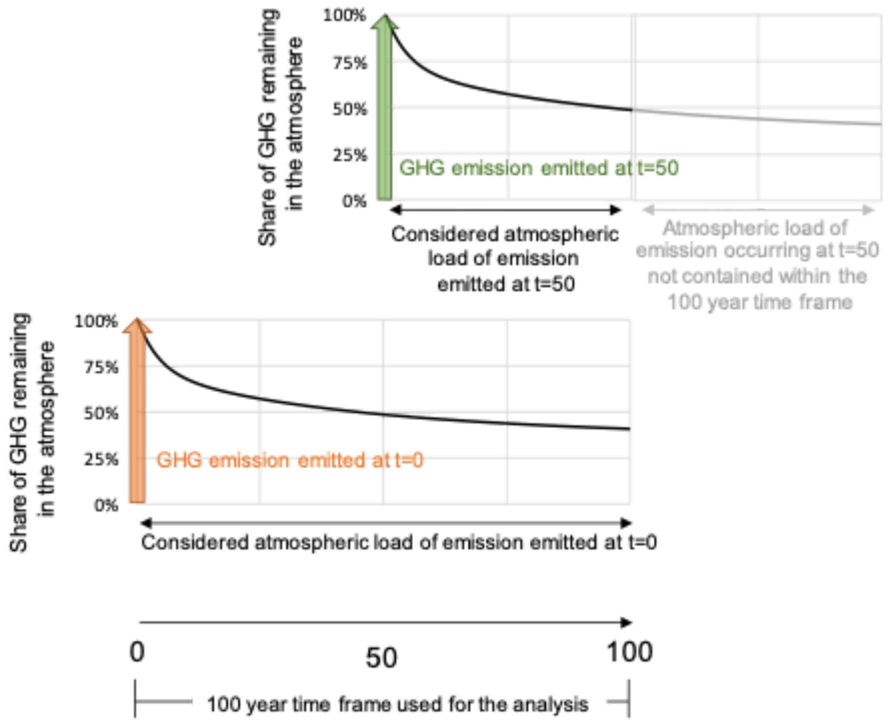

***Figure 7** Schematic depiction of the influence of time and time horizons in studies using GWP_{100}. Graph taken from (Buchspies et al., 2020), published under a CC BY license.*

On the studies used in this paper: The studies reviewed in Füchsl et al. 2022 that we used to model the impact of insulation contains dynamic and static approaches. Röck et al. (2022) and all other studies and values considered use a static approach.

3.5. Limitations

The assessment is subject to important limitations

- **System boundaries, methodology and data:** The results of LCAs of buildings and building materials are strongly dependent on methodological choices, system boundaries and data. We used review studies whenever possible to cover the best possible range of methodological choices and data used. The two most important studies used in this assessment, Röck et. al. (2022) and Füchsl et al. (2022) harmonize hundreds of LCA studies and individual values to make them as comparable as possible. We used these studies as they provide harmonized datasets. It should be noted that we seek to apply a consequential LCA perspective, meaning that we seek to assess the change in environmental impacts. This is best accomplished using datasets based on consequential LCA methodology. Unfortunately, there is only a very limited number of consequential LCA studies on building materials. To cover the wide range of scenarios and conditions possible, we decided to use the abovementioned review papers comprising hundreds of values instead of relying on a very limited number of consequential LCA studies.
- **Data limitations:** Unfortunately, data was unavailable in certain cases, requiring us to rely on a limited number of data sources or assumptions, e.g.,

- Very few studies assess the reduction in workforce transportation. We used studies from the US that collected primary data from construction sites. The data is therefore representative of very specific cases. Due to the lack of other studies, this information was used for all other cases assessed in this study, too. The lack of such information indicates that almost no LCA study considers the transportation of the workforce. Thus, GHG intensities of different buildings that are replaced by AUAR (Table 1 and Table 3) would be even higher, if this is taken into account.
- The GHG intensity of building materials is predominantly from Europe.
- The GHG intensities of building materials and insulation materials vary substantially, see Table 1 and Figure 2.
- We extrapolated the use of insulation material in a simplistic way. The required insulation depends on many factors but the assessment of many different building types and design choices exceeds the scope of this work. We therefore emphasize the fact that the quantity of insulation material needed is a rough estimate.

- **Linear scaling:** We scaled impacts per m^2. Most commonly, emissions are reported per m^2 or per m^2a. We linearly scaled these impacts to the building sizes. In reality, not all impacts scale linearly, e.g. worker transportation is likely to not scale linearly.
- **Temporal dynamics:** Most values used in this study do not account for temporal dynamics (section 3.4). Accounting for a delayed release of carbon dioxide provides additional benefits in terms of climate change within a fixed time horizon. The inclusion of such temporal dynamics would result in even more beneficial impacts of AUAR. Yet, temporal dynamics of carbon pools in forests might need to be taken into account, too. The impact of the alteration of carbon pools in forests is discussed in literature cited in Part II.

4. Conclusion

AUAR's automated timber frame construction solution offers significant potential for reducing greenhouse gas (GHG) emissions in the building sector. In the European market, where timber construction is less prevalent, the shift to AUAR's technology can lead to substantial GHG reductions, primarily by replacing more carbon-intensive materials like concrete and steel. The average net avoidance is estimated at 291 kg CO_2-eq./m^2 for single-family homes (SFH) and 241 kg CO_2-eq./m^2 for multi-family homes (MFH). In the US market, where timber frames are already dominant, the benefits come from increased material efficiency, reduced workforce transportation, and the incentivization of sustainable insulation materials, resulting in average net avoidances of 141 kg CO_2-eq./m^2 for SFH and 135 kg CO_2-eq./m^2 for MFH.

The study highlights the importance of considering regional market differences and system-wide impacts when assessing the environmental benefits of new construction technologies. While the shift to timber frames provides significant carbon storage and material substitution benefits, sustainable forest management and efficient timber use are critical to ensure long-term sustainability. AUAR's approach, which combines automation with design optimization, promotes resource efficiency and reduces waste, contributing to overall environmental performance. Despite limitations in data availability and methodology, the assessment provides a comprehensive overview of the potential environmental benefits of AUAR's technology.

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A. Annex

Table A.1 *GHG intensity of different insulation materials in kg CO_2-eq. per mass of material required to achieve 1 R over 1 m^2 extracted from Füchsl et al. (2022) using a plot digitizer. Minimum and maximum values correspond to the first and third quartiles, respectively.*

Material	Min	Median	Average	Max
Stone wool	1.5	2.5	3.3	5.1
Glass wool	1.1	1.7	4.2	7.9
EPS	3.3	4.3	4.6	5.2
XPS	2.7	4.2	4.0	4.9
PUR	3.3	3.7	3.9	4.4
Cellulose	0.8	1.0	1.6	1.8

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