

PAPER • OPEN ACCESS

Towards a net-zero, whole-life carbon trajectory for the EU building stock

To cite this article: N Alaux *et al* 2025 *IOP Conf. Ser.: Earth Environ. Sci.* **1554** 012127

View the [article online](#) for updates and enhancements.

You may also like

- [A State of Play Review of Methods to Define Net Zero Carbon Buildings](#)
V Gomes, P Schneider-Marín, M Roberts et al.
- [Evaluating the sustainability of the bahareque construction technique using environmental and social Life Cycle Assessments \(e-LCA and s-LCA\): a case study on a minimum house in Ecuador](#)
C E Gómez-Camacho, J S Martínez, M M Capelli et al.
- [Natural Ventilation in Public Housing: Comparing Practice with Singapore's Green Building Standards](#)
K Zheng, S Chng, S Chan et al.

Towards a net-zero, whole-life carbon trajectory for the EU building stock

N Alaux¹, D Steinberger-Maierhofer¹, N Bechstedt¹, D Ramon², X Zhong^{3,4},
A Mastrucci³, M Röck², K Allacker² and A Passer^{1*}

¹ Institute of Structural Design, Graz University of Technology, Graz, Austria

² Department of Architecture, KU Leuven, Leuven, Belgium

³ Energy, Climate, and Environment (ECE) Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

⁴ Institute of Environmental Sciences (CML), Leiden University, Leiden, The Netherlands

*E-mail: alexander.passer@tugraz.at

Abstract. To achieve climate neutrality by 2050, anthropogenic greenhouse gas (GHG) emissions must be reduced to net-zero. Due to its high contribution to global GHG emissions, addressing the built environment is a critical step to reaching this target. This study aims to determine the extent to which GHG emissions from the European Union's (EU) building stock can be reduced by 2050 and which carbon removal measures are required to achieve net-zero whole life cycle emissions. Two future scenarios are assessed via bottom-up, life cycle assessment-based building stock modelling to project GHG emissions of buildings in the EU from 2020 to 2050. The first scenario represents a business-as-usual approach, while the second includes additional GHG emission reduction strategies targeting material production, selection, recycling, energy efficiency, as well as other supply- and demand-side changes. Carbon dioxide removal technologies are investigated to offset the residual GHG emissions. Results of this measure-driven modelling show that the life cycle GHG emissions of the EU building stock have the potential to be reduced by up to 72% by 2050, with residual GHG emissions of around 229 MtCO₂eq in 2050. To completely offset residual emissions with currently available technologies, all new building constructions would have to be equipped with additional direct air capture technologies, starting from 2030. Feasibility concerns regarding this technology emphasize the importance of stronger action on initial decarbonization measures.

1. Introduction

Achieving net-zero emissions is a critical goal outlined by the Intergovernmental Panel on Climate Change (IPCC) to mitigate the impacts of climate change [1], particularly in the building sector, which is responsible for 21% of global greenhouse gas (GHG) emissions [2]. To limit global warming to 1.5°C, the IPCC emphasizes that CO₂ emissions must stay under the remaining carbon budget and CO₂ emissions must reach net-zero by 2050 [1], necessitating substantial reductions in emissions across all sectors, especially in the buildings and real estate sector. To reach this goal, the European Union (EU) is aiming to reduce its GHG emissions by 55% by 2030 and be climate neutral by 2050 [3]. This requires fundamental changes with consideration to both operational emissions (use phase of buildings) and embodied emissions (production,



Content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

construction, maintenance, renovation, and end-of-life phases of the building materials). Therefore, comprehensive policy measures have been implemented to reduce the life cycle GHG emissions of the European building stock. Various strategies are being promoted that are believed to enable emission reduction and removal (e.g., negative emission technologies) from buildings. However, the potential of these strategies to reduce, avoid, and remove emissions across the whole-life cycle of buildings remains unknown.

Environmental modelling of building stocks offers a structured way to analyze the evolution of buildings over time and assess their environmental impacts across various life cycle stages [4]. By capturing changes in building stocks, flows, and turnovers—through construction, renovation, and demolition—these models help estimate future material and energy demands, as well as associated emissions. This enables a comprehensive evaluation of how different strategies reduce both operational and embodied emissions, while also identifying the extent to which additional carbon removal measures are needed to reach emission reduction targets. Using a recently developed building stock model based on the PULSE concept [5], which combines dynamic material flow analysis and prospective life cycle assessment (LCA), this study aims to determine the extent to which GHG emissions from the EU buildings can be reduced in 2050, as well as the required scale of carbon removal measures to offset the residual emissions and achieve net-zero.

The net-zero concept of a building stock is defined as the balance between anthropogenic GHG emissions and sinks [6]. In Figure 1 we represent this concept as it would be applied at building stock level. For every time period, buildings in the stock might be in different phases of their life cycle (construction, operation, renovation, demolition). As a result, there is a constant flow of operational and embodied emissions. The cumulative sum of GHG emissions (operational and embodied) from 2020 to 2050 needs to stay within the remaining carbon budget until 2050, and once it is exhausted, emissions must remain net-zero. Considering that there will be hard-to-abate remaining emissions (also known as residual emissions), the deployment of active carbon removal technologies will be needed to offset them, which is what we investigate in this study.

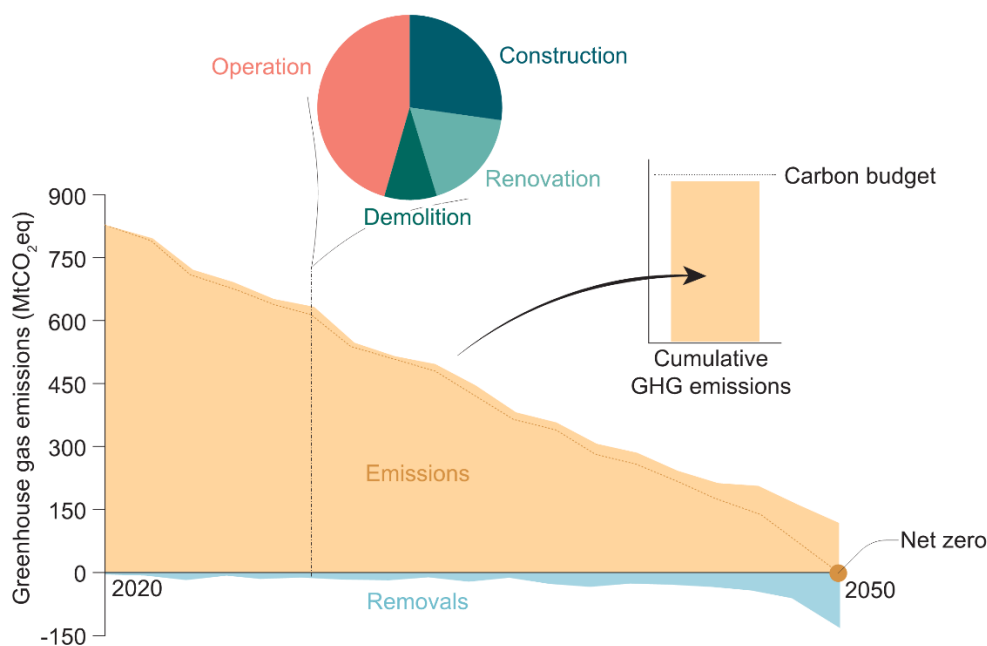


Figure 1. Graphical representation of the net-zero concept applied to the EU building stock.

2. Methods

2.1. Overview

We use a bottom-up, archetype-based building stock model (PULSE-EU), developed using the PULSE logic [5] with the MMG-SLiCE model [7] to project the life cycle GHG emissions of the EU27 building stock from 2020 to 2050. We apply ten ambitious strategies to reduce GHG emissions, considering all dimensions of the avoid, shift, and improve framework, to project their effect in a main scenario. We then explore which carbon removal strategies would be needed to offset the hard-to-abate, remaining emissions in 2050.

2.2. Building stock characterization and aggregation

The existing building stock is characterized using an archetype-based, bottom-up approach. Archetypes are typically developed through statistical analysis to reflect the diversity in building age, size, construction practices, equipment, appliances, behaviors, and emission profiles. To define the EU building stock, representative archetypes are created at the Member State level, clustering buildings based on sector (residential or service), building type (e.g., single-family house, office), and construction period. These archetypes represent buildings as they currently exist, whether as originally built or after renovations. A total of nine building types are modelled, including residential (single-family houses, multi-family houses, and apartment blocks) and non-residential (offices, trade, education, health, hotels and restaurants, and other non-residential buildings). The defined archetypes align with the classification used in the Building Stock Observatory (BSO) [8], the most advanced and up-to-date framework in the EU. Geometrically, the existing building stock is represented by 66 building archetypes per EU Member State, resulting in a total of 1,782 archetypes. Including variants in technical systems, this leads to 4,493 archetypes. The existing building stock is characterized by its total useful floor area, which is taken from the BSO for different building archetypes, as shown in Figure 2.

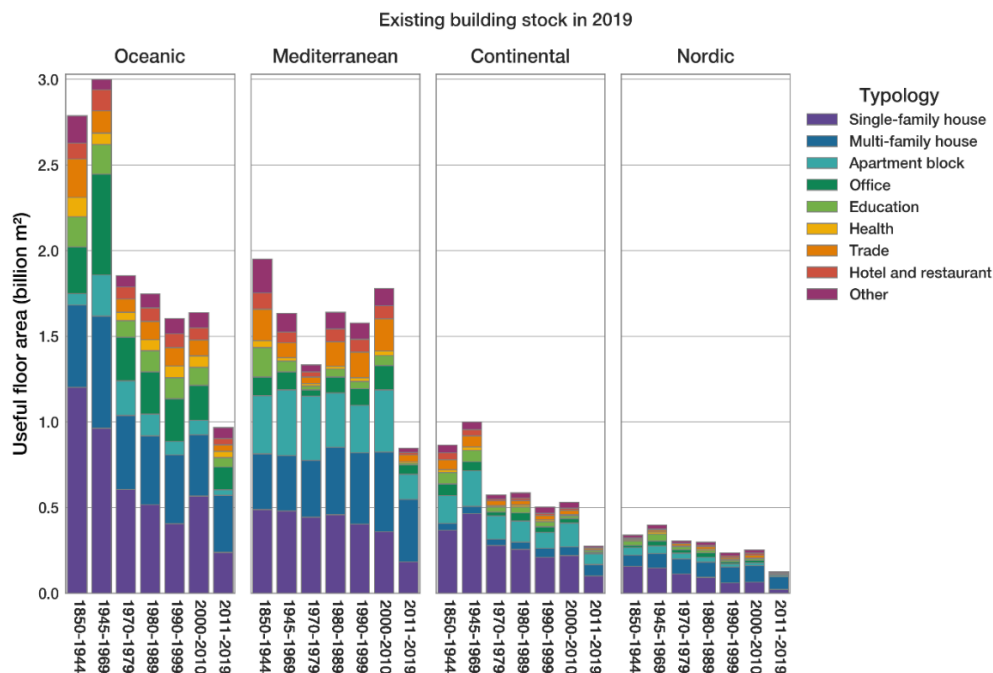


Figure 2. Characterization and aggregation of the EU building stock for the year 2019. While the countries are aggregated as climatic regions for this overview, the aggregation in the model is country-dependent, e.g., the building stocks of all 27 EU Member States are separately modelled.

2.3. Life cycle assessment

Building archetype inventory and life cycle modelling are carried out using the SLiCE data model through coupling with the MMG+ KU Leuven LCA tool. The inventories are developed using a modular life cycle approach based on EN 15978, with a hierarchical method for building decomposition. This approach organizes the modelling from the building level down to the material level. The SLiCE framework enables a detailed analysis of environmental hotspots, offering insights into the timing of emissions across different life cycle stages. It also provides in-depth information on the contribution of materials at various levels—building, element, and work-section. For LCA, we use the MMG-SLiCE model to evaluate whole life carbon emissions and carbon removals, in line with the EN 15978 [9] and EN 15804+A2 [10] standards. The life cycle inventory (LCI) data are based on generic LCI data from ecoinvent 3.6 [11] assessed with the MMG impact assessment method. The building archetypes are assessed using a reference study period (RSP) of 50 years. National scenarios for transport and end-of-life waste treatment have been defined at the Member State level. The B-PCR [12] serves as a structure for these scenarios, and a literature review has been conducted to define values on a national level. Similarly, replacement rates of building elements and building components are established on a national level based on a literature review.

A prevailing topic of GHG removal for buildings is the use of bio-based materials, i.e., wood, in order to store atmospheric carbon into the long-lasting products of the buildings in a building stock. In this context, on stock level, the approaches for GHG accounting defined by the IPCC are prevailing, which allow for an inflow of wood into the so-called harvested wood product pool (HWP) to be accounted for as a GHG sink and an outflow of wood into this HWP as a GHG source—accounted for as inflows and outflows in a specific year. In this sense, accounting for the biogenic GHG fluxes on stock level, the modelling approach is most closely related to the so-called atmospheric flow approach, which aims at quantifying the actual fluxes from and to the atmosphere occurring within national boundaries—in this case, the EU27 Member States.

2.4. Building stock development

The upscaling of building archetype data to establish a baseline for the building stock, along with the modelling of future scenarios for building stock development until 2050, is performed with the PULSE-EU building stock model (v1.0). This model expands upon the foundational PULSE-AT model [5], extending its scope to cover all EU27 countries. Using this data, the PULSE-EU model projects future building stock activities, including new construction, maintenance, renovation, replacement, and demolition from 2020 to 2050. These activities are then linked to carbon emission data derived from the MMG-SLiCE model [7]. Both the building stock activities and emission data are influenced by scenarios that include carbon reduction and removal strategies, the implementation of which is further detailed in the following sections.

2.5. Scenario modelling and carbon reduction strategies

Two future scenarios are applied to project the GHG emissions from 2023 to 2050. The first one, “business-as-usual (BAU)”, is a projection of the past activity rates until 2050 and is only affected by population development. There is no implementation of any strategies. This scenario is purely theoretical and serves as a counterfactual reference for comparing the impact of the second scenario on emissions reduction. The second scenario, “Net-zero trajectory (NZE)”, considers the implementation of ten key strategies that were previously identified to reduce the life cycle embodied GHG emissions of buildings in the EU, based on literature review and stakeholder consultation [13]: 1) prioritize better use, renovation, and repair over demolition and new

construction; 2) reduce the per capita space demand; 3) optimize the use of materials; 4) increase circular material use; 5) increase the use of bio-based materials; 6) reduce emissions from traditionally high impact construction materials; 7) reduce emissions from the transport of construction materials; 8) reduce emissions from the construction site; 9) reduce operational GHG emissions, and; 10) reduce construction and demolition waste. These strategies are implemented in the following ways:

- The potential diffusion of each strategy is quantified for three key decades (2030, 2040, and 2050) according to three levels of ambition (low, medium, and high). For example, the reduction of per capita space demand is estimated to be 20% lower in 2050 as compared to 2020 with a high ambition level [14].
- The capacity of EU Member States to implement these strategies is also qualitatively assessed according to the low, medium, and high approach. For instance, while Austria might have a high capacity to implement a specific strategy in 2040, Portugal might only have a medium capacity, and vice-versa. This allows for consideration of local conditions within the scenario modelling. They were defined by analyzing suitability condition criteria (e.g., roundwood production in the case of bio-based materials) and discussing them with stakeholders.
- Each quantitative diffusion number of each strategy is then matched with the capacity of each Member State (e.g., a low diffusion number with a low capacity), creating one scenario in which each Member State implements each strategy to their maximum capacity, therefore being ambitious while also respecting local conditions and limits.

3. Results and discussion

3.1. Carbon emission trajectories of the scenarios

The annual life cycle GHG emissions of the EU building stock from 2020 to 2050 are represented in Figure 3 (aggregated for the EU) and in Figure 4 (disaggregated per climatic region). While the BAU scenario is shown as a dashed line, the NZT scenario is divided per life cycle stage. Results show that the life cycle GHG emissions of the EU building stock have the potential to be reduced by 72% by 2050, with residual GHG emissions being around 229 MtCO₂eq in 2050. As use-phase operational carbon emissions represent close to 73% of the life cycle emissions of the EU building stock in 2020, it is crucial to reduce these with high renovation rates, exchanges of heating systems, and investments in renewable energy generation. As a result, they only represent about 40% of the emissions in 2050, which represents an 84% reduction compared to 2020. Construction embodied emissions can also be drastically reduced, by 92% in 2050 compared to 2020, due to a range of material-related measures and lifestyle changes. However, while construction, demolition, and use-phase embodied GHG emissions are decreased, there is a sharp increase in the embodied GHG emissions from renovation, due to the increased need for materials (such as insulation) to thermally refurbish buildings and increase their energy efficiency. When comparing climatic regions, it can be seen that the absolute levels of emissions reflect the sizes of the building stocks (shown in Figure 2), with the difference that operational GHG emissions from the Continental region are higher than those of the Mediterranean region, which is expected due to the warmer temperatures requiring less heating. Apart from this aspect, there is little difference in the way GHG emissions are affected by the NZT scenario. In other words, the GHG emission reduction trend is similar across climatic regions.

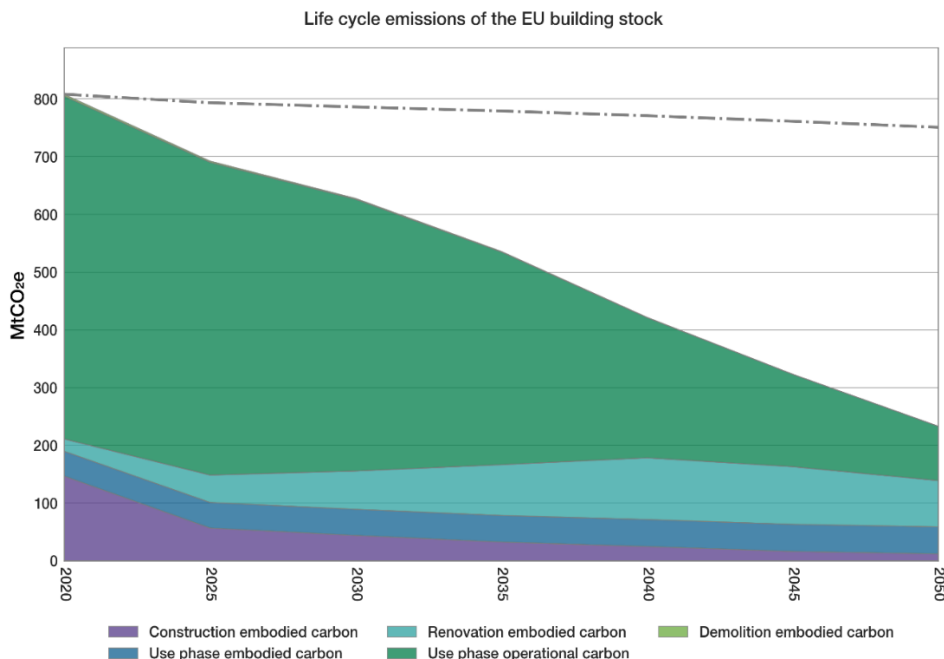


Figure 3. Annual life cycle GHG emissions (assessed with the global warming potential total indicator) of the NZT scenario for the EU. The dashed line represents the BAU scenario. The life cycle stages are linked to the modules of the EN 15978 in the following way: Construction embodied carbon (A1-A5), Use phase embodied carbon (B1-B4), Renovation embodied carbon (B5), Use phase operational carbon (B6), and Demolition embodied carbon (C1-C4).

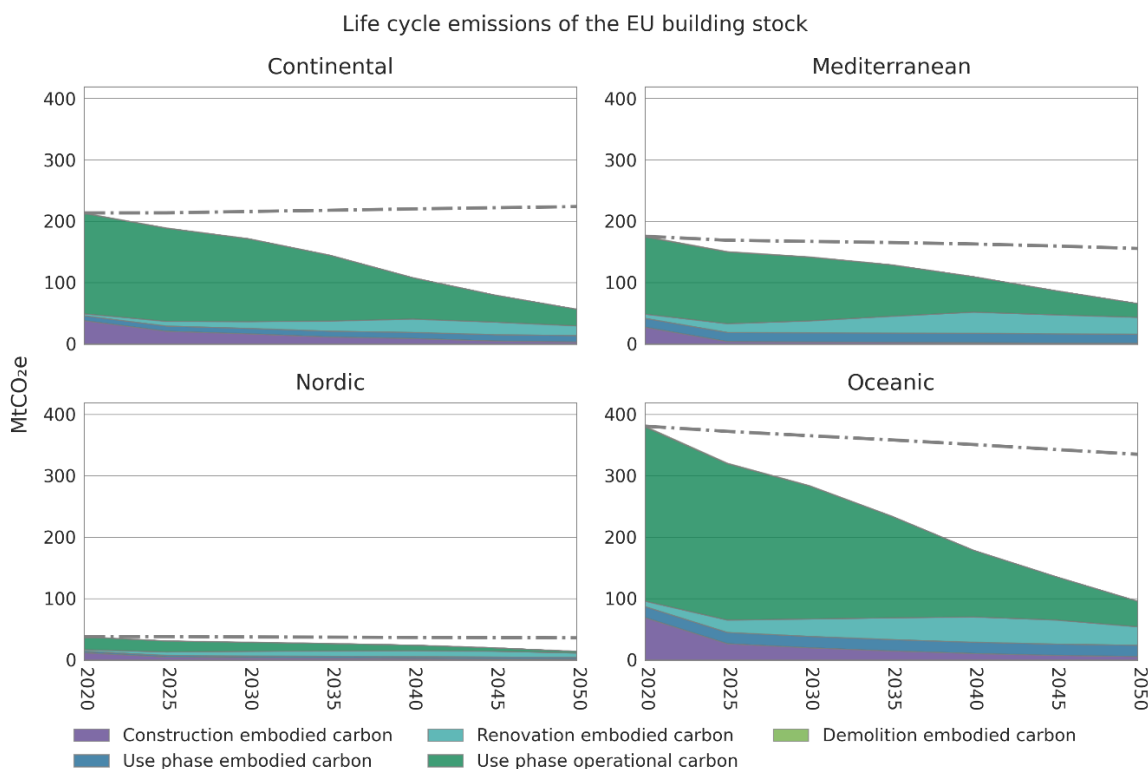


Figure 4. Annual life cycle GHG emissions of the NZT scenario for the EU, per climatic region.

3.2. Carbon removal technologies needed for net-zero

In the NZT scenario, the remaining hard-to-abate GHG emissions in 2050 are about 229 MtCO₂eq, including the effects caused by using more bio-based materials and the carbonation of cement-based materials (about 4 MtCO₂eq in total for the latter [15]). In order to reach a state of net-zero, GHG emissions into the atmosphere must be compensated by an equal amount of removed GHGs from the atmosphere over a period of time. In a prior study, which considered the basis of the strategies we implemented in the NZT scenario [13], there is also a list of carbon removal technologies that could be deployed in the building sector. They include green roofs and green façades, biochar, heating, ventilation and air conditioning systems equipped with direct air capture and storage (HVAC-DACCS), the carbonation of cement-based materials, and bioenergy and carbon capture and storage (BECCS). Estimations of their carbon removal potential are also provided for some of these technologies. These can be used to give a first quantification of the necessary deployment of these technologies.

For instance, with a carbon sequestration potential of green roofs ranging from 0.31 to 1.89 kg CO₂/m² [16], between 121 and 732 billion m² of roofs would have to be greened, which is far larger than the floor area in 2020 (about 31 billion m²). The long duration of carbon storage must also be ensured. Similarly, with biochar having an estimated carbon uptake potential of 2.7–9.54 t CO₂/ha/a when applied to soils [17], between 0.8 and 2.8 billion ha of land would have to be covered with biochar in 2020 to offset the remaining emissions in 2050. While little data are available for carbonation and BECCS, a study estimated the CO₂ sequestration potential of integrated HVAC-DACCS solutions at 104–209 kgCO₂/m²/year for a large office building, 270–319 kgCO₂/m²/year for a standard grocery store, and 10–12 kgCO₂/m²/year for a 70 m² apartment in an apartment building [18]. Considering the number of offices, retail, and apartment buildings that are assumed to be built in the NZT scenario, achieving net-zero GHG emissions in 2050 would mean that at least all the aforementioned buildings being built between 2030 and 2050 be equipped with such technologies.

3.3. Challenges in implementing carbon removal technologies

Implementing carbon removal technologies on the scale needed to reach net-zero emissions in 2050 faces multiple challenges. First, technologies such as HVAC-DACCS are still at a low level of technological readiness and deploying them at such a large scale by 2030 is unlikely, especially due to the lack of past investments in these technologies [19]. In addition, these technologies come with high electricity requirements [18] and significant trade-offs are expected if renewable energy generation cannot scale in time. With the electrification of processes remaining a main lever in the reduction of GHG emissions from various industrial sectors, adding a need for renewable electricity for such technologies might exceed the overall potential of the EU27 to generate renewable energy. Embodied emissions for the production of materials required to build such technologies should also be considered to ensure that there are no emission trade-offs.

One additional option discussed in the current scientific discourse could be to expand the system boundary from the buildings within the stock towards the inclusion of natural and geological sinks, such as the forest system or other. These systems would be able to sequester GHGs on a large scale if their GHG sink behavior is ensured and managed properly. These sinks could then be accounted for within the whole stock level, although they would need to be locked for usage by other sectors. However, there is a risk of double counting, as the stakeholders from the building sector might well be different from those of the land. In any case, this should be a last resort; more ambitious action is required to reduce the life cycle emissions of buildings in the first place rather than merely accounting for natural sinks to compensate for the lack of mitigation

actions in the built environment. Recent publications have indeed highlighted the risks from the over-reliance on land for carbon dioxide removal pledges [20] and the necessity to go towards geological net-zero, with carbon dioxide being permanently restored to the solid Earth [21].

4. Conclusion

The life cycle GHG emissions of the EU building stock have the potential to be reduced by 72% by 2050. This would require high renovation rates (especially deep thermal refurbishments with exchange of heating systems) and investments in renewable energy generation, ambitious material-related measures, and lifestyle changes. To compensate for the remaining emissions by 2050, direct air capture and storage technologies would need to be installed in at least all HVAC systems of newly constructed office, trade, and apartment buildings from 2030 to 2050. The broader implications of our results suggest an apparent need to extend the system boundary of carbon removal outside of the building sector toward more advanced system thinking in the built environment and its link to other systems to assess the intersectoral trade-offs that decarbonizing the building industry might have.

Acknowledgements

This study builds upon results produced within the EU research project "Analysis of Life-Cycle Greenhouse Gas Emissions and Removals of EU Buildings and Construction" [GROW/2022/OP/0005] contracted by the European Commission, DG GROW. The opinions expressed in this paper are those of the authors only and do not represent the European Commission's official position. Additional information is available on the project website (<https://c.ramboll.com/life-cycle-emissions-of-eu-building-and-construction>) and via the related project reports published by the European Commission. We also thank Benedict Schwark for his support in creating Figure 1.

Contributions

N Alaux: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing - Original Draft. **D Steinberger-Maierhofer:** Conceptualization, Formal analysis, Investigation, Writing - Review & Editing. **N Bechstedt:** Software, Formal analysis, Data Curation, Writing - Review & Editing, Visualization. **D Ramon:** Methodology, Formal analysis, Investigation, Data Curation, Writing - Review & Editing. **X Zhong:** Conceptualization, Methodology, Validation, Writing - Review & Editing. **A Mastrucci:** Conceptualization, Methodology, Validation, Writing - Review & Editing. **M Röck:** Conceptualization, Methodology, Validation, Writing - Review & Editing, Project administration, Funding acquisition. **K Allacker:** Methodology, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **A Passer:** Methodology, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

References

- [1] IPCC 2023 Summary for Policymakers *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed Core Writing Team, H Lee and J Romero (Geneva: IPCC)
- [2] IPCC 2022 *Climate Change 2022: Mitigation of Climate Change* ed J S P.R. Shukla R. Slade A. Al Khourdajie R. van Diemen D. McCollum M. Pathak S. Some P. Vyas R. Fradera M. Belkacemi A. Hasija G. Lisboa S. Luz J. Malley (New York: Cambridge University Press)

- [3] European Commission 2020 *Amended proposal for a regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law)*, COM(2020) 80 final
- [4] Röck M, Baldereschi E, Verellen E, Passer A, Sala S and Allacker K 2021 Environmental modelling of building stocks – An integrated review of life cycle-based assessment models to support EU policy making *Renewable and Sustainable Energy Reviews* **151**
- [5] Alaux N, Schwark B, Hörmann M, Ruschi Mendes Saade M and Passer A 2024 Assessing the prospective environmental impacts and circularity potentials of building stocks: An open-source model from Austria (PULSE-AT) *J Ind Ecol* **28** 1435–48
- [6] Kuittinen M, Lützkendorf T and Foliente G 2024 Net-Zero Requires Improved Collaboration between Researchers and Policymakers *Buildings and Cities*
- [7] Röck M, Passer A and Allacker K 2024 SLiCE: An open building data model for scalable high-definition life cycle engineering, environmental hotspot analysis and dynamic impact assessment *Sustain Prod Consum*
- [8] European Commission 2020 EU Building Stock Observatory
- [9] CEN 2012 *EN15978:2012: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*
- [10] CEN 2019 *EN15804+A2:2019: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*
- [11] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E and Weidema B 2016 The ecoinvent database version 3 (part I): overview and methodology *Int J Life Cycle Assess* **21** 1218–30
- [12] NBN 2017 *Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products – National supplement to NBN EN 15804+A1:2014*. NBN/DTD B 08-001:2017
- [13] Alaux N, Marton C, Steinmann J, Maierhofer D, Mastrucci A, Petrou D, Potrč Obrecht T, Ramon D, Le Den X, Allacker K, Passer A and Röck M 2024 Whole-life greenhouse gas emission reduction and removal strategies for buildings: Impacts and diffusion potentials across EU Member States *J Environ Manage* **370** 122915
- [14] Hertwich E, Lifset R, Pauliuk S, Heeren N, Ali S, Tu Q, Ardente F, Berrill P, Fishman T, Kanaoka K, Kulczycka J, Makov T, Masanet E and Wolfram P 2020 *Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. A report of the International Resource Panel*.
- [15] Steinberger-Maierhofer D, Alaux N, Ramon D, Popek S, Potrč Obrecht T, Kockat J, Zhong X, Mastrucci A, Ruschi Mendes Saade M, Allacker K, Passer A and Röck M 2025 Carbon Dioxide Storage and Removal in EU Buildings *Submitted*
- [16] Shafique M, Xue X and Luo X 2020 An overview of carbon sequestration of green roofs in urban areas *Urban For Urban Green* **47** 126515
- [17] Kuittinen M, Zernicke C, Slabik S and Hafner A 2021 How can carbon be stored in the built environment? A review of potential options <https://doi.org/10.1080/00038628.2021.1896471>
- [18] Dittmeyer R, Klumpp M, Kant P and Ozin G 2019 Crowd oil not crude oil *Nature Communications* **2019 10:1** 10 1–8
- [19] Reisinger A, Cowie A L, Geden O and Al Khourdajie A 2024 Science-based targets miss the mark *Communications Earth & Environment* **2024 5:1** 5 1–5
- [20] Dooley K, Christiansen K L, Lund J F, Carton W and Self A 2024 Over-reliance on land for carbon dioxide removal in net-zero climate pledges *Nature Communications* **2024 15:1** 15 1–10
- [21] Allen M R, Frame D J, Friedlingstein P, Gillett N P, Grassi G, Gregory J M, Hare W, House J, Huntingford C, Jenkins S, Jones C D, Knutti R, Lowe J A, Matthews H D, Meinshausen M, Meinshausen N, Peters G P, Plattner G K, Raper S, Rogelj J, Stott P A, Solomon S, Stocker T F, Weaver A J and Zickfeld K 2024 Geological Net Zero and the need for disaggregated accounting for carbon sinks *Nature* **2024 638:8050** 638 343–50