Negative emissions in the LCA of buildings – measures to achieve net zero whole life cycle carbon buildings

A contribution to IEA EBC Annex 89

April 2026

Negative emissions in the LCA of buildings – measures to achieve net zero whole life cycle carbon buildings

A contribution to IEA EBC Annex 89

April 2026

Author

Rolf Frischknecht, treeze Ltd., Switzerland

Contributing Authors (in alphabetical order)

Aurora Luigia Teresa Bertini, Université de Liège, Université catholique de Louvain, Belgium
Carlos Enrique Caballero Güereca, Graz University of Technology, Graz, Austria
Adrien Dupire, École de technologie supérieure, Université du Québec, Montréal, Canada
Leo Ettl, Graz University of Technology, Graz, Austria
Thomas Lützkendorf, KIT, Karlsruhe, Germany
Claudiane Ouellet-Plamondon, École de technologie supérieure, Université du Québec, Montréal, Canada
Alexander Passer, Graz University of Technology, Graz, Austria
Matt Roberts, University of California, Berkeley, USA
Charlotte Roux, Mines Paris Tech, Paris, France
Marcella Ruschi Mendes Saade, Graz University of Technology, Graz, Austria
Dominik Steinberger Maierhofer, Graz University of Technology, Graz, Austria

Author:
Rolf Frischknecht, treeze Ltd., Switzerland
Contributing Authors:
Aurora Luigia Teresa Bertini, Université de Liège, Université catholique de Louvain, Belgium
Carlos Enrique Caballero Güereca, Graz University of Technology, Graz, Austria
Adrien Dupire, École de technologie supérieure, Université du Québec, Montréal, Canada
Leo Ettl, Graz University of Technology, Graz, Austria
Thomas Lützkendorf, KIT, Karlsruhe, Germany
Claudiane Ouellet-Plamondon, École de technologie supérieure, Université du Québec, Montréal, Canada
Alexander Passer, Graz University of Technology, Graz, Austria
Matt Roberts, University of California, Berkeley, USA
Charlotte Roux, Mines Paris Tech, Paris, France
Marcella Ruschi Mendes Saade, Graz University of Technology, Graz, Austria
Dominik Steinberger Maierhofer, Graz University of Technology, Graz, Austria

Cover picture: Picture from https://www.climeworks.com

2026 Verlag der Technischen Universität Graz
Technikerstraße 4, 8010 Graz
verlag@tugraz.at
www.tugraz-verlag.at

DOI 10.3217/978-3-99161-096-0-001

This background report was developed within Annex 89 “Ways to implement net-zero whole life carbon buildings” of the International Energy Agency (IEA) Implementing Agreement for a Programme of Research and Development on Energy in Buildings and Communities (EBC) and does not constitute an official deliverable. Official deliverables and Background Reports of IEA EBC Annex 89 are available at: https://annex89.iea-ebc.org/

Funding: The work within Annex 89 has been supported by the IEA research cooperation on behalf of the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology via the Austrian Research Promotion Agency (FFG, grant #908095), by the Fonds de la Recherche Scientifique (FNRS) in Belgium under the PDR project RENOWAVE [T.0004.23F] 2023-2027, by the NSERC Mission Alliance (ALLRP 577152-2022), Canada Research Chair program (CRC-2019-00074), and Mitacs

Acceleration (IT31140), by the Agence de l’Environnement et de la Maitrise de l’Energie (ADEME) in France (grant number 23IFD0510), by the Federal Ministry for Economic Affairs and Energy, Germany (BMWK, Projektträger Jülich, funding code 03EN1090), by the Swiss Federal Office of Energy (grant number SI/502710-01), and by the ClimateWorks Foundation, located in San Francisco, USA.

Acknowledgment: The author thanks Guillaume Habert, ETH Zürich for his highly valuable feedback on previous versions of this background report. It substantially improved the quality of its contents.

Summary

The background report addresses negative emissions in the life cycle analysis of buildings and measures to achieve net zero greenhouse gas emissions over the entire life cycle of individual buildings (net zero whole life carbon buildings, NZWLC buildings).

Buildings and their supply chains are responsible for 37% of global energy-related CO_2 emissions. The construction and real estate sector must drastically reduce its emissions to support the climate goals of the Paris Agreement. Buildings are increasingly seen - in addition to the traditional perception of being a direct and indirect source of GHG emissions - as carbon sinks, with materials such as wood and selected recycled products offering potential for carbon removal. There is a need for international harmonisation of terms and concepts to avoid greenwashing.

The background report defines key terms related to negative emissions in the life cycle of buildings. Three main categories are described: (1) carbon dioxide removal, (2) emission reduction and (3) potentially avoided emissions. Carbon dioxide removal refers to technologies that remove CO_2 from the atmosphere and store it permanently. Emission reductions refer to technical measures that lead to lower emissions without removing CO_2 from the atmosphere. Potentially avoided emissions are based on a model approach to avoiding emissions through substitution. Examples include the use of recycled steel or feeding PV electricity into the grid.

The effects of temporary and permanent storage on the development of the global mean temperature are discussed. Temporary storage can delay the rise in temperature by 8 to 20 years but has no significant long-term impact. Permanent carbon storage, i.e. a period of at least 1,000 years is necessary to minimise the rise in global average temperature. Based on this knowledge, accountable carbon removal certificates shall rely on carbon removal measures with a permanent carbon storage.

Building materials can contribute to carbon removal (negative CO_2 emissions), but their potential is limited. Materials are divided into three classes: (a) mineral, (b) bio-based and (c) mineral-organic materials. Mineral materials such as concrete with recarbonated recycled aggregates allow for permanent storage of biogenic or atmospheric CO_2. The amounts of CO_2 stored are usually small compared to the amounts of new fossil and geogenic CO_2 emitted in production. The storage potential of CO_2 in bio-based materials is rather high, while storage is temporary only. Mineral-organic materials are more diverse in terms of storage potential and permanence.

The accounting practices for carbon removal (negative CO_2 emissions) in life cycle assessment are discussed and requirements for net-zero WLC buildings are defined. Accounting for carbon storage in buildings is complex and requires clear methods. Time-dependent life cycle analyses take into account the effects of emissions over different time periods. Critics warn against using short time frames such as 100 years, as they ignore long-term effects. Net-zero WLC buildings must meet strict emission requirements. Emissions must be minimised throughout the entire life cycle. Carbon removal must be legally guaranteed and permanent.

Recommendations are given for building owners, public authorities, institutional investors. owners of building stocks and public policy makers. They cover in particular:

- the drastic reduction of life cycle emissions of buildings (with measures including the use of photovoltaic electricity production on buildings),

- the monitoring and active management of biogenic carbon stored in building stocks (including a minimum biogenic carbon content in buildings and combined with regulations on the conservation of the carbon stock in forests),
- a regulation of the end-of-life treatment of bio-based and mineral-organic building materials to prevent premature release of biogenic carbon, and
- the establishment of a system for carbon removal certificates based on long-term carbon removal technologies (at least 1'000 years).

Table of content

Abbreviations

Abbreviations	Meaning
CCS	Carbon Capture and Storage
CF	Carbon Footprint
BECCS	Bioenergy Carbon Capture and Storage
CO_2	Carbon dioxide
DACCS	Direct Air Carbon Capture and Storage
GHG	Greenhouse Gas
HWP	Harvested Wood Product
IEA	International Energy Agency
LCA	Life Cycle Assessment
LULUC	Land Use and Land Use Change
MSWI	Municipal Solid Waste Incineration plant
NET	Negative Emission Technology
NZ	Net Zero
NetZ-WLC	Net Zero Whole Life Carbon
SSP	Shared Socioeconomic Pathways
TOC	Total Organic Carbon
WLC	Whole Life Carbon

1 Introduction context and overview

1.1 Subject and goal

Buildings and their supply chains are a major source of greenhouse gas emissions. According to the global status report for buildings and construction published by UN Environment Programme buildings cause 37 % of global energy related CO_2-emissions (United Nations Environment Programme 2024). This includes direct and indirect operational emissions caused by building sector and energy sector as well as emissions of construction product industries as part of the industry sector, including concrete, steel, aluminium glass and bricks.[1]. Like all other industries, construction and real estate industry including upstream and downstream supply chains have to dramatically cut their emissions to support the achievement of the Paris goal regarding greenhouse gas emissions and climate change.

In the recent past, buildings are getting into the focus to be used as carbon sinks and by that contribute to carbon removal. Forced carbonation, sometimes also called “re-carbonation” and bio-based materials such as wood, bamboo or straw are mentioned as potential resource of carbon removal in significant amounts. Buildings are increasingly being labelled as energy positive, climate positive, carbon neutral or net zero whole life carbon using a large variety of different methods and drawing a tiered or an encompassing system boundary. This plurality of concepts, terms and labels calls for an international harmonisation and for clarification, also to avoid greenwashing.

This background report systematically addresses the different relevant aspects regarding the life cycle assessment of buildings and in particular regarding buildings which claim to achieve net zero greenhouse gas emissions along the whole life cycle of the building, from resource extraction, manufacture of construction products, erection of the building, its operation and maintenance, and its deconstruction and the end of life treatment of the building materials. It answers the question which building materials have the potential to qualify for carbon dioxide removal technologies and which among them qualify for balancing greenhouse gas emissions caused by buildings. This background report serves as one source for the official deliverable “Guidelines for selection and application of assessment methods to estimate and determine Paris-goal compatible NetZ-WLC status of buildings” of Subtask 2 “Paris-goal compatible assessment methods” of the IEA EBC Annex 89 “Ways to implement net-zero whole life carbon buildings”.

1.2 Buildings Breakthrough Initiative & IEA related activities (including zero carbon ready)

The Buildings Breakthrough, successfully launched at COP28, aims to achieve "near-zero emissions and resilient buildings to be the new normal by 2030". It supports accelerating decarbonization and enhancing resilience in the sector through international collaboration. Given the sector’s fragmented nature, a coordinated response from national governments is essential to steer the direction and pace of the transformation.”[2] This international initiative is focussed on areas of the priority actions which are: "B1: Standards and Certifications", "B2: Demand Creation", "B3: Finance and Investment", "B4: Research and Deployment" and "B5:

---

[1] Additionally, cement, glass and brick production causes substantial amounts of CO_2 emissions related to carbonation.

[2] https://globalabc.org/news/buildings-breakthrough-priority-international-actions-2024-2025-launched-buildings-and-climate, access in May 2025

Capacity and Skills". In B1 the main targets are to develop the definitions and assessments for near-zero emission and resilient buildings (NZERB) and to identify pathways for implementation by (1) working to establish a model transparency framework; (2) working to establish a model measurement frameworks for aligning whole life cycle carbon assessments and resilience assessments; (3) developing principles to align current standards and certification schemes with near-zero emissions and resilient buildings (NZERBS).

The goal of achieving "near zero" greenhouse gas emissions refers to the complete life cycle of the buildings under consideration. The definition of other system boundaries in the calculation and assessment of GHG emissions is still part of current activities. A discussion on the topic of "net zero" GHG emissions in the life cycle of buildings is still pending. Therefore, the options of including technical measures for negative CO_2 emissions in the balance sheet of emissions have not yet been discussed in detail. But in the medium term, this discussion is indispensable. The goal of "near zero" can only be a step towards "net zero". It is therefore possible and sensible to start looking at ways to achieve net zero greenhouse gas emissions over the life cycle. Precisely because Buildings Breakthrough was and is aimed at the governments of the countries of the world, it is recommended here to define compensatory measures - here measures for negative CO_2 emissions as early as possible.

The IEA has defined its own level of performance "zero-carbon-ready building" (IEA 2021). "A zero-carbon-ready building is highly energy efficient and uses either renewable energy directly or from an energy supply that will be fully decarbonised by 2050 in the NZE (such as electricity or district heat). A zero-carbon-ready building will become a zero-carbon building by 2050, without further changes to the building or its equipment." Further information is given in the information box below (IEA 2021, p. 144).

Zero-carbon-ready buildings should adjust to user needs and maximise the efficient and smart use of energy, materials and space to facilitate the decarbonisation of other sectors. Key considerations include:

- *Scope*. Zero-carbon-ready building energy codes should cover building operations (scope 1 and 2) as well as emissions from the manufacturing of building construction materials and components (scope 3 or embodied carbon emissions).
- *Energy use*. Zero-carbon-ready energy codes should recognise the important part that passive design features, building envelope improvements and high energy performance equipment play in lowering energy demand, reducing both the operating cost of buildings and the costs of decarbonising the energy supply.
- *Energy supply*. Whenever possible, new and existing zero-carbon-ready buildings should integrate locally available renewable resources, e.g. solar thermal, solar PV, PV thermal and geothermal, to reduce the need for utility-scale energy supply. Thermal or battery energy storage may be needed to support local energy generation.
- *Integration with power systems*. Zero-carbon-ready building energy codes need buildings to become a flexible resource for the energy system, using connectivity and automation to manage building electricity demand and the operation of energy storage devices, including EVs.
- *Buildings and construction value chain*. Zero-carbon-ready building energy codes should also target net-zero emissions from material use in buildings. Material efficiency strategies can cut cement and steel demand in the buildings sector by more than a third relative to baseline trends, and embodied emissions can be further reduced by more robust uptake of bio-sourced and innovative construction materials.

According to IEA (2021), mandatory zero-carbon-ready building energy codes should be in place globally by 2030, for both new buildings and the retrofit of existing buildings. In order to pursue the goal of net zero GHG emissions in the life cycle of buildings, the IEA also raises the question of how unavoidable emissions (e.g., in cement production) can be balanced.

In a Swiss consensus finding research project on “Net-zero greenhouse gas emissions in the building area (NN-THGG)” (Priore et al. 2024) the authors and the stakeholders involved agreed to define the term “net zero greenhouse gas emissions ready” for buildings differently. According to them, a building is “net zero greenhouse gas emissions ready” if the amount of biogenic carbon stored in it is potentially able to balance its unavoidable whole life greenhouse gas emissions. However, the prevention of the rerelease of the biogenic carbon contained in such a building has still to be ensured legally across a sufficiently long timeframe.

1.3 Contents of this background report

Chapter 2 contains the definition and characterisation of key terms used in the context of negative emissions and buildings LCA. Chapter 3 explains the difference and effects of temporary versus permanent (or sufficiently longterm storage of biogenic carbon. Chapter 4 deals with the topic of carbon removal (negative CO_2 emission) certificates and their eligibility for balancing greenhouse gas emissions. A synopsis on negative emission technologies and their characteristics related to construction materials is provided in Chapter 5. Different approaches used for accounting negative emissions in building’s LCA are described in Chapter 6. Chapter 7 contains the definition of net zero whole life carbon buildings. The report ends with discussion, conclusions and recommendations in Chapter 8.

2 Definitions of terms and concepts

2.1 Introduction

In life cycle assessment (LCA) and in carbon footprinting (CF), environmental impact and greenhouse gas emission contributions with a negative sign may occur due to different reasons (see also Tanzer & Ramírez 2019). In this chapter the following three main terms and concepts occurring in LCA are described and defined:

1. Carbon Dioxide Removal (Negative CO_2 emissions generated for instance by BECCS, DACCS or afforestation, Subchapter 2.2);
2. Greenhouse gas emission reduction (e.g. change to low carbon cement in concrete mixture, natural stone cladding instead of aluminium cladding; Subchapter 2.3);
3. Potentially avoided greenhouse gas emissions (e.g. fed in PV electricity substituting fossil based electricity, recycled steel substituting primary steel; Subchapter 2.4).

The chapter ends with a synthesis (Subchapter 2.5).

2.2 Carbon Dioxide Removal (Negative CO_2 emissions)

Carbon Dioxide Removal is indispensable to reach net zero greenhouse gas emissions. Firstly, fossil CO_2 emissions, the predominant part of greenhouse gas emissions shall be reduced and avoided to the extent possible (see Figure 1). Secondly, CO_2 emissions difficult to avoid shall be balanced with CO_2 removal. Carbon Dioxide Removal (CDR) refers to technologies, practices, and approaches that remove and durably store carbon dioxide (CO_2) from the atmosphere (IPCC AR6 WGIII 2022).

CO_2 removal is generated with various methods, sometimes called negative emission technologies (NET). They remove CO_2 either directly from the atmosphere or they capture biogenic CO_2 and sequester and store it over decades, centuries, millenia or longer (see Table 1) in either materials or underground.

Most of these technologies cause greenhouse gas emissions themselves (upstream and downstream). Those emissions shall be part of the overall life cycle impact assessment and carbon footprint assessment.

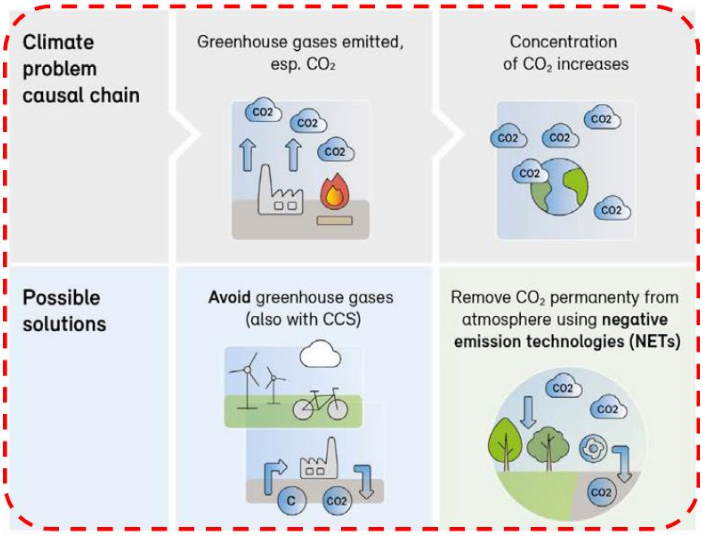

Figure 1 Achieving net zero: Avoid emissions when possible (also with CCS), balance remainder with Carbon Dioxide Removals (also called negative emission technologies, NETs), Source BAFU

According to the current status, the following CO_2 removal (negative emission) technologies are distinguished (Rueda et al. 2021; IPCC AR6 WGIII 2022, see also Figure 2):

- Afforestation and reforestation, improved forest management;
- Soil carbon sequestration;
- Biochar (in soils and sediments);
- Bioenergy with carbon capture and storage (BECCS);
- Direct CO_2 removal from the atmosphere and storage (Direct Air Carbon Capture and Storage, DACCS);
- Enhanced rock weathering;
- Peatland and wetland restoration;
- Blue carbon management;
- Ocean alkalinity enhancement;
- Ocean fertilisation.

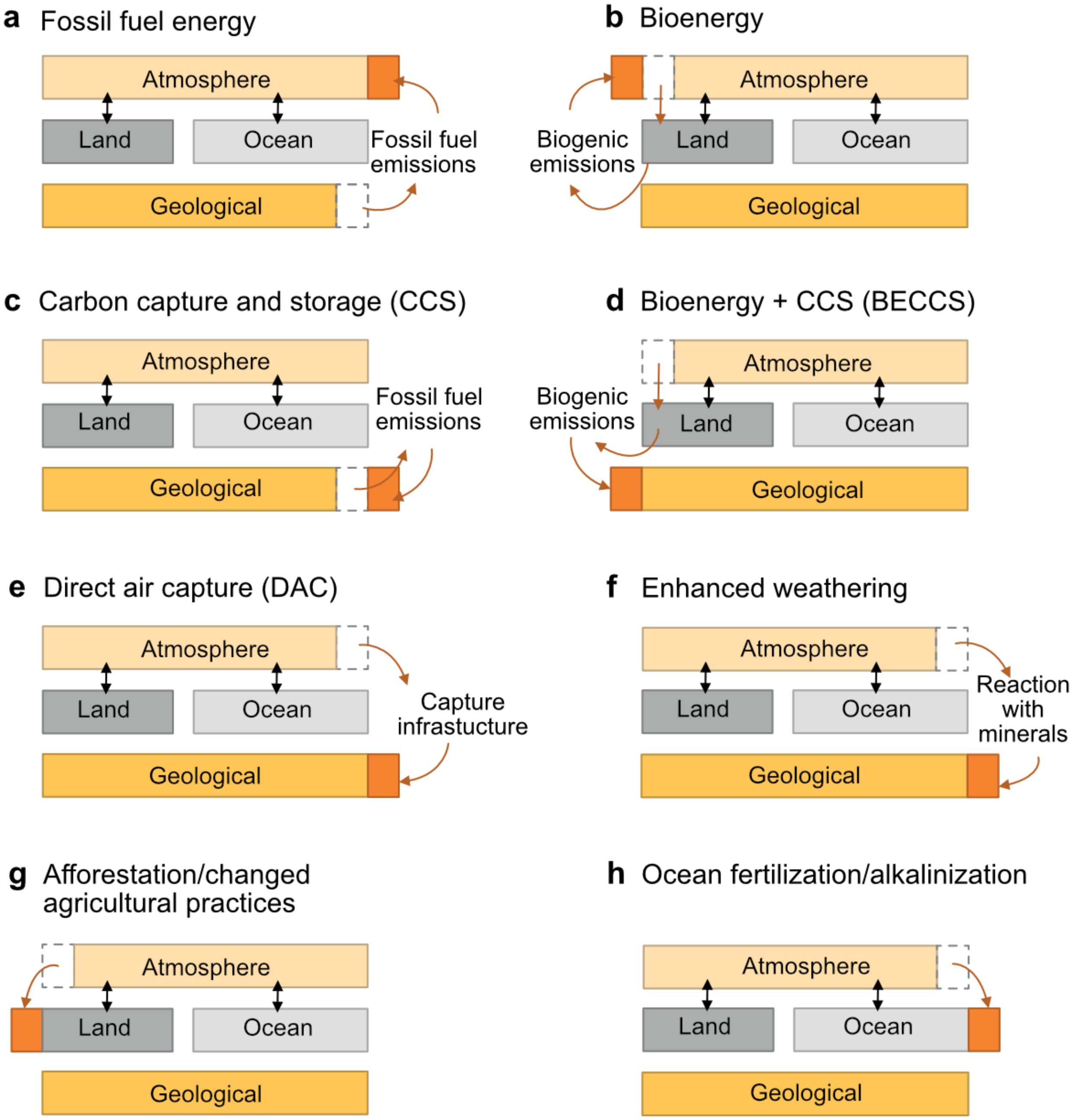

Figure 2 Schematic representation of carbon flows among atmospheric, land, ocean and geological reservoirs (based on Smith et al. 2016).

The storage time scale of the methods listed and mentioned above varies between decades up to 10’000 years and more (see Table 1).

In this background report the following three principles (adapted from IPCC AR6 WGIII 2022; Smith et al. 2024) apply to make carbon dioxide removals (CDR) eligible to balance greenhouse gas emissions (caused by buildings):

1. Principle 1: The CO_2 captured must come from the atmosphere (either directly or via biomass), not from fossil nor geogenic sources.

2. Principle 2: The subsequent storage must be durable, such that CO_2 is not reemitted to the atmosphere before at least 1’000 years.
3. Principle 3: The removal must be a result of human intervention, additional to the Earth’s natural processes feeding natural sinks.

The permanence criterion is crucial to ensure that the effect of CDR on the global mean temperature is also permanent. The CDR technologies listed differ significantly in terms of the permanence of storage/sequestration. While BECCS, DACCS, enhanced rock weathering and Ocean alkalinity enhancement are attested a storage time scale of 10’000 years and more, this time scale is one order of magnitude lower for biochar and ocean fertilisation and two orders of magnitude lower for afforestation, carbon sequestration in soils, peatland and wetland restauration and blue carbon management (IPCC AR6 WGIII 2022). The technologies also differ in terms of risk of reversal (University of Oxford 2024, see Table 1).

Table 1: Carbon dioxide removal (Negative emission) technologies and their characterization regarding permanence and uncertainty (IPCC AR6 WGIII 2022; Rueda et al. 2021; University of Oxford 2024)

Carbon dioxide removal (negative emission) technology	Storage time scale	Uncertainty
Afforestation and reforestation	Decades to centuries	higher
Carbon sequestration in soils	Decades to centuries	higher
Biochar, incorporated into (agricultural) soils	Centuries to millenia	higher
Bioenergy with carbon capture and storage (BECCS)	10’000+ years	lower
Direct air carbon capture and storage (DACCS)	10’000+ years	lower
Enhanced rock weathering	10’000+ years	lower
Peatland and wetland restauration	Decades to centuries	higher
Blue carbon management	Decades to centuries	higher
Ocean alkalinity enhancement	10’000+ years	-
Ocean fertilization	Centuries to millenia	higher

According to climate scientists CO_2 directly or indirectly withdrawn from the atmosphere must not be reemitted for at least one thousand years (Brunner et al. 2024). This is more than 30 times longer than the 35 years requested in carbon removal certification of the European Parliament (2024).

Figure 3 (operation of a bioenergy plant with carbon capture and storage in a permanent repository (BECCS) and Figure 4 (full life cycle of a construction material with biogenic carbon, including permanent storage after end of life) show examples of carbon dioxide removal methods which are eligible for accounting negative CO_2 emissions. The two examples are not intended to be compared in terms of functions provided or initial investment required nor do they cover the same life cycle stages.

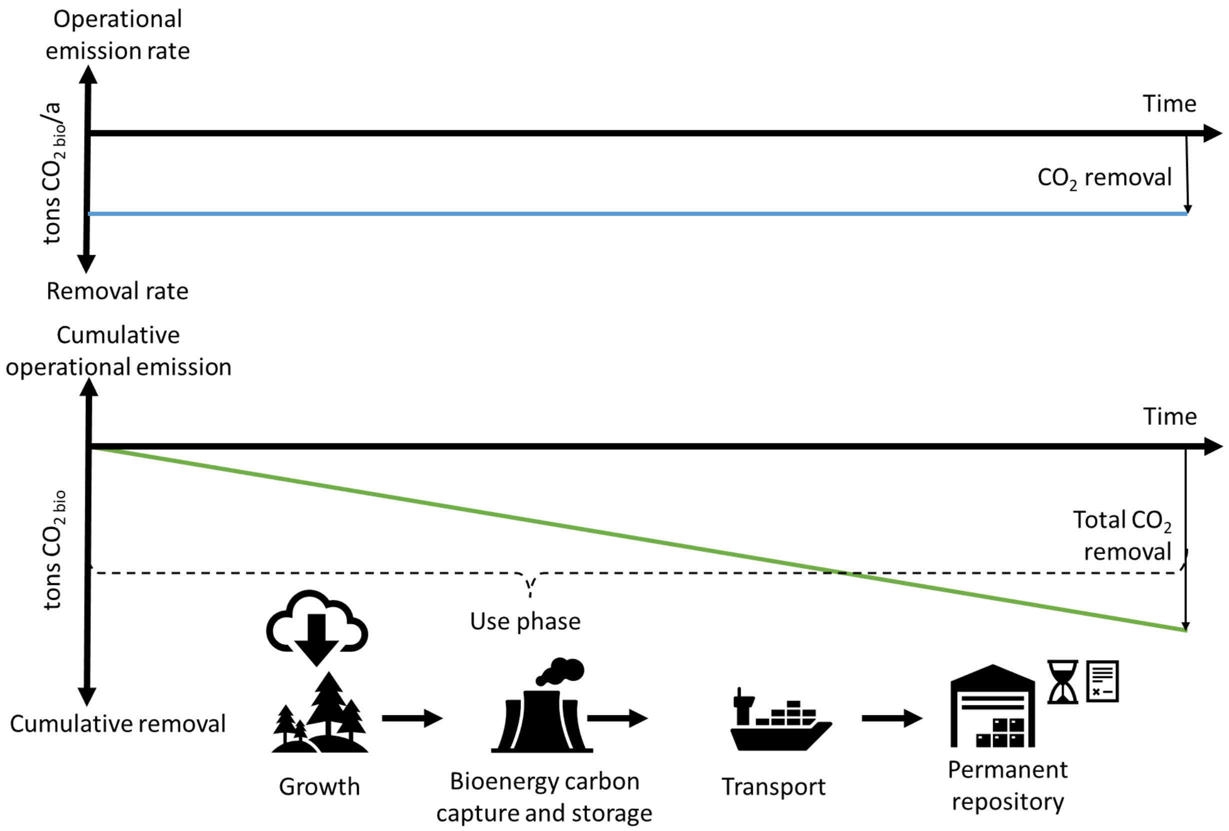

Figure 3 CDR generating negative CO_2 emissions by burning a certain amount of biomass in a heat and/or power plant equipped with carbon capture and legally assured permanent storage; use phase only. Permanent means at least one thousand years (Brunner 2022; Brunner et al. 2024; Frischknecht et al. 2022). Upper part: operational emission/removal rate of biogenic CO_2; lower part: cumulative operational emissions/removal of biogenic CO_2. For the sake of simplicity any emissions of biogenic greenhouse gases caused during harvesting, biofuel production and burning are disregarded.

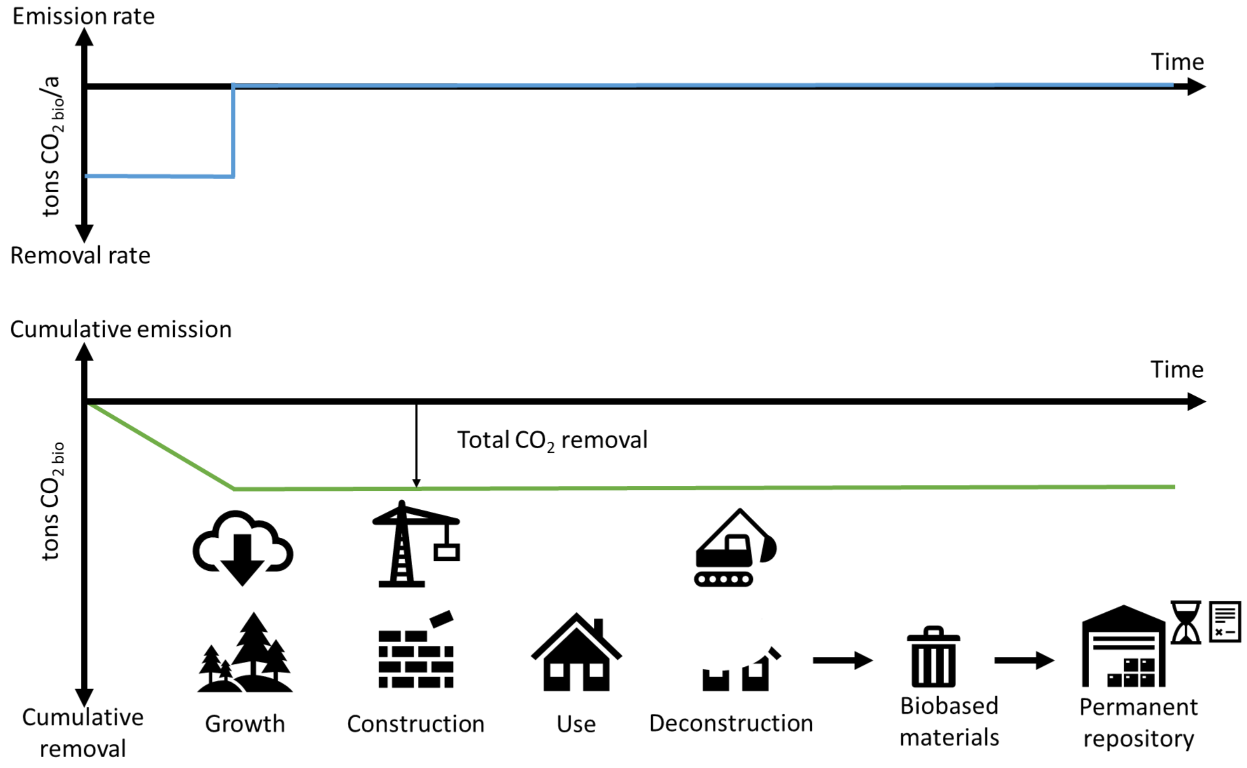

Figure 4 CDR generating negative CO_2 emissions by use of biobased construction materials including legally assured permanent storage after end of life. Permanent means at least one thousand years (Brunner 2022; Brunner et al. 2024; Frischknecht et al. 2022). Upper part: emission/removal rate of biogenic CO_2; lower part: cumulative emissions/removal of biogenic CO_2. For the sake of simplicity any emissions of biogenic greenhouse gases caused during harvesting, material production, use, and deconstruction are disregarded.

2.3 Emission reductions

Technical measures and investments may result in lower greenhouse gas emissions compared to the prior situation (see Figure 5). Such technical measures and investments may occur either in the process itself (scope 1) or in its supply chain (scope 2 and scope 3)[3]. Examples are:

- Installation of and investment in carbon capture and storage technologies in a cement kiln to produce “low carbon” cement (scope 1);
- Switch from fossil to renewable energy sources in the production of steel in an electric arc furnace (scope 2);
- Concrete producer switches from a traditional cement to a “low carbon” cement (scope 3).

Such emission reduction could appear with a negative sign in LCA results, although no CO_2 is removed from the atmosphere. It is not a carbon removal method nor a negative emission technology. It requires the definition of a forward looking, counterfactual baseline. This baseline is usually defined as the previously existing technology being kept in operation. The difference in emissions of operating the previously existing (current) and the new technology during years or decades give rise to a reduction of emission sometimes displayed as negative impacts in LCA.

---

[3] See WBCSD (2004) for the definition of scopes 1, 2 and 3.

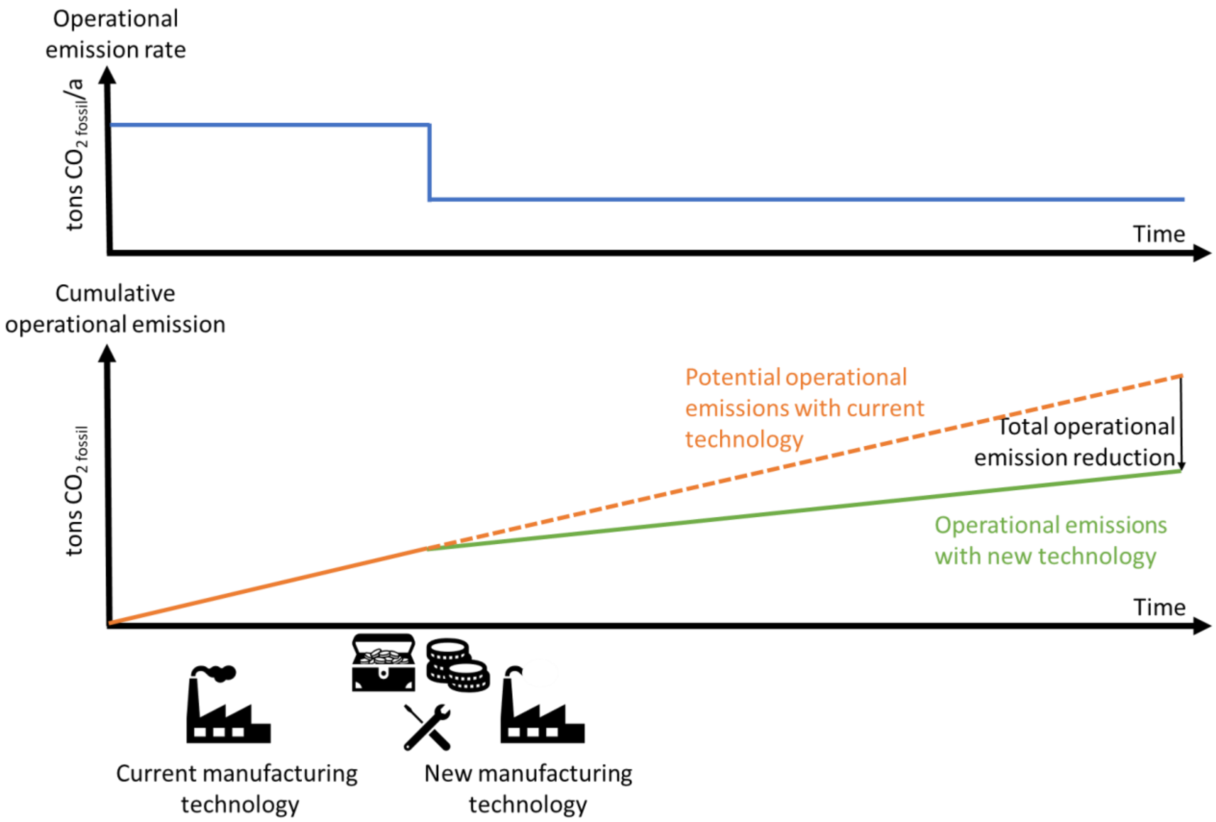

Figure 5 Emission reduction in manufacturing achieved by investing in a new low fossil CO_2 emission technology. The dotted line indicates the counterfactual emissions if the old technology were used instead of the new one. Upper part: operational emission rate of fossil CO_2; lower part: cumulative operational emissions of fossil CO_2. For the sake of simplicity any emissions of fossil CO_2; caused by the investment in the new technology are disregarded.

2.4 Potentially avoided emissions

Potentially avoided emissions are the result of a modelling approach ("avoided burden" approach with product system expansion) mostly used in consequential life cycle inventory modelling (Ekvall & Weidema 2004; Weidema 2001). In these simplified consequential models, co-products, co-services or material for recycling are assumed to substitute dedicated alternative production and thus avoid its emissions. Examples are:

- Co-product manufacturing (module D1 according to FprEN 15978 2025): Sawmills produce sawn wood and wood chips. The latter is used as a fuel and may replace fossil fuels such as natural gas or light fuel oil.
- By product valorisation (module D1): Blast furnace slag is produced as a by-product in primary steel production and may replace clinker in cement production.
- End of life recycling (module D1): Recycled steel may replace sourcing and production of primary steel.
- Building integrated or attached PV electricity production (module D2): Exported electricity may replace electricity production with other power plant technologies. The PV system may be installed on a new building or on an existing building (refurbishment measure, see Figure 6)

Such potentially avoided emissions are not based on a carbon removal method nor on a negative emission technology. As described above they require the definition of a forward looking, counterfactual baseline which is represented by an alternative production.

In environmental product declarations of construction products and buildings, potentially avoided emissions (and environmental impacts) are reported under module D "loads and benefits beyond the system boundary". Module D1 and D2 benefits are quantified based on counterfactual scenarios.

- Module D2: What would have been the emissions and environmental impacts of the electricity mix of a utility during the next decades of building operation, if no PV electricity were exported to the grid (see Figure 6)?
- Module D1: And what would have been the emissions and environmental impacts of producing a material from primary resources in the future (20 to 60 years from now) if wasted materials were not recycled after end of life (see Figure 7)?

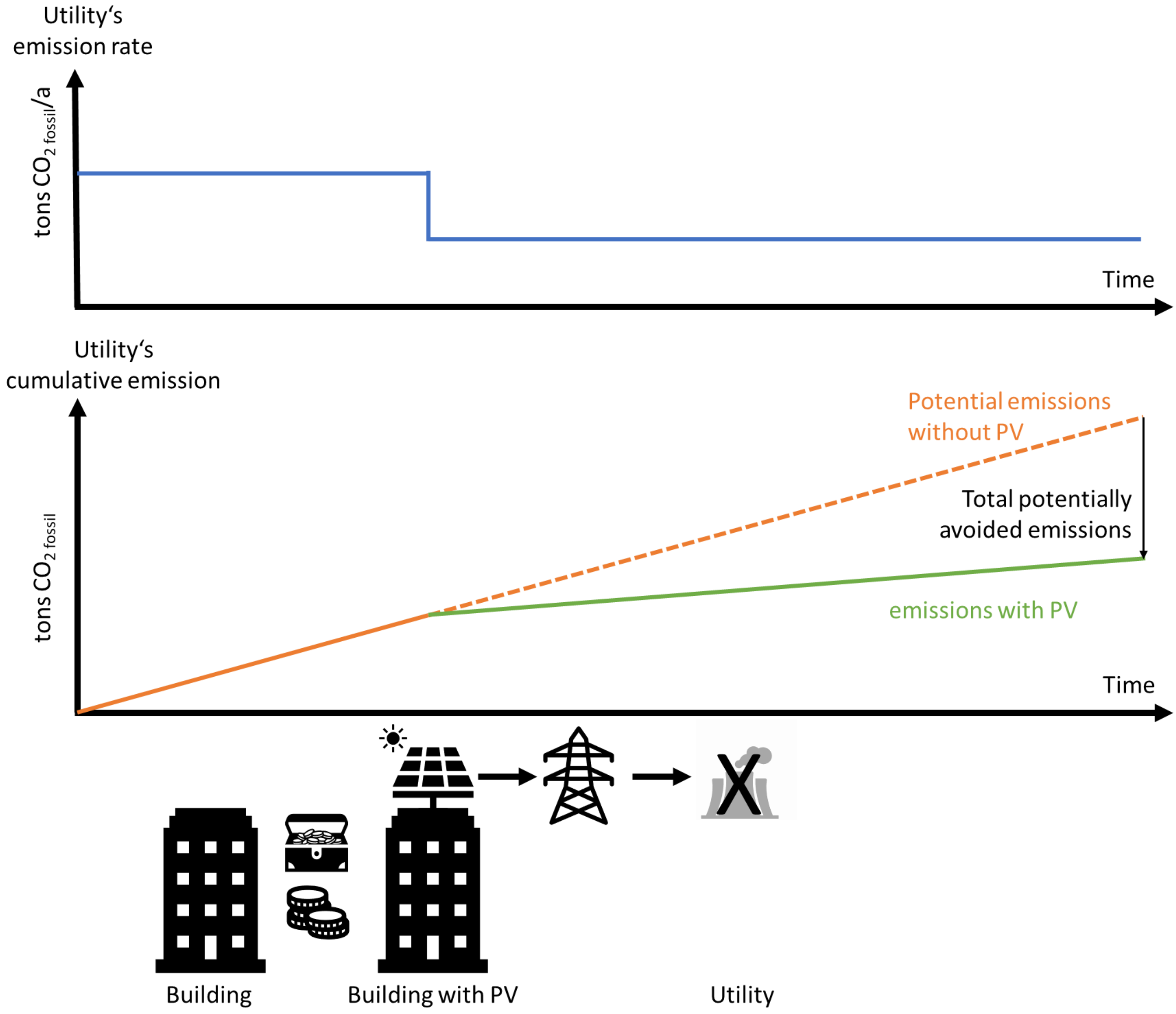

Figure 6 Potentially avoided emissions attributed to the building by feeding part of its photovoltaic electricity production into the grid. The dotted line shows the assumed emissions of the electric utility if no electricity were fed into the grid. Upper part: utility's operational emission rate of fossil CO_2; lower part: utility's cumulative emissions of fossil CO_2. Emissions of fossil CO_2 caused by the investment in the PV system are attributed to each kWh PV electricity produced. Temporal variation in PV electricity production and feed-in is disregarded for the sake of simplicity and clarity.

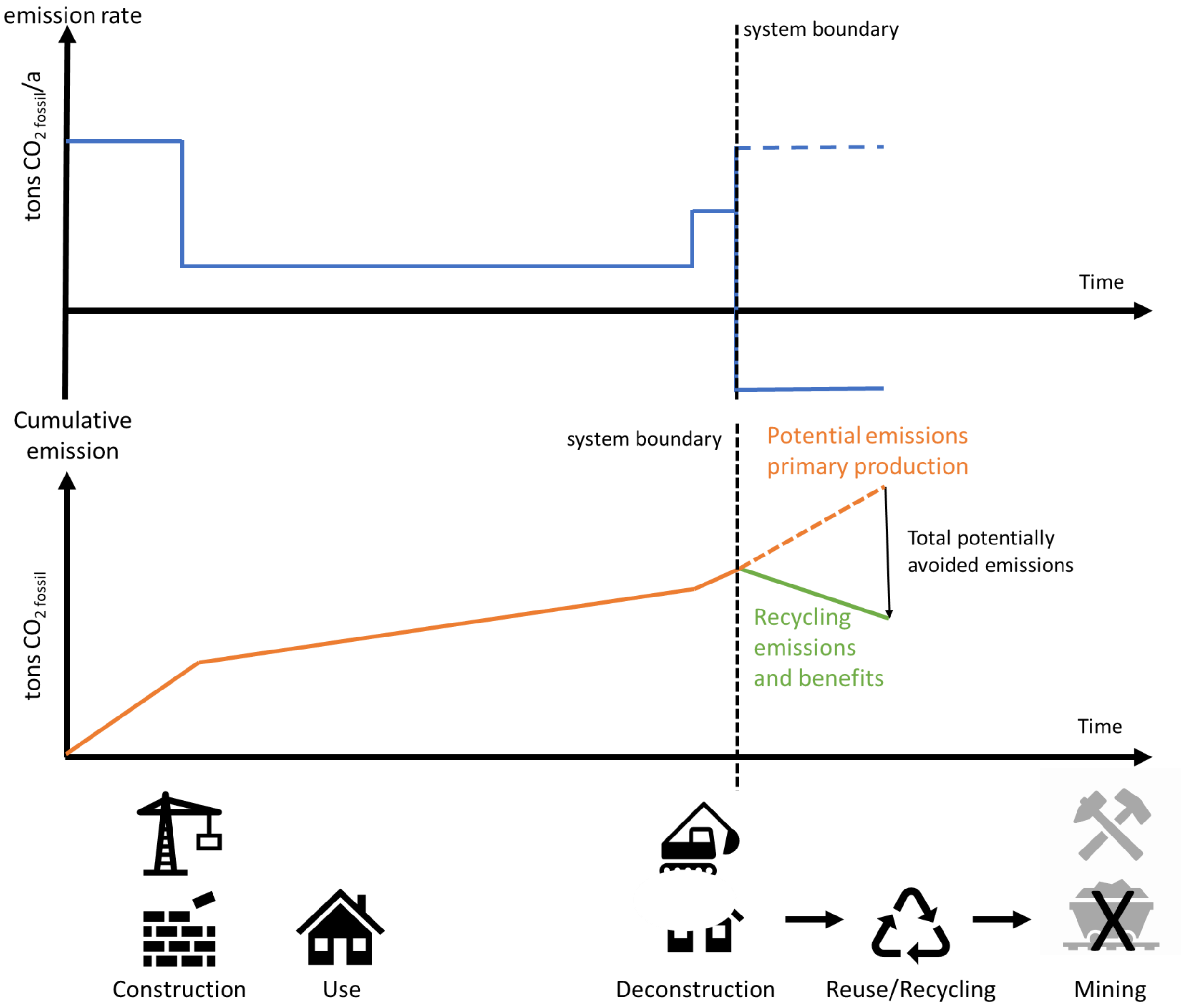

Figure 7 Potentially avoided emissions generated by recycling and refining construction material waste into new products. The dotted line shows the assumed emissions of mining and refining if no material were recycled. Upper part: building's life cycle emission rate of fossil CO_2; lower part: building's cumulative life cycle emissions of fossil CO_2, including potential benefits.

2.5 Synthesis

The three categories "Carbon dioxide removal (negative CO_2 emissions)", "(third party) emission reductions" and "potentially avoided emissions" are usually presented in life cycle assessments as emission contributions with a negative sign. They however represent distinctly different (potential) effects (see Table 2).

Carbon dioxide removal (Negative CO_2 emissions) describe and quantify the removal of CO_2 from the atmosphere and its permanent storage. They do not represent emission reductions and no counterfactual scenario is needed to quantify it. The carbon of carbon dioxide removal is either biogenic (if captured from flue gases with carbon capture and storage (CCS) or fixed in materials based on renewable raw materials) or atmospheric (if captured with direct air carbon capture and storage, DACCS). And the carbon (dioxide) is stored permanently either in biogenic or in mineral materials or in geological stocks.

In contrast, capturing CO_2 from fossil and geogenic sources in the flue gas with CCS as for example in cement kilns is not a carbon dioxide removal method. The CCS applied on fossil and geogenic CO_2 is an emission reduction measure (see Subchapter 2.3).

(Third party) emission reductions do not represent a removal of CO_2 from the atmosphere but a real emission reduction. The emission reduction is achieved by a change in technology, energy efficiency improvement, change of energy carrier and the like. A counterfactual, future-oriented scenario is needed to quantify the amount of emission reduction in future, which then often is expressed in negative amounts. The carbon of reduced CO_2 emissions is always fossil, geogenic or long-term stored biogenic.

Like emission reductions, potentially avoided emissions do not represent a removal of CO_2 from the atmosphere. They represent a model based potential emission reduction eventually realised by third parties (beyond the system boundary of the building). A counterfactual “what if”-scenario is needed to quantify potentially avoided emissions. The carbon of potentially avoided CO_2 emissions is fossil, geogenic or long-term stored biogenic.

Table 2: Characteristics of CO_2 removal (negative CO_2 emissions), (third party) emission reduction and potentially avoided emissions
$^{1)}$: or atmospheric; $^{2)}$: including geogenic and long-term stored biogenic (e.g. carbon in native forests)

Characteristic	CO_2 removal	(third party) emission reduction	Potentially avoided emissions
Removal of CO_2 from atmosphere	Yes	No	No
Emission reduction	None	Within system boundary	Beyond system boundary
Need for counterfactual scenario	No	Yes	Yes
Type of Carbon	Biogenic $^{1)}$	Fossil $^{2)}$	Fossil $^{2)}$
Storage	Longterm	None	None

3 Temporary versus permanent storage of biogenic carbon

3.1 Introduction

After introducing the time scales of decay of CO_2 emitted to the atmosphere in Subchapter 3.2, the results of research about the effect of temporary carbon storage on the evolution of global mean temperature under different shared socioeconomic pathway scenarios of IPCC are summarised in Subchapter 3.3. In Subchapter 3.4 the concept of tonne-years is introduced.

3.2 Lifetime of CO_2 in the atmosphere

A significant fraction of CO_2 emitted remains in the atmosphere for long time. After 100 years about 40 % of a pulse emission of CO_2 is still present in the atmosphere (IPCC 2013). The remaining 60 % were taken up by land uptake and ocean invasion. It drops to about 25 % after 1’000 years (ocean invasion) and to not less than 15 % after 10’000 years (reaction with $CaCO_3$). This persistence of CO_2 in the atmosphere shows the need for technically remove it from the atmosphere to reduce its warming effect.

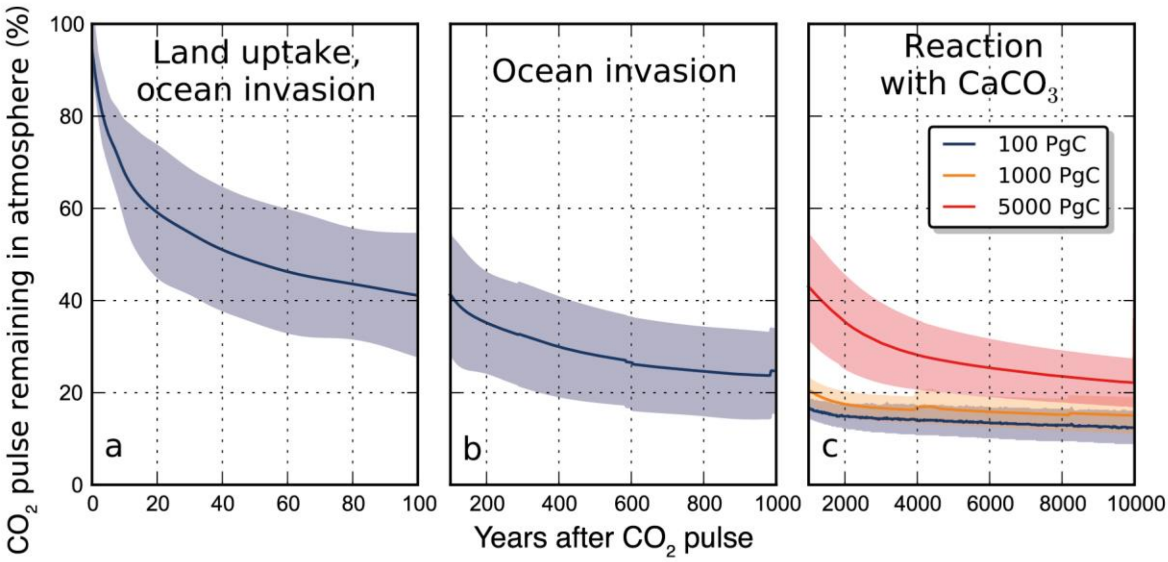

Figure 8 A percentage of emitted CO_2 remaining in the atmosphere in response to an idealized instantaneous CO_2 pulse emitted to the atmosphere in year 0 as calculated by a range of coupled climate-carbon cycle models. Text at the top of the panels indicates the dominant processes that remove the excess of CO_2 emitted in the atmosphere on the successive timescales (IPCC 2013).

3.3 The effect of temporary carbon storage on mean global temperature

Model calculations by leading climate researchers (Matthews et al. 2022) clearly show that temporarily storing biogenic carbon during 30 years delays the rise in temperature by about 8 to not more than 20 years (depending on the emission scenario) while subtly lowering the temperature peak in the most stringent emission reduction scenario (SSP 1-1.9). Matthews et al. (2022) have modelled various scenarios to estimate the effect of temporarily storing different amounts of biogenic or atmospheric carbon, either by a perturbation to prescribed CO_2 emissions in the model or as a regrowth of forests to mid-19th century distributions, under two different climate scenarios (with a relatively weak reduction target, shared socio-economic pathway SSP2-4.5, or with a Paris-compatible (max. 1.5°C) reduction target, SSP1-1.9) (see Figure 9).

With a relatively weak reduction in greenhouse gas emissions, the rise in temperature can be delayed by a few years at most by temporarily storing biogenic carbon, but not reduced (see dashed lines in Figure 9, c.). In any case, the long-term temperature increase is slightly more than 2.8°C (see Figure 9, e.). In the case of a very strong reduction, which requires a rapid and complete decarbonisation of the energy sector, the maximum temperature increase (peak warming) can be reduced by around one tenth of a degree by temporarily storing biogenic carbon (1.45°C instead of 1.55°C, see solid lines in Figure 9, c. and e.). The mitigating effect of temporary storage disappears after the stored CO_2 is emitted again and the long-term increase in global mean temperature is also practically identical in this climate scenario with and without temporary storage from the year 2100 onwards (see solid lines in Figure 9, c.).

It is argued that the benefits of slightly delaying and subtly reducing (SSP 1-1.9 scenario only) the peak temperature cannot be quantified with reduced/discounted Global Warming Potentials (see Subchapter 6.2) of delayed rerelease of biogenic/atmospheric CO_2.

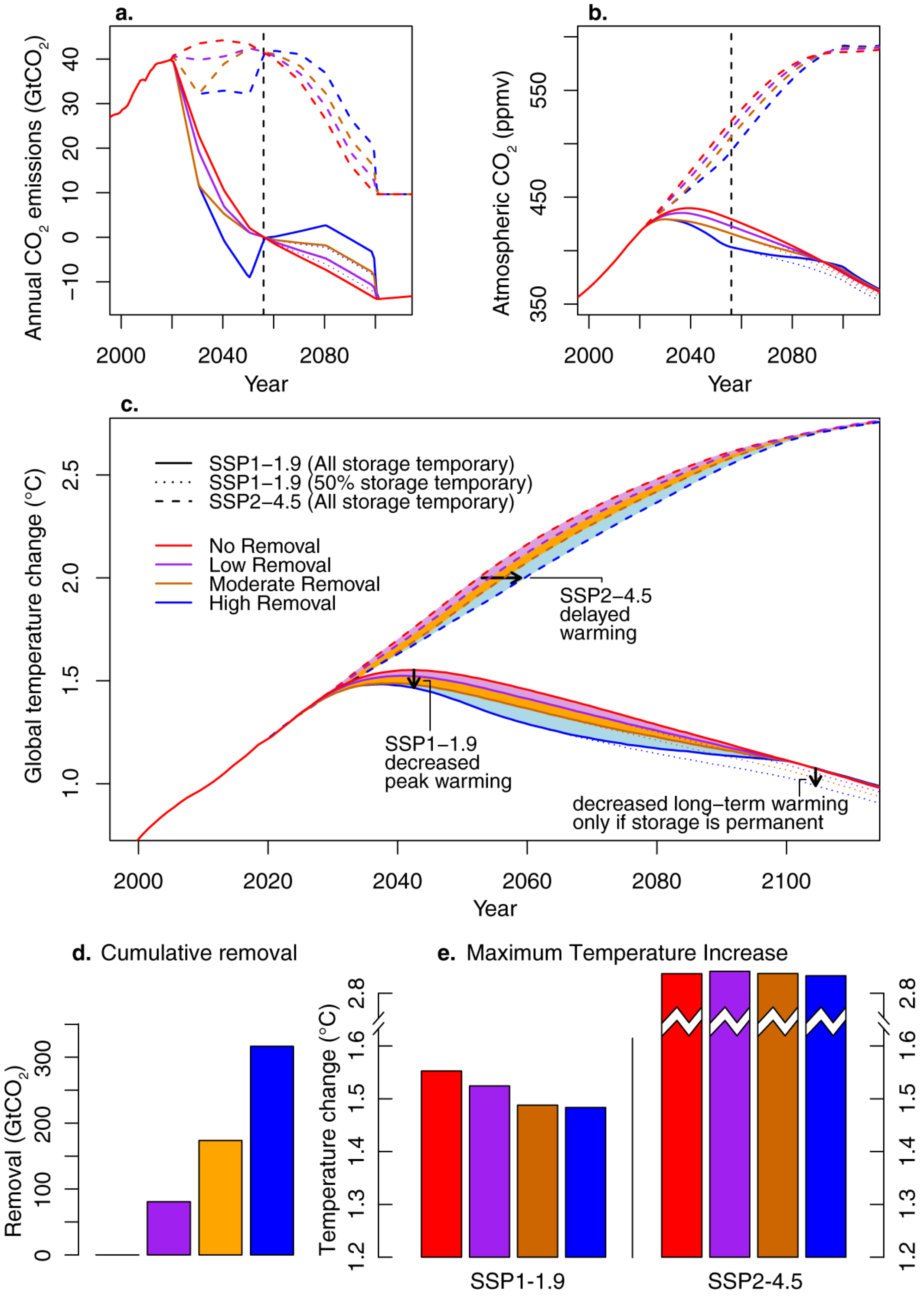

Figure 9 Reactions of world climate /mean global temperature on exogeneous scenario of temporally withdraw CO_2 from the atmosphere, based on two global emissions scenario (shared socio-economic pathways SSP1-1.9 and SSP2-4.5) and four removal scenario (no, low, medium and high removal), (Matthews et al. 2022).

Matthews et al. (2023) conclude the following:

“Our results show that successful carbon sequestration via NbCS [nature-based climate solutions] can have climate benefit, even in the case that the carbon storage is temporary such that the stored carbon is returned to the atmosphere later this century. However, the most important climate benefit—a decrease in the level of peak warming—is only realized in a scenario where fossil fuel CO_2 emissions are decreased rapidly to net-zero, resulting in global temperatures that peak and decline during the time period that NbCS-stored carbon remains sequestered in nature. This implies that realizing a tangible climate benefit from NbCS will require net-zero fossil fuel CO_2 emissions to be achieved on the same timescale as the successful implementation of NbCS. In the absence of this level of stringency in future mitigation efforts, temporary NbCS-based carbon storage would not affect peak warming and would serve only to delay the occurrence of a given warming level, with no other long-term climate benefit.”

“... the climate effect of nature-based carbon sequestration is only equivalent to a fossil fuel CO_2 emissions reduction if: (1) the carbon is permanently sequestered in nature; and (2) the additional non-CO_2 effects of NbCS are small relative to the climate benefit of carbon sequestration.”

Removing CO_2 from the atmosphere reduces CO_2-induced global warming for the duration of carbon removal. The temporary sequestration of biogenic carbon has a positive effect on climate change in the sense of a slight reduction (between 0.04 and 0.17°C) of the temperature maximum, if this measure is implemented in addition to the massive reduction of fossil CO_2 emissions to an absolute minimum and is accompanied by permanent negative emissions of several gigatonnes per year.

CO_2 removed from the atmosphere and biogenic CO_2 must be permanently stored (=sequestered) in order to minimise the long-term increase in global mean temperature. According to current knowledge, storage/sequestration over a period of at least 1000 years should fulfil the criterion of permanence (Brunner et al. 2024). In other words, for biogenic or atmospheric carbon that is stored in buildings today, it must be ensured that it does not re-enter the atmosphere for at least 1000 years.[4]

In order to completely eliminate the warming effect of emitting one tonne of CO_2, more than one tonne of CO_2 must be removed from the atmosphere (Zickfeld et al. 2021; Zickfeld et al. 2023). The use of greenhouse potentials of less than 1 kg CO_2-eq per kg CO_2 for the release of temporarily stored biogenic CO_2 as done in dynamic LCAs with a fixed time horizon of 100 years and time dependent discount factors on GWP (see Subchapter 6.2) is discouraged by leading climate physicists.[5] Based on this the experts of IEA EBC Annex 72 formulated the rule not to apply physical discounting in assessing greenhouse gas emissions (Lützkendorf et al. 2023).

3.4 The “tonne-year” concept

In another paper, Matthews et al. (2023) discuss the effect of temporary storage on global mean temperature using the concept of tonne-years. Its figure 2, partly reproduced in Figure 10 shows the effect of temporary storage of biogenic carbon in four different cases. Although modelled to show the effects of land carbon storage, they are well transferable to the effect of biogenic carbon in the building stock. It is essential

---

[4] Such permanence may be ensured by storing biogenic carbon from an individual building for more than 1000 years or to ensure that the entire stock of biogenic carbon in the built environment of a community, city or country remains constant (or – even better – increases) for at least 1000 years.

[5] See also report on climate scientists’ workshop “Ways to Implement Net-Zero Whole Life Carbon Buildings”, held on 26 June 2025, at ETH Zürich.

though to take into consideration the interface between carbon storage in land and forestry on one hand and in buildings using bio-based building products on the other.

In Case 1 the amount of biobased materials used in buildings is increased every year, in Case 2 it remains constant, in Case 3 it is reduced at a rather low rate and in Case 4 it is reduced rather quickly. According to the results of Matthews et al. (2023) the temperature benefit (reduction in global mean temperature) continues to increase when increasing the stock of biobased materials and thus the stock of biogenic carbon in buildings (Case 1). In contrast, if for some reason one stops using biobased materials in buildings and the stock of biobased materials is emptied (when replacing the buildings), the initial temperature benefit is completely lost (Case 3 and 4).

Finally, introducing a legal requirement of a mandatory minimum amount of biobased material in buildings, expressed as biogenic carbon content in “kg C per m^2”, will in a first phase increase the rate of tonne-year accumulation and then pass to a constant rate of tonne-year accumulation (Case 2). This will result in an increasing temperature benefit in the first phase turning to a constant temperature benefit in the second phase. If a sustainable management of the building stock is achieved where the amount of its biobased material is maintained by replacing demolished buildings with new buildings containing the same amount of biogenic carbon[6], the temperature benefit is maintained (case 2).

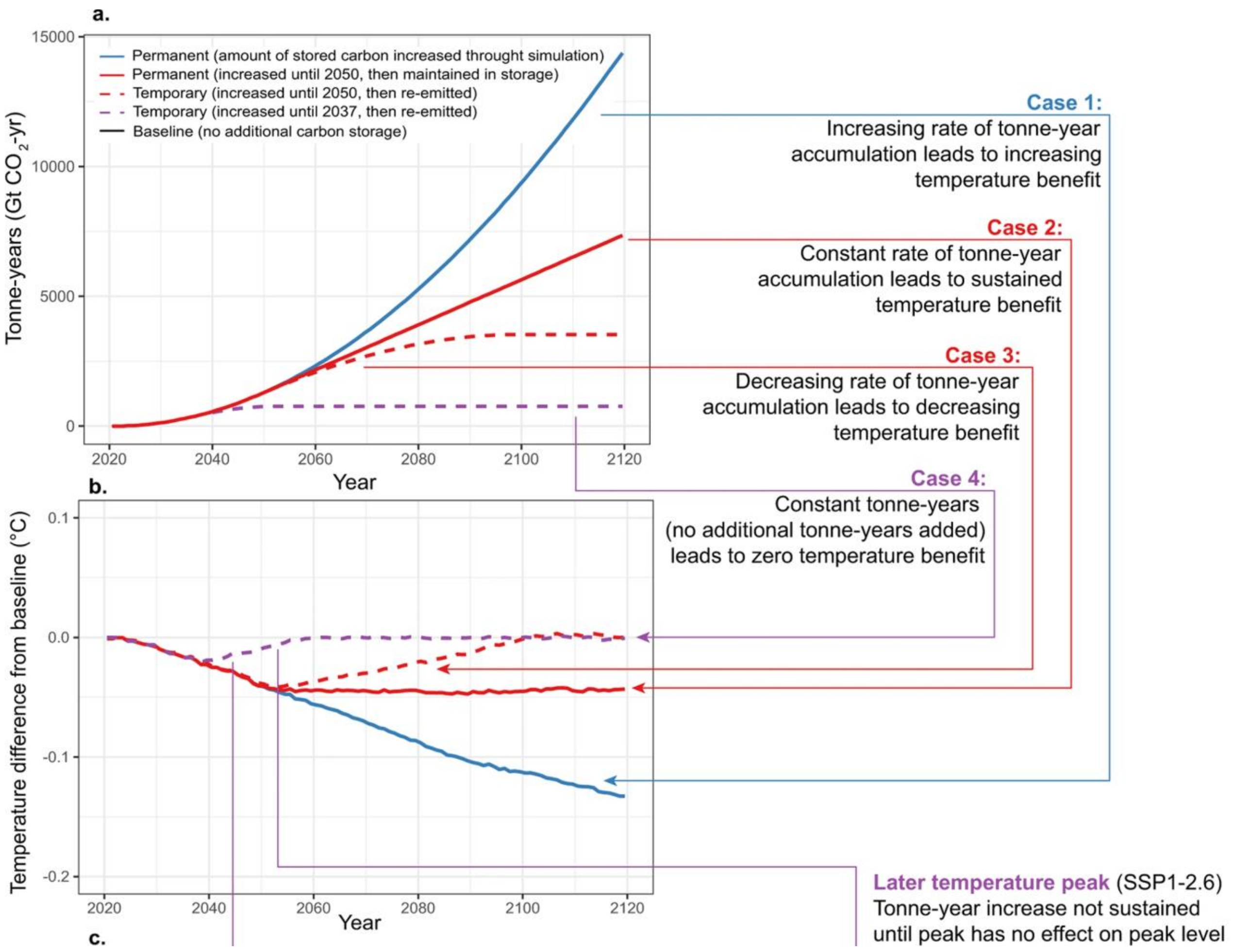

Figure 10 The climate effect of tonne-years of land carbon storage, (Matthews et al. 2023). Increasing rate of tonne-year accoumulation (Case 1): increase of the stock of biogenic carbon; Constant rate of tonne-year accumulation (Case 2): constant stock of biogenic carbon; Decreasing rate of tonne-year accumulation (Case 3): reduction of the

---

[6] Based e.g. on a «non-deterioration clause».

stock of biogenic carbon; Constant tonne-years (no additional tonne-years added, Case 4): reduction of the stock of biogenic carbon to 2020 volume.

Irrespective of these considerations temporarily storing biogenic carbon buys time to develop technical solutions for the capture and permanent sequestration of biogenic CO_2 and bring them to market maturity. Given the urgency of the situation, this gain in time is important and a great opportunity. However, it is still uncertain whether the time gained will be utilised as described.

4 Negative CO_2 emission certificates

4.1 European Union legislation

In April 2024 the European Parliament adopted the provisional agreement on the Carbon Removals and Carbon Farming (CRCF) Regulation (European Parliament 2024), which created the first EU-wide voluntary framework for certifying carbon removals, carbon farming and carbon storage in products across Europe. In this regulation, various carbon removal mechanisms are distinguished. They differ in the time period during which the biogenic or atmospheric CO_2 is removed directly or indirectly from the atmosphere and stored, ranging between several years and several centuries:

1. ‘permanent carbon removal’ means any practice or process that, under normal circumstances and using appropriate management practices, captures and stores atmospheric or biogenic carbon for several centuries, including permanently chemically bound carbon in products, and which is not combined with Enhanced Hydrocarbon Recovery;
2. ‘permanently chemically bound carbon in products’ means that the carbon does not enter the atmosphere under normal use, including any normal activity taking place after the end of life of the product,
3. ‘carbon storage in products’ means any practice or process that captures and stores atmospheric or biogenic carbon for at least 35 years in long-lasting products and which allows on-site monitoring of the carbon stored and certified throughout the monitoring period;
4. ‘carbon farming’ means any practice or process, carried out over an activity period of at least five years, related to terrestrial or coastal management and resulting in capture and temporary storage of atmospheric and biogenic carbon into biogenic carbon pools or the reduction of soil emissions.

It is planned to issue certificate units for these types of (temporary or rather permanent) carbon removals. The certificates specify the temporary or permanent nature of the CO_2 removal activity.

4.2 Eligible carbon removal (negative CO_2 emission) certificates

Emission certificates offered on the market today are generally based on emission reductions (sometimes also called “avoidance credits”), often determined in comparison with a counterfactual reference development. This type of certificate can serve to reduce emissions, but not to (permanently) remove CO_2 from the atmosphere.Requirements for the eligibility of these traditional CO_2 avoidance credits are currently under development.

For carbon removal (real negative CO_2 emissions), further requirements must be placed on eligible CO_2 removal certificates. Carbon removal certificates are eligible for balancing WLC greenhouse gas emissions of buildings, if they fulfil the following requirements:

Certificates of carbon removal (negative CO_2 emissions) acquired from third parties must be issued on the basis of measures to remove CO_2 from the atmosphere combined with sequestration with a relatively high permanence (scientifically: more than 1000 years, see Chapter 3[7]). Examples are Direct Air Carbon Capture and Storage (DACCS), Biogenic Energy Carbon Capture and Storage (BECCS) or enhanced carbonation.

Carbon removal certificates issued by third parties on the basis of measures with relatively low (decades to centuries) or uncertain or highly variable permanence, such as afforestation projects, biochar applications, carbon stored in products or carbon farming, are not eligible. The same applies for carbon removal by natural processes (e.g. natural carbonation of concrete after end of life).

---

[7] Although the European Union plans to issue certificates of permanent carbon removal if stored for several centuries at most (see Subchapter 4.1), the authors follow the recommendation of leading climate scientists of more than 1000 years.

5 Negative emission technologies and construction materials

5.1 Introduction and overview

Today and in the foreseeable future, building materials are being used that could potentially contribute to negative CO_2 emissions. The carbon removal potential of these materials is low compared to current emissions as Arehart et al. (2021) pointed out. The authors state that “current figures for carbon storage in buildings is only a fraction of global carbon emissions: even the more optimistic scenarios add carbon at less than 6% of the rate of current emissions (and in many scenarios, less than 1%, ...). So, whilst there may be a real and quantifiable benefit, the additional adoption of HWPs [harvested wood products] cannot make a major contribution until global GHG emissions are reduced significantly.” Furthermore the stock of biogenic carbon in forests and the stock of biogenic carbon in the built environment are interlinked and call for an optimal management of both (Maierhofer et al. 2024b). Nevertheless it is worthwhile to look at the carbon removal potential of building materials.

The materials can be grouped into three classes, namely those,

1. that result from forced mineral carbonation processes (e.g. concrete with a proportion of recycled, carbonated concrete granulate or cement made from accelerated carbonated raw materials such as magnesium silicate);

2. which are made from renewable raw materials (bio-based materials such as wood, wood-based materials, bamboo, hemp insulation or straw bales);

3. made from a mixture of mineral and renewable raw materials (e.g. concrete mixed with biochar, hempcrete).

The three aforementioned types of materials are described and characterised in the following sub-chapters. The following topics are covered:

a. Manufacture: Description of the way in which atmospheric carbon is fixed in the building material;

b. End of life treatment: Fate of the stored biogenic/atmospheric carbon;

c. Normative aspects;

d. Uncertainties and need for research;

e. Recommendations on modelling, boundary conditions and requirements.

5.2 Carbonated mineral building materials

5.2.1 Description and examples

Recycled concrete granulate comes from the demolition of buildings and infrastructure structures. It is produced in processing plants in the grain sizes required in building construction and civil engineering and used in the production of recycled concrete. The recycled concrete granulate is suitable for forced/accelerated carbonation due to its favourable surface-to-volume ratio. Other raw materials and wastes which are suitable for carbonation are ground granulated blast furnace slag, steel and magnesium slag, cement kiln dust or waste incineration bottom ash (Li et al. 2022). Carbonated mineral building materials are already available on the market.

5.2.2 Manufacture

The production of cement emits large quantities of CO_2. One third of this is attributable to the provision of thermal energy from mostly fossil (secondary) fuels. The remaining emissions are caused by chemical processes (calcination), which also occur when renewable fuels are used. This chemical process is (partially) reversible and can be accelerated by technical means.

In forced carbonation, the recycled concrete granulate is gassed for several hours with CO_2, which is either biogenic (e.g. separated during the purification of raw biogas or from a BECCS plant) or taken directly from the atmosphere (DACCS)[8]. The biogenic or atmospheric CO_2 binds during the reaction with the calcined cement to form calcium carbonate ($CaCO_3$). In this way, part of the CO_2 emitted during the production of cement is bound again. Today's plants can bind around 10 kg of CO_2 (i.e. around 2.7 kg of carbon) per m^3 of concrete or 5.7 kg of CO_2 per tonne of recycled concrete granulate in this way (Braune 2022). According to an LCA carried out in Switzerland (see reference before) the net CO_2 removal efficiency is more than 90 %.

5.2.3 End of life treatment

Concrete with forced carbonated concrete granulate is deconstructed, crushed and processed for the next use in the same way as conventional concrete. According to the current state of knowledge, just over a third is sent to landfill and the rest is recycled (Klingler & Savi 2021). The chemically bound biogenic carbon remains in the concrete (granulate) during dismantling, processing and production of recycled concrete or the use of recycled concrete granulate as a cofferdam material (base layer for roads).

5.2.4 Normative aspects

CO_2 emissions resulting from calcination and atmospheric CO_2 removal through (re-)carbonation are part of the fossil greenhouse gas emissions in accordance with the European standard EN 15804+A2 (2019), section C.2.3.

5.2.5 Uncertainties and need for research

High temperatures are required to re-release the carbon bound in the calcium carbonate. The recycled concrete granulate would therefore have to be fired like clinker to release it. It is very unlikely that this process

---

[8] The CO2 could also be captured at the stack of the cement kiln. In that case carbonation of concrete granulate is rather an emission reduction than a carbon removal.

takes place under natural conditions or that recycled concrete granulate is intentionally thermally treated in waste incineration plants. The CO_2 forcibly bound in carbonated building materials can therefore be regarded as permanently sequestered (IPCC AR6 WGIII 2022; University of Oxford 2024).

At the time of writing, a significant uncertainty lies in the still sparse life cycle assessment data currently available for the production of carbonated recycled concrete granulate. However, it is to be expected that the manufacturers of accelerated carbonated building materials will draw up life cycle assessment studies in the near future.

5.2.6 Modelling, boundary conditions and requirements

The removal of biogenic carbon from the atmosphere is recognised as a negative CO_2 emission when it is removed from the atmosphere or when it is separated from the raw biogas (purification).

No biogenic CO_2 originating from the building material is released when the component or building is disposed of at the end of its service life.

The costs of extracting CO_2 from the atmosphere or separating it from raw biogas, storing the extracted CO_2, transporting it to the treatment plants (usually concrete and gravel plants) and the subsequent forced carbonation of the recycled concrete granulate must be quantified and modelled in a classic, detailed life cycle assessment.

5.3 Bio-based building materials

5.3.1 Description and examples

Bio-based building materials continue to have the essential characteristics of renewable raw materials. Renewable raw materials based on plants used in bio-based materials bind carbon from the atmosphere as part of photosynthesis, i.e. during growth. The amount stored depends on the mass, density, age and lifespan of the plants. The most important renewable raw material is timber in the Northern Hemisphere (Göswein et al. 2021)[9] and Bamboo in the Southern Hemisphere (Göswein et al. 2022). There is also a rather large potential of straw used as insulation material in the Northern Hemisphere (Göswein et al. 2022). Timber and timber-based materials are used as primary load-bearing structures, but also as cladding and in interior fittings. Pomponi et al. (2020) showed the limited supply availability of timber for construction.

5.3.2 Manufacture

Building materials based on renewable raw materials can have a widely varying depth of manufacture. The range of wood-based materials in particular is wide, from beams, battens or boards made from rough-sawn solid wood to glued laminated beams, soft fibreboards and coarse chipboards. The actual proportion of renewable raw materials in the wood-based materials varies accordingly. The amount of stored biogenic carbon varies between the type of bio-based material and ranges between 0.4 and 0.46 kg C per kg (KBOB et al. 2022). Other sources publish values between 0.42 and 0.5 kg C per kg wood (IPCC 2019).

---

[9] They provide an overview on the availability of biomass for construction in Europe:
hemp shives: 5.6 mio. t; straw: 2 mio. t.; cork: 4.2 mio. t. and softwood: 23 mio. m^3 per year.

Building materials made from other renewable raw materials such as straw or sheep's wool are usually waste or by-products from production chains in agriculture or animal husbandry. In most cases, this raises the question of the appropriate allocation of agricultural expenditure and emissions to the raw materials used in the construction materials. One example of this is the straw and wheat grains from the cultivation of wheat.

5.3.3 End of life treatment

According to the latest studies on the deconstruction and disposal of building materials in Switzerland (Klingler & Savi 2021), just under 16.5 % of wood and wood-based materials in Switzerland are disposed of in a waste incineration plant and just under 0.5 % in a type E landfill. The remaining 83 % is utilised as material (36.5 %) and energy (46.5 %). This means that almost two thirds of the biogenic carbon is currently released, either in waste incineration plants or in waste wood cogeneration (heat and electricity) plants.

In an international case study within the IEA EBC Annex 72, a wooden reference building was assessed by 16 organisations in Europe, America and Australia (Ouellet-Plamondon et al. 2023). Different shares of the end of life waste incineration of wood and wood-based products (ranging from from 0 % to 100 %) and different perceptions of the permanence of biogenic carbon in landfills were major sources of variability in the whole life greenhouse gas emissions of this building calculated by the different institutes.

In some countries bio-based materials are allowed to be disposed of in landfills (e.g., Canada, Australia and New Zealand). The decomposition rate of wood in landfills differs between these countries (CA: 11 %, AU: 10 %, NZ: 0.1 %) as reported in Ouellet-Plamondon et al. (2023).

The energy generated by burning waste wood can be used to potentially reduce greenhouse gas emissions elsewhere. These are potentially avoided emissions beyond the system boundary (of buildings) that are reported in Module D. They are not negative emissions generated with carbon dioxide removal methods (as described and discussed in Subchapters 2.2 and 2.4).

5.3.4 Normative aspects

The European standard EN 15804+A2 (2019) requires an even balance of biogenic CO_2 emissions, regardless of the disposal method (recycling, incineration, landfill). According to this standard, even permanent storage may not be taken into account when determining biogenic greenhouse gas emissions (Section 5.4.3 of the aforementioned standard). In the Swiss CO_2 Ordinance Article 5, paragraph 2 (Swiss Federal Council 2022), projects and programmes in which storage lasts at least 30 years are certified as having a permanent sink effect. The European Commission proposes 35 years storage time to generate eligible negative CO_2 emissions. All contradict the scientific findings that biogenic carbon sequestered over a period of at least 1000 years has a reducing effect on the rise in the average global earth temperature. The same effect is achieved with carbon storage chains when the 30 or 35 years storage of CO_2 is followed by another 30 to 35 years storage of the same amount of CO_2 until reaching at least 1000 years (see Chapter 3, in particular Figure 10 and also Habert 2025).

5.3.5 Uncertainties and need for research

Building materials based on renewable raw materials can be used in buildings as temporary or permanent storage (if the re-release of biogenic carbon is prevented after the end of life of the building). When buildings are constructed, it is not known how these building materials will be deconstructed and recycled or disposed of. It is therefore uncertain whether the CO_2 extracted from the atmosphere will be released or whether the biogenic carbon will be stored for a further product life cycle (of unknown duration) through reuse or recycling. In some countries policies are in place for how biobased materials are treated at end-of-life for buildings. In the European Union as well as in the UK for instance, biobased materials are sent for incineration to avoid the use of fossil fuels for energy generation. In countries without such policies, the uncertainties about future end of life treatment cannot be reduced by research, but are in the nature of things, because the long-term tightness and loss rates of underground carbon dioxide storage facilities are not yet well known.

One fundamental issue is the dichotomy of individual building versus building stock. On one side there is a demand for considerations about biogenic material potentially (partly) balancing the whole life greenhouse gas emissions of an individual building. This includes a rather inherent uncertainty about the fate of the biogenic carbon stored in an individual building. On the other side, accumulation of biogenic material and its potential contribution to negative CO_2 emissions as permanent storage could better be quantified and monitored at the building stock level (given these data are being collected, see Steinberger-Maierhofer et al. 2025). The question of coherence between individual building and building stock accounting and the clear distribution of roles (burdens and benefits) between the multiple actors involved has to be clarified.

5.3.6 Modelling, boundary conditions and requirements

According to the EN 15804+A2 standard (2019), the biogenic carbon balance should be balanced over the entire life cycle of a building material. The removal of biogenic CO_2 during the growth of renewable raw materials and the emissions of biogenic CO_2 during disposal or recycling must be balanced and thus result in net-to-zero biogenic CO_2 emissions (-1/+1 approach). According to FprEN 15978:2025 the effects of temporary carbon storage, delayed emissions and permanent biogenic carbon storage shall not be included in the calculation of total greenhouse gas emissions. It may though be reported separately, in accordance with national or European regulation.

In the greenhouse gas balance of a building, one may deviate from the above under the following condition. If there is a legally binding assurance[10] that the biogenic carbon contained in the building materials will be separated and permanently disposed of when the building component is replaced or dismantled only the CO_2 removal, but not the CO_2 emission, may be recognised. If the building material is recycled or reused, this legally binding assurance must be transferred to the purchaser of the material, to ensure the carbon storage chain. Accidental release of biogenic CO_2 caused by fires should be prevented with fire-protection measures.

5.4 Mineral-organic building materials (MO)

5.4.1 Description and examples

Two types of materials fall under the category of mineral-organic building materials. On the one hand, typical mineral building materials such as concrete or bricks are mixed with materials made from renewable

---

[10] Options are long lasting contracts, entries in the land register or advance decommissioning fees and measure to remove an equivalent amount of CO_2 from the atmosphere. It may require a sequence of contracts, if bio-based construction materials are reused or recycled.

raw materials. These can be little-processed by-products from agriculture such as straw (typically from the cultivation of wheat) or mineralised products such as biochar.[11]

On the other hand, organic materials are consolidated with cement or other mineral binders. This category includes, for example, gypsum fibre and wood cement boards or hempcrete.

5.4.2 Manufacture

The materials in this category are essentially produced by mixing organic and mineral raw materials. A key feature of production is therefore the lack of a chemical reaction/mineralisation of the biogenic carbon in the construction material. The biogenic carbon is not present in oxidised (mineralised) form (such as CO_2 or CaCO3), but in the form of organic compounds such as C_6H_2O (lignite).

5.4.3 End of life treatment

The organic carbon content of materials in this category is usually (well) above the limit of total organic carbon (TOC) of 2% by mass for inert building materials that may be deposited in a type B landfill. They are usually disposed of in a municipal solid waste incineration (MSWI) plant or landfilled in a type E landfill (non-combustible waste from composite materials). According to Klingler and Savi (2021), 97.5 % of mineral-organic composites are incinerated in Switzerland and 2.5 % are landfilled, while the majority of gypsum materials are landfilled.

5.4.4 Normative aspects

The materials in this category fall under the group of materials for which the -1/+1 balancing of biogenic CO_2 of standard EN 15804+A2 (2019) is to be applied, including their reuse and use in refurbishment.

5.4.5 Uncertainties and need for research

The greatest uncertainty exists in the behaviour of biogenic carbon in the sorting of construction waste and the processing of raw materials. The various materials in the ‘mineral-organic’ category differ in terms of disposal and the fate of the organic carbon.

When concrete mixed with biochar is disposed of or when concrete granulate is produced from this material, the biogenic carbon remains in the concrete matrix (in the concrete granulate) or in the fine fraction, which is also used for the production of new building materials. Mass flow analyses of biochar concrete recycling are yet missingand should be conducted. The behaviour and material fate of the biochar in the landfilled concrete rubble is to be determined and quantified using eluate tests.

In the case of materials such as hempcrete or wood cement boards, attempts are being made to separate lime/cement and hemp/wood. The cement is currently landfilled and the hemp hurds are composted (Talandier et al. 2016a, b). In some countries the hemp hurds might also be incinerated. The carbon present in the organic material which is currently composted will sooner or later be released again as biogenic CO_2.

A further uncertainty lies in the current, at the time of writing, lack of life cycle assessment data for the production of biochar and in the allocation between hemp seeds and hemp straw (shives). The agricultural costs of cultivating hemp were allocated to seeds and straw/shafts on the basis of specific prices and yields

---

[11] See Section 5.3.1 for the availability of some of these renewable resources for construction in Europe.

per hectare (Talandier et al. 2016a). And the efforts and emissions of pyrolysis of wood are allocated between the co-products biochar, exported heat and exported electricity on the basis of specific prices and yields.

6 Accounting negative emissions in building's LCA

6.1 Fundamentals and work

The potential of storing biogenic carbon in buildings was addressed in two studies for the Environmental Construction Department of the Office for Buildings of the City of Zurich (Pittau & Habert 2021; Savi & Klingler 2021).

The storage effect of greenhouse gas emissions is assessed using different approaches. They are categorised here from a scientific perspective.

Fifteen years ago, an approach called "dynamic life cycle assessment" was applied on global warming potentials (Levasseur et al. 2010), resulting in time dependent factors. This approach is repeatedly used when balancing the greenhouse gas emissions of timber buildings (Hoxha et al. 2020), when using building materials based on renewable raw materials in buildings (Mennibus et al. 2019; Pittau et al. 2018; Pittau et al. 2019a; Pittau et al. 2019b; Pittau & Habert 2021) or to show the overestimation of cement carbonation at end of life (Van Roijen et al. 2024). Time-dependent greenhouse gas potentials are now also used in French legislation (Ministère de la Transition Ecologique 2021), where they are called "weighting coefficients". The use of time-dependent (discounted) global warming potentials is a controversial topic (see e.g. Ventura 2023) and is not recommended by the experts of IEA EBC Annex 89 and Annex 72 (Lützkendorf et al. 2023; Saade et al. 2023).

The Öko-Institut in Germany recently published a method called "CO_2 storage balance" for determining the greenhouse gas emissions of wood and wood-based materials.[12]

Subchapter 6.2 describes and critically assesses the approach and methodology of the study by Pittau & Habert (2021), which is based on the 'dynamic' approach. Subchapter 6.3 presents an accounting and assessment method that is compatible with the 1.5°C target. Subchapter 6.4 contains a description of the effect of short and long term storage of biogenic carbon on global mean temperature.

6.2 Time dependent balancing of greenhouse gas emissions

The time dependent LCA was originally developed and published by Levasseur et al. (2010). The methods are used by Pittau & Habert (2021). Their application is based on three essential principles (fixed time horizon, choice of the time of CO_2 removal, influence of the rotation period of renewable raw materials), which are described and discussed in the three following sections. In a separate section, the results presented in the cited study are described in relation to natural carbonation and compared with results from another study.

---

[12] https://co2-speichersaldo.de/en/index.html, access on 19 August 2025

6.2.1 Fixed time horizon of 100 years

The authors of the study discussed here with a time dependent approach set the time horizon at 100 years. In doing so, they refer to the integration period of 100 years used in climate policy to determine the relative effectiveness (radiative forcing) of greenhouse gases (global warming potential, GWP, integrated over 100 years). The greenhouse effect corresponds to the white area below the black curve in Figure 11.

Due to the chosen and fixed time horizon, the radiative forcing of emissions that occur later is (partially) not taken into account (orange shaded area labelled "benefits" in Figure 11 using the example of a delayed emission in the year 50). According to this approach, greenhouse gases that are emitted later in the life cycle of buildings, for example in the disposal phase after 60 years, have a significantly lower climate-warming effect (white area under the dashed curve) than emissions during manufacture (and the production of building materials) in year 1 (white area under the black curve).

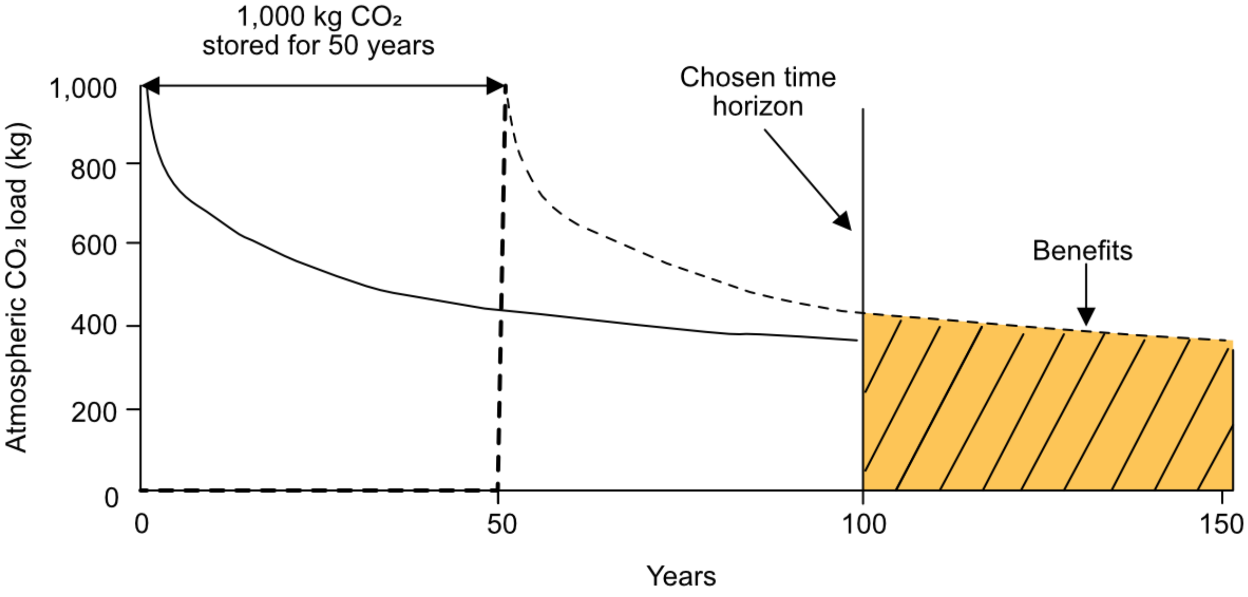

Figure 11 Instantaneous radiative forcing of the emission of 1 kg CO_2 in year 1 and delayed in year 50, with a (fixed) time horizon of 100 years (based on Levasseur et al. 2012)

However, the integration period of generally 100 years for determining the relative effectiveness of the emission of 1 kg of a greenhouse gas, expressed with the 'global warming potential' (GWP), applies unchanged for all emissions and regardless of the time of emission.

The integration period for determining the relative effectiveness of the emission of 1 kg of a greenhouse gas (usually 100 years) therefore has no connection and nothing in common with the time horizon of the life cycle assessment study (usually 50 as in EPBD or 60 years as in some European countries; 100 years in Figure 11), which corresponds to the reference study period for building life cycle assessments.[13]

---

[13] One could perform a time dependent carbon footprint assessment using GWP 100 with a fixed time horizon of 20, 50, 60, 100, 500 or 2000 years. Or one could perform a time dependent carbon footprint assessment using GWP 20, 50 or 100 using a fixed time horizon of 2000 years. The assessments will all differ in results while the results of those assessments with a time horizon of 2000 years would be very close to those of the static carbon footprint assessment.

Time dependent LCA provides correct results of climate change effects during the reference study period while not accounting the (often significant) climate change effects beyond this reference study period.

Static LCA provides correct results of climate change effects in the long term (1‘000 years and beyond) as long as climate system is kept constant during this period.[14]

Climate researchers such as Cyril Brunner, ETHZ and H. Damon Matthews, Concordia University, Montréal, Canada, both present at the Annex 89 climate scientists workshop[5] spoke out against this type of ‘time dependent balancing with a relatively short time horizon (100 years) and the associated consideration of a reduced climate impact of future emissions.

6.2.2 CO_2 removal before or after harvesting

In time dependent LCAs, the CO_2 removal of harvested or newly planted renewable raw material in the same place is taken into account. In the first case, CO_2 removal takes place before harvesting. This models the storage of the carbon actually contained in the raw material. In the second case, CO_2 removal takes place after harvesting. This modelling is based on the consideration that for sustainable forest management, a new tree must be planted and grown for every tree felled.[15]

By fixing the time horizon at 100 years, the choice between these two options is of great importance leading to highly variable results (Maierhofer et al. 2024a).

If the CO_2 removal by the regrowing biomass after harvesting is recognised as negative CO_2 emissions (CO_2 removal after harvesting) and evaluated using the time dependent approach, the supposedly beneficial effect is greater for fast-growing raw materials such as straw than for slow-growing ones such as wood due to the decreasing global warming potential of CO_2 over time (see Section 6.2.1). This leads to the recommendations formulated, for example, in Pittau et al. (2018) and Pittau & Habert (2021) in favour of fast-growing raw materials.

6.2.3 Connection between retention time in storage and rotation time

In the partially time dependent method, the retention period of renewable raw materials in buildings (lifetime or amortisation period of the components) and the rotation period of renewable raw materials (period between sowing and harvesting) are related to each other. CO_2 removal is only taken into account for the period of time during which the raw materials remain in the building or the product life cycle.

Theoretically, the use of renewable raw materials with a long rotation time, such as wood for products with a short lifespan, would mean that the forests are not used sustainably, if their wood were to serve these short cycle products. However, the sustainability of forest management does not depend on the lifespan of the products made from the wood, but on the ratio between the amount of wood harvested and the amount of wood that grows back or more precisely on the evolution of the carbon stock (above and under the ground) of the forest (as well as on other aspects not related to material flow such as species richness).

---

[14] CO_2 absorption relies heavily on ocean dynamic which might change if tipping points are crossed.

[15] Some argue that only harvest and growing of a new tree generates negative emissions.

6.2.4 Natural carbonation

Carbonation, i.e. the rebinding of the geogenic CO_2 released into the atmosphere during calcination (essentially from limestone), occurs naturally on the one hand, but is also increasingly forced on the other. In the study by Pittau & Habert (2021), natural carbonation is modelled and its contribution to CO_2 removal is quantified using various approaches, including the time dependent method. The contribution of carbonation over 100 years in the (current and future) building stock of the city of Zurich is very low at less than 0.5 % of total greenhouse gas emissions, regardless of the modelling approach chosen (classic or time dependent).

The findings of Pittau & Habert (2021) are consistent with those of an estimate based on a residential building (Werner & Frischknecht 2018). For this residential building (Rauistrasse Zurich, Switzerland, solid construction), the CO_2 removal through natural carbonation over 60 years is between 0.5 % (realistic) and 1.5 % (optimistic) of the total greenhouse gas emissions from construction (i.e. excluding greenhouse gas emissions during operation).

6.2.5 Criticism and assessment

Time dependent LCA as defined in this Subchapter looks at a given time horizon and provide accurate modelling of the climate evolution during this time horizon. It disregards climate change effects occurring beyond this time horizon. In most LCA case studies a 100 years time horizon was chosen, which ignores emissions and climate change effects beyond 100 years. If the timeframe s suffiently long, the time dependent assessment renders similar results to those of a static assessment (Saade et al. 2023).

There is a risk of misuse when using results of such time dependent LCAs in (public or private) policy making because their results could be misinterpreted as the effective climate effect over the many millenia climate science is considering climate change and related damages. Without a good understanding of the limited time horizon consideration and thus without knowing the real and long-term consequences of their actions, policy makers will shift the burden to future generations.

Recommendations based on time dependent LCAs with a relatively short time horizon (i.e. 100 years), in particular favouring fast-growing raw materials such as straw over other renewable raw materials such as timber, should not be made.

It is not the speed of growth that is decisive in terms of influencing the change in the global mean temperature, but the permanence of the storage of biogenic carbon.[16]

6.2.6 Conclusion

The use of time dependent balancing with a short time horizon such as 100 years and the use of time dependent GWP is not recommended. Instead, a 1.5°C target-compliant balance is recommended (see Subchapter 6.3).

For climate policy decisions covering the coming decades, which are crucial for reaching the national and global net zero greenhouse gas emission goal, it is recommended to use a timeline of at least 500 years to

---

[16] If land use favours more fast-growing species, these fast growing species are turned into materials and they are coupled with policies that incentivize longterm permanence, fast growing biobased materials would lead to a faster growing carbon pool compared to slow-growing biobased materials on the same piece of land.

display greenhouse gas emissions and removals when using time dependent LCA. This recognises short term as well as long term effects of policy decisions.

6.3 1.5°C Target-compliant balancing and assessment

This Subchapter deals with the conditions of eligibility of negative CO_2 emissions and (biogenic) carbon contained in building materials (Section 6.3.1) as well as with options for legally binding regulations that ensure long-term storage (avoid re-emission) of (biogenic) carbon contained in building materials (Section 6.3.2). Finally the interrelationships between single buildings and a building stock are discussed in Section 6.3.3.

6.3.1 Eligibility of Carbon contained in building materials

Based on the scientific findings summarised in Chapter 3, the following can be postulated with regard to balancing and assessment and in particular with regard to the conditions under which negative CO_2 emissions are eligible:

1. the building material contains (biogenic) carbon that has been removed from the atmosphere (through photosynthesis or directly or indirectly through technical processes);
2. the carbon contained in the building material is either permanently bound or the permanence has to be secured by a long-term[17], legally binding regulation well beyond the building's service life;
3. The negative emission certificates related to the carbon stored in the building material are purchased by or in the hands of the building owner. (Negative emissions shall not be counted for the quantities of CO_2 removed from the atmosphere for which emission allowances were sold to third parties.)

Time-dependent assessment of the climate change impact of CO_2 removal and emissions shall be refrained from. Each kg of CO_2 is assessed with the global warming potential 100 years (GWP100) of 1 kg CO_2-eq/kg CO_2 (emission) or -1 kg CO_2-eq/kg CO_2 (removal).

If the permanence of storage is assured and carbon dioxide removal certificates are purchased, the eligible CO_2 removal should be determined on the basis of the biogenic carbon content in the building material and conversion to CO_2. Any losses during removal and storing should be accounted for.

6.3.2 Options for legally binding regulation of long-term storage of biogenic Carbon

Long-term storage of (biogenic) Carbon in buildings requires a legally binding regulation to avoid reemission within at least 1'000 years. The following options give an idea of how such a regulation could look like without claiming to be exhaustive nor going into legal details[18]:

1. *Land registry entry:* In addition to ownership structures, rights and encumbrances are also recorded in the land registry. Rights and encumbrances remain with the property when it changes hands, as they are linked to the property and the buildings erected on it. Therefore, a land registry

---

[17] Long-term means at least 1‘000 years (see Chapter 3).

[18] National laws regulating the safe and secure final disposal of radioactive waste demonstrate that society is able to properly manage even longer-term environmental threats.

entry (such as a removal agreement) has the potential to guarantee long-term legal validity. A land register entry required by law should stipulate that materials containing biogenic carbon must either be reused, recycled or permanently sequestered. In the case of recycling or reuse, the party purchasing the building materials/elements must enter into a similar legal obligation.

2. *Take-back guarantee and advance decommissioning fee:* A federal law must require manufacturers and importers to guarantee the take-back of building materials containing biogenic carbon and introduce advance disposal fees to finance this. At the same time, the thermal utilisation of these materials in plants without carbon capture and storage (CCS) shall be prohibited.
3. *Managing Carbon pool in the building stock:* The building permit for a future new or a replacement building shall assure that the new building built has at least as much biogenic carbon as what was present on the property before (demolition and) construction ("prohibition of reduction").
4. *End of pipe solution:* Equipping waste incineration plants and waste wood cogeneration plants with CCS throughout a country or in individual cities and municipalities, combined with a legal obligation to dispose of combustible construction waste in such plants, represents a possible alternative for ensuring permanence. Cities and municipalities can introduce a corresponding voluntary commitment for their own properties.

There are certainly further options on the level of individual buildings, of building stocks or of countries about how to ensure that the biogenic carbon present in buildings is not being reemitted within at least 1'000 years. In the next section a possible solution on building stock level is described.

6.3.3 Interrelationship between individual buildings, a building stock and forests

The LCA of one single building or one single construction material fails to grasp the dynamics of building stocks. The fundamental question for building owners, investors and public authorities is how the use of biobased materials, that temporarily store biogenic carbon, can contribute to a permanent storage and therefore permanent effect on the change in global mean temperature.

Such a permanent climate effect can be achieved either on each individual building or on building stock level. Options on how to ensure legally binding regulation of permanent carbon removal on a individual building are described in the previous Section 6.3.2. Permanent carbon storage and thus accountable carbon removal may also be achieved on a building stock level as is described below.

Permanent carbon storage on building stock level requires a steady state flow of biogenic carbon contained in biobased materials in and out of a building stock during at least 1'000 years. Future accountable carbon removal requires biogenic carbon inflows into the building stock higher than its outflows. Ideally the net inflow rate is constantly increased during the next decades.[19] This approach is independent of the kind of waste management (or recycling or reuse) of biobased materials that flow out of the building stock. it requires more than 1'000 years monitoring of biogenic carbon flows in building stocks.

To ensure net inflow of biogenic carbon national laws and regulations need to contain legal provisions on the minimum biogenic carbon inflow rate into new buildings and major renovations, expressed in kg C/m^2. This minimum inflow rate depends on the current level of biogenic carbon content in the national building stock and the end of life treatment of outflowing bio-based materials and should be steadily increased in future.

---

[19] Like when water is poured into a well with a hole in the bottom. The well can still be full of water as long as the same amount of water into the well as flows out of it. And the volume in the well increases if there is a net inflow of water.

The stock of biogenic carbon in buildings shall not be increased at the expense of the carbon stock of forests. Whether or not a strong inflow of biogenic carbon into building stocks leads to a depletion of the carbon stock in forests is currently hardly known nor assessed. There is one recent study from Gingrich et al. (2025) addressing this issue.

6.4 Effects of short and long term carbon storage in global warming

NETs with temporary CO_2 storage have two possible applications within a climate strategy, which can also be combined. On the one hand, temporary NETs can be used in the same way as permanent NETs, but the loss of the stored CO_2 must be recorded and accounted for like a CO_2 emission. For example, in order to constantly offset residual emissions with temporary NETs to net zero, NETs must be operated again to the extent of the re-emitted CO_2 during the loss of the storage. On the other hand, temporary NETs can be used in addition to permanent NETs, while the latter first completely offset the remaining residual emissions to net zero and later cause net negative emissions (on balance, more CO_2 is removed from the atmosphere than is emitted at the same time). Net zero is thus achieved earlier and the temperature maximum is dampened.

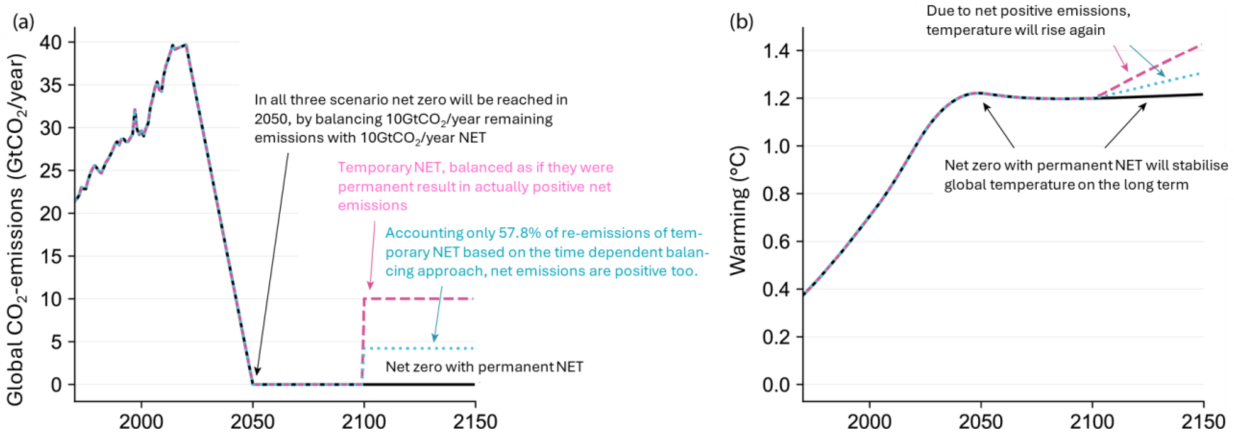

Figure 12 Global CO_2 emissions for three fictitious scenarios (a) and the resulting warming (b). All three scenarios reach net-zero CO_2 emissions after 2050 in the man-made balance (= formal), whereby the actual CO_2 emissions can be positive. Net-zero scenario with permanent NET (black), with temporary NET and a formally ignored loss of stored CO_2 after 50 years (red, dashed) and with temporary NET, where only 57.8% of the re-emissions from the loss of stored CO_2 are formally accounted for according to the time dependent accounting approach (blue, dotted). The warming only includes the CO_2 effects, but ignores the effects of other greenhouse gas and air pollutant emissions that prevail in reality; adapted from (Frischknecht & Pfäffli 2023).

The incorrect calculation of temporary NETs can have serious consequences for achieving climate targets. To illustrate this, three scenarios were simulated using the Finite Amplitude Impulse Response simple climate model (FaIR; Millar et al. 2017; Smith et al. 2018) and visualised in Figure 12. In all three scenarios, global CO_2 emissions are reduced linearly to net zero between 2020 and 2050. It is assumed that after 2050 in a formal balance, i.e. a man-made balance, the remaining residual emissions of 10 $GtCO_2$/year are offset with NET of 10 $GtCO_2$/year to net zero in each case.

In the first scenario (black), permanent NETs are used and thus the actual CO_2 emissions are identical to the formally balanced emissions. This means that there is no additional warming once net-zero CO_2 emissions have been achieved.

In the second scenario (red, dashed), temporary NETs with a CO_2 storage period of 50 years are used, but formally recognised as permanent NETs. As a result, the actual CO_2 emissions after 50 years in 2100 are positive because the residual emissions of 10 $GtCO_2$/year and the loss of stored CO_2 (another 10 $GtCO_2$/year) are incompletely offset by the negative emissions of 10 $GtCO_2$/year achieved in this year. In the formal balance sheet, the re-emissions are ignored, so that it still simulates a CO_2 balance of net zero. Due to the positive net emissions, the temperature rises again.

In the third scenario (blue, dotted), it is taken into account that the NETs used only have a temporary CO_2 storage capacity of 50 years, but based on the time dependent balancing approach (Ministère de la Transition Ecologique 2021), only around 58 % of the re-emissions are recognised as such. This means that from 2100 onwards, NETs will only be operated to the tune of around 5.8 $MtCO_2$/year. The actual CO_2 balance after 2100, on the other hand, is positive, which increases the temperature again.

To summarise, NETs with temporary CO_2 storage have a positive effect on global temperature, but they must be correctly accounted for. It would be valuable to quantify this benefit and assess it accordingly. However, the benefit should not be offset as a ‘discount’ on re-emissions due to the loss of CO_2 storage, as this would otherwise lead to an unconscious increase in global temperature.

7 Definition of Net zero WLC buildings

7.1 Requirements

7.1.1 Introduction

On the level of an individual building an appropriate assessment of the climate change effect of biogenic Carbon stored in buildings is challenging and requires a firm legal and technical framework. An attempt is made to formulate the preconditions and requirements to be met for a net zero whole life cycle Carbon building. After intensive discussions among the experts, two major positions became apparent. They differ in the treatment and consideration of electricity produced onsite and exported to the grid and are described in Section 7.1.2 (majority of authors of this report) and in Section 7.1.3 (minority of authors of this report).

7.1.2 Requirements for net zero WLC buildings

Buildings and some of its materials offer the opportunity to remove and permanently store biogenic or atmospheric carbon. They also offer the opportunity to reduce greenhouse gas emissions with the help of onsite electricity generation which is partly exported to the grid. The exported electricity may potentially reduce greenhouse gas emissions beyond the system boundary of the building. According to FprEN 15978:2025 such potential emission reductions are reported in Module D2. They shall not be confused nor mixed with negative emissions resulted by carbon removal measures (which includes permanent storage).

That is why a majority of the authors **excludes potentially avoided emissions**[20] in the assessment of buildings with net zero greenhouse gas emissions, or ‘NZWLCC buildings’ for short and proposes that the following should apply:

- The system boundary includes production, construction, maintenance including replacement, operation and end of life (whole life cycle).[21]
- The reduction of greenhouse gas emissions remains the primary approach (ambitious national target and guidance values must be met) and is always preferable. Hence, their whole life cycle greenhouse gas emissions per m^2 should be ambitiously low.
- Contributions from carbon dioxide removal methods (negative emission technologies) with a high degree of permanence (i.e., >1’000 years) are permitted to balance for “hard to avoid” greenhouse gas emissions. Corresponding carbon removal certificates need to be purchased and kept.
- Greenhouse gas emissions caused by energy and material expenditure and losses in the provision of carbon removal must be taken into account.
- Potentially avoided emissions and emission reductions, for instance generated with the export of electricity generated with building integrated or attached photovoltaic, do not remove CO_2 from the atmosphere and thus do not count as carbon removal.

---

[20] The D2 as additional and separate information can be interpreted as „contribution to decarbonatisation of the grid“.

[21] Allocation based on physical causality is used to determine the share of greenhouse gas emissions attributed to the building (self-consumed electricity, PV panel frame and cover glass in case of building integrated PV) on one hand and to the electric utility purchasing the exported electricity on the other.

If the negative CO_2 emissions from the building materials and components used in the building are not sufficient to balance the greenhouse gas emissions from construction and operation, a building owner can use eligible third party negative emission certificates to achieve net-zero greenhouse gas emissions.

Buildings that require additional eligible certificates in order to achieve net-zero greenhouse gas emissions in production, construction, maintenance, operation and end of life must be specially labelled.

The eligibility of CO_2 certificates is given for measures to remove CO_2 from the atmosphere combined with long-term sequestration (at least 1’000 years, Brunner et al. 2024).

7.1.3 Requirements for net zero WLC buildings, including potentially avoided emissions

Buildings that produce electricity serve not only a building function (such as housing or hosting activities), but also an energy production function that must be accounted for. Buildings are contributing to the transition toward a net-zero carbon society by producing energy for other users. Accounting for exported electricity in addition to the self-consumed part of the produced energy allows a more global optimization of the overall system, as the energy-producing system's benefit (exported electricity) is accounted for, which is particularly important if the grid is carbon-intensive. Accounting for exported electricity also ensures consistent results at the building and neighbourhood scale, as the level of self-consumption would be larger at the neighbourhood or district than at the building scale.

A minority of the authors proposes alternative requirements for energy-producing buildings with net-zero greenhouse gas emissions, **including potentially avoided emissions**:

- The system boundary includes production, construction, maintenance including replacement, operation, including exported electricity, and end of life.[22]
- The reduction of greenhouse gas emissions remains the primary approach (ambitious national target and guidance values must be met) and is always preferable. Hence, their whole life cycle greenhouse gas emissions per m^2 should be ambitiously low.
- Contributions from carbon dioxide removal methods (negative emission technologies) with a high degree of permanence (i.e., >1’000 years) are permitted to balance for “hard to avoid” greenhouse gas emissions. Corresponding carbon removal certificates need to be purchased and kept.
- Greenhouse gas emissions resulting from energy and material expenditures and losses in the provision of carbon removal must be taken into account.
- Potentially avoided emissions and emission reductions are integrated (but are displayed separately from carbon removal, e.g. from biogenic carbon), or the system should be expanded to incorporate a potential supplementary electricity production.

If the negative and avoided emissions from the building materials and components used in the building are not sufficient to offset and balance, respectively, the greenhouse gas emissions from construction and operation, a building owner can use eligible third-party negative emission certificates to achieve net-zero greenhouse gas emissions including potentially avoided emissions.

Buildings that require additional eligible certificates in order to achieve net-zero greenhouse gas emissions including potentially avoided emissions in production, construction, maintenance, operation, and end of life must be specially labelled.

---

[22] Greenhouse gas emissions of the entire PV system are attributed to the building.

The eligibility of CO_2 certificates is given for measures to remove CO_2 from the atmosphere combined with long-term sequestration (at least 1’000 years, Brunner et al. 2024).

7.2 NZWLC building

A building with net-zero whole life cycle greenhouse gas emissions has minimum greenhouse gas emissions for production, construction, use, maintenance, repair, replacement, operation[23] and end of life over its entire life cycle (“close to zero”) and reduces the remaining greenhouse gas emissions from construction and operation that are difficult to avoid to net zero through accountable carbon dioxide removals (negative CO_2 emissions). Carbon dioxide removals (negative CO_2 emissions) can be accounted for if the permanent (>1’000 years) removal of atmospheric and biogenic CO_2 is legally secured and corresponding carbon removal certificates are purchased and kept together with the negative emission construction materials used in the building.

CO_2 that is stored in building materials based on renewable raw materials and in mineral-organic building materials in the form of biogenic carbon and for which there is a legally binding obligation for permanent storage (>1’000 years) is deemed to be an accountable carbon dioxide removal (negative emission). The eligibility also applies to atmospheric CO_2, which is permanently bound by forced carbonation in mineral building materials used in the building for which the corresponding carbon removal certificates are purchased and kept.

7.3 Definition of ‘NZWLC building, with ex-situ balancing’

A building with net-zero whole life cycle greenhouse gas emissions has minimum greenhouse gas emissions for production, construction, maintenance including replacement, operation and end of life over its entire life cycle (“close to zero”) and reduces the remaining greenhouse gas emissions from construction and operation that are difficult to avoid to net zero through accountable carbon dioxide removals (negative CO_2 emissions). Carbon dioxide removals (negative CO_2 emissions) can be accounted for if the permanent (>1’000 years) removal of biogenic CO_2 is legally secured and corresponding carbon removal certificates are purchased and kept together with the negative emission construction materials used in the building.

Besides the CO_2 mentioned in Subchapter 7.2 carbon dioxide removal (negative emissions) certificates for CO_2 removal and permanent sequestration (>1’000 years) issued by third parties are eligible (see also Subchapter 4.2).

---

[23] Excluding operational energy use due to user related activities (Module B6.3) and building related users‘ activity (Module B8).

8 Discussion, conclusions and recommendations

8.1 Discussion and conclusions

Buildings and their supply chains are today a major source of greenhouse gas emissions. At the same time buildings are indispensable for social and economic development, for human life and work as they provide the necessary shelter and comfort. To comply with the goals of the Paris agreement, a drastic emission reduction in the area of buildings is urgently needed. And the remaining hard to avoid emissions shall be balanced with CO_2 removed from the atmosphere and safely and permanently stored. In this context net zero whole life greenhouse gas emission buildings seem to be an attractive solution for the building and construction sector's contribution. It may also be questioned whether or not it is appropriate to request net zero and permanent carbon removal for individual buildings. Some argue that permanence of carbon fixed in building materials can more easily be monitored and ensured on building stocks rather than individual buildings.

Leading climate scientists argue that only carbon removal for longer than 1'000 years results in reducing the long-term increase of global mean temperature. This is much longer than the average lifetime of buildings of between a few decades to a century (not considering the tiny share of iconic and historic buildings which may last for centuries). This mismatch between required storage time and the lifetime of a building calls for special measures to ensure effective carbon removal by buildings and cope with the uncertainties that are intrinsic to such long timeframes.

In this report, the characteristics, role and potential of different types of construction materials in removing and storing carbon from the atmosphere are described. While CO_2 embedded in mineral materials by forced carbonation will most likely not be rereleased for thousands of years, the biogenic carbon present in biobased and in mineral-organic materials will likely be reemitted to the atmosphere too early. That is why long-term carbon removal achieved with these materials shall be legally secured; different options exist, some of them on individual buildings, some on building stocks or on national/regional level.

In some life cycle assessment studies of buildings (and also other investment and consumer goods) negative emissions are reported. These negative emissions represent net potential benefits and loads beyond the system boundary of a building. They are the result of a contrafactual scenario established for the export of electricity produced on or at the building with PV systems or for the recycling of construction materials at the end of life of the building. These negative emissions represent an emission reduction elsewhere (not on the building) and shall not be mixed up with CO_2 removal from the atmosphere, which is a real negative CO_2 emission. Nevertheless some authors consider it important to address and quantify these potentially avoided impacts in the assessment of potential net zero greenhouse gas emission buildings. That is why two sets of requirements for net zero WLC buildings are proposed in this report:

The approach supported by the majority of authors includes real and long-term carbon removal measures to balance life cycle based greenhouse gas emissions whereas the other one includes potentially avoided greenhouse gas emissions which reduce the amount of greenhouse gas emissions to be balanced by long-term carbon removal measures.

8.2 Recommendations

8.2.1 Introduction

Based on the contents of this report and the discussions and agreements of the IEA EBC experts, the following recommendations were approved. They are grouped in recommendations to individual building owners, additional recommendations for public entities, institutional investors and owners of building stocks, and additional recommendations for public policy makers.

8.2.2 Recommendations for individual building owners

1. Life cycle related greenhouse gas emissions of buildings shall drastically be reduced.
2. PV systems in and on the building and on its plot of land shall be installed to reduce the operational greenhouse gas emissions of the building and to support electric utilities in reducing the greenhouse gas emission intensity of their electricity mix.
3. Carbon removal technologies with longterm carbon storage are eligible to balance the remaining, hard to avoid greenhouse gas emissions of buildings.
4. The following carbon removal building materials, which offer long-term carbon storage are recommended:
    a. Forced carbonated recycled concrete granulate, if used in its loose form (i.e. not as a raw material of new concrete).
    b. Biobased and mineral-organic building materials with legally binding commitment not to rerelease its biogenic carbon to the atmosphere for at least 1’000 years.
5. Carbon removal certificates shall be purchased and kept together with the building materials mentioned above.
6. If needed, additional long-term carbon removal certificates, issued by BECCS and DACCS plants may be purchased to balance remaining greenhouse gas emissions.

8.2.3 Additional recommendations for public bodies, institutional investors and owners of building stocks

1. An inventory of biogenic carbon stored in the building stock shall be established.[24]
2. Minimum biogenic carbon contents (stored in construction products) of new construction and major renovation projects shall be introduced and the minimum content shall be increased over time. Carbon stocks in forests need to be monitored to avoid their reduction or depletion.
3. The biogenic carbon content of the building stock shall be monitored annually or biannually.

8.2.4 Additional recommendations for public policy makers

1. A regulation on minimum biogenic carbon contents (stored in construction products) of new construction and major renovation projects shall be introduced with an increase of the minimum content over time. If not already in place, a similar national regulation on maintaining the carbon stock in forests shall be introduced at the same time.

---

[24] The scope and the range of assessed products differ considerably between the proposed inventory of biogenic carbon stored in building stocks and the IPCC national inventory reports of Harvested Wood Products. Future work should explore on harmonization potential and synergies bewteen these two perspectives.

2. A regulation on an appropriate end of life treatment of biobased and mineral-organic building materials shall be introduced to prevent early rerelease of its biogenic carbon. x
3. A carbon removal certificate system shall be established and operated based on long-term carbon removal technologies (>1’000 years). This may also cover carbon storage chains.

9 References

Arehart J. H., Hart J., Pomponi F. and D’Amico B. (2021) Carbon sequestration and storage in the built environment. *In: Sustainable Production and Consumption*, **27**, pp. 1047–1063, https://doi.org/10.1016/j.spc.2021.02.028.

Braune L. (2022) Life Cycle Assessment of Biogenic CO2 Permanently Stored in RCA (confidential). Neustark AG, Bern.

Brunner C. (2022) Climate effect of temporarily stored CO_2 within building materials. *In proceedings from: 80. LCA Forum*, ETH Zürich, Switzerland, LCA Forum Association.

Brunner C., Hausfather Z. and Knutti R. (2024) Durability of carbon dioxide removal is critical for Paris climate goals. *In: Communications Earth & Environment*(5:645), pp., https://doi.org/10.1038/s43247-024-01808-7.

Ekvall T. and Weidema B. (2004) System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. *In: Int. J. Life Cycle Assess*, **9**(3), pp. 161-171, retrieved from: DOI: 10.1007/BF02994190.

EN 15804 (2019) EN 15804:2012+A2:2019 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. European Committee for Standardisation (CEN), Brussels.

European Parliament (2024) Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products, Vol. 2024/3012 (ed. Parliament E.). European Parliament, Brussels, Belgium.

FprEN 15978 (2025) FprEN 15978:2025 -Sustainability of construction works - Assessment of environmental performance of buildings - Requirements and guidance, Final Draft. European Committee for Standardisation (CEN), Brussels.

Frischknecht R., Bauer C., Brunner C., Habert G., Heeren N., Jungbluth N., Leionen I., Kuittinen M., Norton A., Passer A., Peuportier B., Schmid H. and Stettler C. (2022) Biogenic carbon and climate change mitigation: silver bullet or flash in the pan?; 80th LCA forum, Swiss Federal Institute of Technology, Zürich, 9 June 2022. *In: Buildings and Cities*, **forthcoming**, pp.

Frischknecht R. and Pfäffli K. (2023) Bilanzierung von Negativemissionen (NET) im Bauwesen. treeze Ltd., preisig:pfäffli, Architekturbüro K. Pfäffli, Uster und Zürich.

Gingrich S., Matej S., Erb K.-H., Haberl H., Le Noë J., Kaufmann L., Magerl A., Schaffartzik A., Wiedenhofer D. and Pauliuk S. (2025) An option space approach to wood use: Providing structural timber for buildings while safeguarding forest integrity. *In: iScience*, **28**(10), pp. 113472, https://doi.org/10.1016/j.isci.2025.113472, retrieved from: https://www.sciencedirect.com/science/article/pii/S258900422501733X.

Göswein V., Reichmann J., Habert G. and Pittau F. (2021) Land availability in Europe for a radical shift toward bio-based construction. *In: Sustainable Cities and Society*, **70**, pp. 102929, https://doi.org/10.1016/j.scs.2021.102929.

Göswein V., Arehart J., Phan-huy C., Pomponi F. and Habert G. (2022) Barriers and opportunities of fast-growing biobased material use in buildings. *In: Buildings and Cities*, **3**, pp. 745-755, DOI: 10.5334/bc.254.

Habert G. (2025) Biogenic carbon storage calculation method: are we solving the right problem? *In proceedings from: Sustainable Built Environment Conference 2025, SBE25*, 25-27 June 2025, Zürich.

Hoxha E., Passer A., Saade M. R. M., Trigaux D., Shuttleworth A., Pittau F., Allacker K. and Habert G. (2020) Biogenic carbon in buildings: a critical overview of LCA methods. *In: Buildings and Cities*, **1**(1), pp. 504-524, http://doi.org/10.5334/bc.46.

IEA (2021) Net zero by 2050; a Roadmap for the Global Energy Sector. International Energy Agency IEA, Paris, France.

IPCC (2013) The IPCC fifth Assessment Report - Climate Change 2013: the Physical Science Basis. Working Group I, IPCC Secretariat, Geneva, Switzerland.

IPCC (2019) Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use, Chapter 12: Harvested Wood Products. IPCC, retrieved from: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch12_HarvestedWoodProducts.pdf.

IPCC AR6 WGIII (2022) CDR Factsheet: Carbon Dioxide Removal. Intergovernmental Panel on Climate Change, Working Group III Mitigation of Climate Change.

KBOB, ecobau and IPB (2022) KBOB/ecobau-Liste 2009/1:2022: Ökobilanzdaten im Baubereich, Version 7.0, Stand Juni 2025. Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren c/o BBL Bundesamt für Bauten und Logistik, retrieved from: http://www.bbl.admin.ch/kbob/00493/00495/index.html?lang=de.

Klingler M. and Savi D. (2021) Harmonisierte Ökobilanzen der Entsorgung von Baustoffen. Büro für Umweltchemie, Zürich, Schweiz.

Levasseur A., Lesage P., Margni M., Deschênes L. and Samson R. (2010) Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *In: Environ. Sci. Technol.* , **44**(8), pp. 3169-3174, https://doi.org/10.1021/es9030003.

Levasseur A., Brandão M., Lesage P., Margni M., Pennington D. W., Clift R. and Samson R. (2012) Valuing temporary carbon storage. *In: Nature Climate Change*, **2**, pp. 6-8, https://doi.org/10.1038/nclimate1335

Li N., Mo L. and Unluer C. (2022) Emerging CO2 utilization technologies for construction materials: A review. *In: Journal of CO2 Utilization*, **65**, pp. 102237, https://doi.org/10.1016/j.jcou.2022.102237.

Lützkendorf T., Balouktsi M. and et al. (2023) Context-specific assessment methods for life cycle-related environmental impacts caused by buildings. International Energy Agency IEA, Energy in Buildings and Communities Technology Collaboration Programme EBC, Uster, 10.5281/zenodo.7468316.

Maierhofer D., Alaux N., Vašatko H., Saade M., Stavric M. and Passer A. (2024a) The influence of biogenic carbon assessment assumptions on biogenic global warming results–case study of an innovative mycelium-based composite block. *In proceedings from: IOP Conference Series: Earth and Environmental Science*, IOP Publishing.

Maierhofer D., van Karsbergen V., Potrč Obrecht T., Ruschi Mendes Saade M., Gingrich S., Streicher W., Erb K.-H. and Passer A. (2024b) Linking forest carbon opportunity costs and greenhouse gas emission substitution effects of wooden buildings: The climate optimum concept. *In: Sustainable Production and Consumption*, **51**, pp. 612-627, https://doi.org/10.1016/j.spc.2024.08.021, retrieved from: https://www.sciencedirect.com/science/article/pii/S2352550924002471.

Matthews H. D., Zickfeld K., Dickau M., MacIsaac A. J., Mathesius S., Nzotungicimpaye C.-M. and Luers A. (2022) Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario. *In: Communications Earth & Environment*, **3**(1), pp. 65, 10.1038/s43247-022-00391-z, retrieved from: https://doi.org/10.1038/s43247-022-00391-z.

Matthews H. D., Zickfeld K., Koch A. and Luers A. (2023) Accounting for the climate benefit of temporary carbon storage in nature. *In: Nature Communications*, **12**, pp. 5485, https://doi.org/10.1038/s41467-023-41242-5, retrieved from: https://doi.org/10.1038/s43247-022-00391-z.

Mennibus A. H. d., Zieger V., Camus A., Menibus A. H. d., Vinceslas T., Guévec Y., Troufflard J. and Grasson L. (2019) Dynamic life cycle assessment to compare conventional and bio-based building construction impact on global warming.

Millar R. J., Nicholls Z. R., Friedlingstein P. and Allen M. R. (2017) A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *In: Atmos. Chem. Phys.*, **17**, pp. 7213–7228, https://doi.org/10.5194/acp-17-7213-2017.

Ministère de la Transition Ecologique (2021) Arrêté du 4 août 2021 relatif aux exigences de performance énergétique et environnementale des constructions de bâtiments en France métropolitaine et portant approbation de la méthode de calcul prévue à l'article R. 172-6 du code de la construction et de l'habitation. In: *JOURNAL OFFICIEL DE LA RÉPUBLIQUE FRANÇAISE*, Vol. Texte 23 sur 66, Paris, France.

Ouellet-Plamondon C. M., Ramseier L., Balouktsi M., Delem L., Foliente G., Francart N., Garcia-Martinez A., Hoxha E., Lützkendorf T., Nygaard Rasmussen F., Peuportier B., Butler J., Birgisdottir H., Dowdell D., Dixit M. K., Gomes V., Gomes da Silva M., Gómez de Cózar J. C., Kjendseth Wiik M., Llatas C., Mateus R., Pulgrossi L. M., Röck M., Saade M. R. M., Passer A., Satola D., Seo S., Soust Verdaguer B., Veselka J., Volf M., Zhang X. and Frischknecht R. (2023) Carbon footprint assessment of a wood multi-residential building considering biogenic carbon. *In: Journal of Cleaner Production*, **404**, pp. 136834, https://doi.org/10.1016/j.jclepro.2023.136834.

Pittau F., Krause F., Lumia G. and Habert G. (2018) Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. *In: Building and Environment*, **129**, pp. 117-129.

Pittau F., Iannaccone G., Lumia G. and Habert G. (2019a) Towards a model for circular renovation of the existing building stock: a preliminary study on the potential for CO2 reduction of bio-based insulation materials. *In: IOP Conference Series: Earth and Environmental Science*, pp.

Pittau F., Lumia G., Heeren N., Iannaccone G. and Habert G. (2019b) Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. *In: Journal of Cleaner Production*, pp.

Pittau F. and Habert G. (2021) Methodology for biogenic carbon accounting and carbonation in LCA of buildings and construction products. Eidgenössische Technische Hochschule Zürich, ETH Zürich, Zürich.

Pomponi F., Hart J., Arehart J. H. and D'Amico B. (2020) Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits. *In: One Earth*, **3**, pp. 157-161, https://doi.org/10.1016/j.oneear.2020.07.018.

Priore Y. D., Jakob M., Stettler C., Habert G., Jusselme T. and Tschannen A. (2024) Net-zero greenhouse gas emissions in the building area (NN-THGG). Swiss Federal Office of Energy SFOE, Bern, Switzerland.

Rueda O., Mogollón J. M., Tukker A. and Scherer L. (2021) Negative-emissions technology portfolios to meet the 1.5 °C target. *In: Global Environmental Change*, **67**, pp. 102238, https://doi.org/10.1016/j.gloenvcha.2021.102238, retrieved from: https://www.sciencedirect.com/science/article/pii/S0959378021000170.

Saade M. R. M., Hoxha E., Passer A., Frischknecht R. and Obrecht T. P. (2023) Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon; a contribution to IEA EBC Annex 72, Graz, Austria, 10.3217/978-3-85125-953-7-08.

Savi D. and Klingler M. (2021) Kohlenstoffspeicherung im Holzbau: Potenzial des Gebäudeparks in der Schweiz. Büro für Umweltchemie, Zürich.

Smith C. J., Forster P. M., Allen M., Leach N., Millar R. J., Passerello G. A. and Regayre L. A. (2018) FAIR v1.3: a simple emissions-based impulse response and carbon cycle model. *In: Geosci. Model Dev.*, **11**, pp. 2273–2297, https://doi.org/10.5194/gmd-11-2273-2018.

Smith P., Davis S. J., Creutzig F., Fuss S., Minx J., Gabrielle B., Kato E., Jackson R. B., Cowie A., Kriegler E., van Vuuren D. P., Rogelj J., Ciais P., Milne J., Canadell J. G., McCollum D., Peters G., Andrew R., Krey V., Shrestha G., Friedlingstein P., Gasser T., Grübler A., Heidug W. K., Jonas M., Jones C. D., Kraxner F., Littleton E., Lowe J., Moreira J. R., Nakicenovic N., Obersteiner M., Patwardhan A., Rogner M., Rubin E., Sharifi A., Torvanger A., Yamagata Y., Edmonds J. and Yongsung C. (2016) Biophysical and economic limits to negative CO2 emissions. *In: Nature Climate Change*, **6**(1), pp. 42-50, 10.1038/nclimate2870, retrieved from: https://doi.org/10.1038/nclimate2870.

Smith S. M., Geden O., Gidden M. J., Lamb W. F., Nemet G. F., Minx J. C., Buck H., Burke J., Cox E., Edwards M. R., Fuss S., Johnstone I., Müller-Hansen F., Pongratz J., Probst B. S., Roe S., Schenuit F., Schulte I. and Vaughan N. E., (eds.) (2024) The State of Carbon Dioxide Removal 2024 - 2nd Edition, DOI 10.17605/OSF.IO/F85QJ (2024).

Steinberger-Maierhofer D., Alaux N., Ramon D., Popek S., Potrč Obrecht T., Kockat J., Zhong X. M., Alessio , Mendes Saade M. R., Allacker K., Passer A. and Röck M. (2025) Carbon Dioxide Storage and Removal in EU Buildings (Preprint, not peer reveiwed). *In*, pp., http://dx.doi.org/10.2139/ssrn.5390549

Talandier G., Lasvaux S., Duret A. and Citherlet S. (2016a) Projet Bâti-Tech Volet 3 - Rapport méthodologique d'analyse du cycle de vie des co-produits de l'agriculture du chanvre (confidentiel). HES-SO, HEIG-VD, LESBAT, Yverdon-les-Bains, CH.

Talandier G., Lasvaux S., Duret A. and Citherlet S. (2016b) Projet Bâti-Tech Volet 3 - Rapport méthodologique d'analyse du cycle de vie du béton de chanvre (confidentiel). HES-SO, HEIG-VD, LESBAT, Yverdon-les-Bains, CH.

Tanzer S. E. and Ramírez A. (2019) When are negative emissions negative emissions? *In: Energy & Environmental Science*, **12**(4), pp. 1210-1218, 10.1039/C8EE03338B, retrieved from: http://dx.doi.org/10.1039/C8EE03338B.

United Nations Environment Programme (2024) Global Status Report for Buildings and Construction: Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector UN Environment Programme, Nairobi, https://doi.org/10.59117/20.500.11822/45095.

University of Oxford (2024) The Oxford Principles for Net Zero Aligned Carbon Offsetting (revised 2024). University of Oxford, Oxford, United Kingdom.

Van Roijen E., Sethares K., Kendall A. and Miller S. A. (2024) The climate benefits from cement carbonation are being overestimated. *In: nature Communications*, **15**, pp. 4848, https://doi.org/10.1038/s41467-024-48965-z.

Ventura A. (2023) Conceptual issue of the dynamic GWP indicator and solution. *In: Int J Life Cycle Assess*, **28**, pp. 788-799, https://doi.org/10.1007/s11367-022-02028-x.

WBCSD and WRI (2004) The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard. World Business Council for Sustainable DevelopmentWorld Resources Institute.

Weidema B. (2001) Avoiding co-product allocation in life-cycle assessment. *In: Journal of Industrial Ecology*, **4**(3), pp. 11-33.

Werner F. and Frischknecht R. (2018) Technische Grundlagen zur Prüfung eines Wechsels auf die europäischen EPD Normen für die ökologische Bewertung von Baustoffen und Gebäuden. cemsuisse, Lignum, Stahlbau Zentrum Schweiz, KBOB, BAFU, AHB Stadt Zürich, Zürich & Uster.

Zickfeld K., Azevedo D., Mathesius S. and Matthews H. D. (2021) Asymmetry in the climate–carbon cycle response to positive and negative CO2 emissions. *In: Nature Climate Change*, **11**, pp. 613 - 617.

Zickfeld K., MacIsaac A. J., Canadell J. G., Fuss S., Jackson R. B., Jones C. D., Lohila A., Matthews H. D., Peters G. P., Rogelj J. and Zaehle S. (2023) Net-zero approaches must consider Earth system impacts to achieve climate goals. *In: Nature Climate Change*, **13**, pp. 1298-1305, https://doi.org/10.1038/s41558-023-01862-7.