Bio-based building products in the Dutch Environmental Database (NMD)

Part 1: Proposal for crediting biogenic carbon storage

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This study was carried out by Wageningen Food & Biobased Research with input from Centrum Hout, Agrodome and Foundation NMD

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Contents

Samenvatting

De Nederlandse overheid streeft ernaar om de CO_2-uitstoot in 2030 met 49% te verminderen en in 2050 vrijwel netto nul CO_2-uitstoot te realiseren om klimaatverandering tegen te gaan. De bouwsector kan een belangrijke bijdrage leveren aan dit doel door bio-based en circulaire bouwproducten toe te passen. Door gebruik te maken van duurzaam geproduceerde bio-based materialen, wordt CO_2 dat recent uit de atmosfeer is opgenomen, opgeslagen als biogene koolstof[1] in plantaardige materialen zolang deze in een gebouw zijn verwerkt. Deze opslag van biogene koolstof betekent feitelijk een tijdelijke maar langdurige negatieve broeikasgasemissie (GHG), waardoor tijd wordt gekocht om de samenleving te transformeren naar een vrijwel broeikasgasemissie-neutrale economie en ruimte wordt gecreëerd om klimaatdoelen te halen. De waarde van langdurige biogene koolstofopslag is echter niet opgenomen in standaard LCA-normen en -richtlijnen, noch wordt deze meegerekend bij het bepalen van de milieu-impact van gebouwen (in het Nederlands 'Milieu Prestatie Gebouwen', MPG).[2]

Het doel van deze studie is tweeledig: 1) Het beoordelen van wetenschappelijke benaderingen voor het kwantificeren van het effect van biogene koolstofopslag in bouwmaterialen op klimaatverandering (in het Engels 'global warming potential', GWP); 2) Een algemeen toepasbare methodologie opstellen om het GWP-voordeel van materialen in duurzame bouwtoepassingen te valoriseren, in lijn met de Bepalingsmethode (zie voetnoot).

Het GWP-voordeel komt voort uit de langdurige reductie van de CO_2-concentratie in de atmosfeer, dat het resultaat is van recente vastlegging van CO_2 uit de atmosfeer als biogene koolstof in plantaardige materialen en daaropvolgende langdurige toepassing van dit materiaal in bijvoorbeeld gebouwen. Daarom levert langdurige opslag van biogene koolstof een GWP-voordeel op.

De verschillende wetenschappelijke benaderingen voor het bepalen van het effect van biogene koolstofopslag op GWP die in de literatuur worden beschreven, vertonen slechts kleine verschillen voor het GWP-voordeel bij bepaalde opslagtijden. De 'dynamische LCA-methode' is het meest nauwkeurig in het beschrijven van de effecten in de loop van de tijd en wordt daarom geselecteerd als basis voor het toekennen van de waarde van biogene koolstofopslag in bouwmaterialen. Het GWP-voordeel kan worden berekend door het vermenigvuldigen van de volgende factoren:

1. de massa van bio-based materiaal; voorwaarde is dat het bio-based materiaal duurzaam is verkregen.
2. het biogene koolstofgehalte van dat materiaal; een eerste experimentele analyse toont aan dat deze waarde verband houdt met de chemische samenstelling van het materiaal, variërend van ongeveer 430 g koolstof per kg droge lignocellulosevezels (bijv. katoen, vlas, hennep) tot ongeveer 500 g/kg droog hout en tot 685 g/kg droge geëxpandeerde kurk.
3. de verhouding tussen de moleculaire massa's van CO_2 en koolstof, zijnde 3,67.
4. de GWP-voordeelfactor, die verband houdt met de levensduur van het bouwproduct en de tijdshorizon waarvoor broeikasgaseffecten worden meegewogen. Deze tijdshorizon is een beleidsbeslissing die lang genoeg moet zijn om te voorkomen dat problemen naar de toekomst worden doorgeschoven (d.w.z. lang genoeg om adequate oplossingen te ontwikkelen om de klimaatsituatie tegen die tijd het hoofd te bieden) en kort genoeg om nu effectieve acties te ondernemen. De meeste normen, experts en overheden hanteren een tijdshorizon van 100 jaar.
5. de netto biogene opslagratio. Deze factor is afhankelijk van de herkomst van de bio-based grondstof en de toepassingsomstandigheden, en varieert van 1 voor nieuwe bio-based materialen in nieuwbouwwoningen en uitbreidingen van woningen, tot 0 voor het gebruik van hergebruikte of gerecyclede materialen en voor renovatie wanneer afvalmateriaal wordt verbrand met CO_2-uitstoot in de atmosfeer.

[1] Biogene koolstof is koolstof die recentelijk is opgeslagen in biologische materialen zoals bomen en planten.
[2] De MPG wordt bepaald volgens de zogenaamde Bepalingsmethode en moet voldoen aan een maximum waarde om een bouwvergunning in Nederland te verkrijgen.

Biogene koolstofopslag levert een GWP-voordeel op dat aanvullend is op zowel standaard LCA-berekeningen als op rekentools voor het bepalen van de milieu-impact, zoals bijvoorbeeld volgens de Bepalingsmethode. Daarom is er geen sprake van dubbeltelling bij het toekennen van de tijdelijke maar langdurige biogene koolstofopslag.

Er wordt voorgesteld om de GWP-voordelen van langdurige biogene koolstofopslag in bio-based bouwmaterialen te waarderen via een van de volgende opties:

- In module D van de Bepalingsmethode.
- Als een aanvullende parameter in de MPG-rekentools, voor overwegingen anders dan het opnemen in de enkelvoudige MPG-score.
- In koolstofvastleggingscertificaten.

Producten op basis van fossiele brandstoffen kunnen ook koolstof bevatten, maar deze koolstof is afkomstig van CO_2 dat lang geleden uit de atmosfeer is gehaald en levert daarom op dit moment geen vermindering van de CO_2-concentratie in de atmosfeer op. De voorgestelde methode is op gelijke wijze van toepassing op alle bouwmaterialen. Bio-based materialen bevatten echter wel biogene koolstof, terwijl fossiele materialen dat niet bevatten.

Biogene koolstofopslag in bouwmaterialen is een langdurig maar tijdelijk GWP-voordeel. Er zijn verdere acties nodig voor de ontwikkeling en implementatie van technologieën en andere maatregelen om te komen tot een permanente vermindering van broeikasgasemissies en aanpassing aan klimaat-verandering.

Summary

The Dutch Government targets to reduce CO_2 emissions by 49% in 2030, and to virtually net zero CO_2 emissions by 2050, in order to combat climate change. The building and construction sector can contribute significantly to this goal by applying bio-based and circular building products. By using sustainably sourced bio-based materials, CO_2 which has been taken up recently from the atmosphere will be stored as biogenic carbon[3] in materials for as long as these are incorporated in a building and eventually in subsequent recycled products. This storage of biogenic carbon actually means a temporary yet long term negative greenhouse gas (GHG) emission, thus buying time to transform our society into a virtually GHG emission neutral economy and creating space to reach climate goals. However, the value of long term biogenic carbon storage is not included in standard LCA standards and guidelines, nor credited when determining the environmental impact of buildings (in Dutch 'Milieu Prestatie Gebouwen', MPG).[4]

The objective of this study is to review scientific approaches for quantifying the effect of biogenic carbon storage in building materials on global warming potential (GWP), which is the LCA impact parameter for climate change, and to draft a generally applicable methodology to valorise the GWP benefit of materials in durable building applications, in-line with the Determination Method (see footnote).

The GWP benefit arises from the long term reduction of CO_2 concentration in the atmosphere, which is a result of (most recent) sequestration of CO_2 from the atmosphere as biogenic carbon in plant materials and subsequent long term application of this material in e.g. buildings. Therefore, all long term biogenic carbon storage presents a GWP benefit.

The different scientific approaches for determining the effect of biogenic carbon storage on GWP described in literature exhibit only small differences for the GWP benefit at given storage times. The 'dynamic LCA method' is the most accurate in describing the effects over time and is therefore selected as the basis for crediting the value of biogenic carbon storage in building materials. The GWP benefit can be calculated as the product of:

1. the mass of bio-based material; precondition is that the bio-based material is sustainably sourced.
2. the biogenic carbon content of that material; initial experimental analysis shows that this value relates to the chemical composition of the materials, ranging from about 430 g carbon per kg of dry lignocellulose fibres (e.g. cotton, flax, hemp) to about 500 g/kg of dry wood and up to 685 g/kg of dry expanded cork.
3. the ratio between the molecular masses of CO_2 and carbon, being 3.67.
4. the GWP benefit factor, which relates to the service life of the building product and the time horizon for which GHG effects are considered. This time horizon is a policy decision which needs to be long enough to avoid passing on problems to the future (i.e. long enough to develop adequate solutions to cope with the climate situation by that time) and short enough to achieve productive action now. Most standards, experts and governments have adopted a time horizon of 100 years.
5. the net biogenic storage ratio. This factor depends on bio-based feedstock origin and the application conditions, and ranges from 1 for virgin bio-based materials in new-built houses and extension of houses, to 0 for using reused or recycled materials and for renovation if scrapped material is decomposed with CO_2 emission to the atmosphere.

Biogenic carbon storage presents a GWP benefit which is additional to both standard LCA calculations as well as to environmental impact calculation tools like e.g. the Determination Method. Therefore, no double counting is involved when crediting the temporary yet long term biogenic carbon storage.

[3] Biogenic carbon is the carbon that has been recently stored in biological materials, such as trees and crops.
[4] This MPG needs to be quantified according to the so called Determination Method and has to meet a maximum target level in order to allow successful application for a building permit in the Netherlands.

It is proposed to credit the GWP benefits of temporary biogenic carbon storage in bio-based building materials via one of several options:

- In module D of the Dutch Determination Method.
- As an additional parameter in the MPG tool, for consideration otherwise than including in the single score MPG calculation.
- In carbon credit certification schemes.

Fossil based products may also contain carbon, however, this carbon is derived from CO_2 extracted from the atmosphere long time ago, and consequently does not deliver a reduction of CO_2 concentration in the atmosphere at present. The proposed methodology applies equally for all building materials. However, bio-based materials do contain biogenic carbon, whereas fossil-based materials do not.

Biogenic carbon storage is a long term yet temporary GWP benefit. Further action is required for the development and implementation of technologies and other measures to achieve permanent GHG emission reductions and climate change adaptation.

1 Introduction

Reduction of green house gas (GHG) emissions by biogenic carbon storage

The Dutch Government targets to reduce CO_2 emissions by 49% in 2030, and virtually net zero CO_2 emissions by 2050, in order to combat climate change. The building and construction sector can contribute significantly to this goal by applying bio-based and circular building products. By using bio-based materials, CO_2 which has been taken up from the atmosphere will be stored as biogenic carbon in materials for as long as these are incorporated in a building and eventually in subsequent recycled products. This storage of biogenic carbon actually means a temporary yet long term negative GHG emission,[5] thus buying time to transform into a GHG emission neutral economy and creating space to reach climate goals.

Quantification of environmental impacts – Value of biogenic carbon storage not credited

Since 2013[6] the environmental impact of buildings (in Dutch 'Milieu Prestatie Gebouwen', MPG) needs to be quantified when applying for a building permit in the Netherlands, and maximum impact levels are decreased over time in order to steer the transition to lower environmental impacts, including lower GHG emissions. The dedicated methodology which is currently used to quantify the environmental impact of buildings and constructions is: The Environmental Performance of Buildings and civil engineering works Determination Method ('Determination Method' in short).[7] This method has been developed in order to calculate the material-related environmental performance of buildings and civil engineering works over their entire life cycle in a clear and verifiable manner. However, the value of long term biogenic carbon storage is not credited in this Determination Method.

Objective of this study

The objective of this TKI Agri & Food funded study[8] is to review scientific approaches for accounting for temporary biogenic carbon storage and draft a general applicable methodology to quantify and valorise the negative CO_2 emissions of bio-based materials in durable building applications in-line with the Determination Method.

In a previous study, SGS has drafted a proposal, starting from the Methodology end;[9] in this report researchers start from the available scientific models to draft a proposal, and forming an addition to the SGS study.

Concept of biogenic carbon storage and crediting its value

Plants absorb CO_2 from the atmosphere during growth. When applying bio-based products in a building, this absorbed CO_2 is stored as biogenic carbon (chapter 2) for the period of time that the product is used in that building (chapter 3). Ultimately, the bio-based product is decomposed into CO_2 and water at the end of a single or multiple lives, and the CO_2 will be released in the atmosphere again.

The stored biogenic carbon may be regarded as temporarily negative CO_2 emissions under specific conditions: Sustainable crop management (presented in chapter 4) and the use of a net positive volume of bio-based materials in buildings and other durable applications (chapter 5). Where 'temporarily' means the duration of product service life, e.g. 75 years or more. The 'negative CO_2 emissions' mean a reduction/delay of the greenhouse effect and allowing mankind some more time to find and implement

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[5] Levasseur A, Brandão M, Lesage P, Margni M, Pennington D, Clift R, Samson R, (2012) Valuing temporary carbon storage. Nature Climate Change 2:6-8.

[6] Dutch Buildings Decree, 1 January 2013. (see section 2.4 of Guide 2020)

[7] In Dutch 'Bepalingsmethode Milieuprestatie Bouwwerken', 'Bepalingsmethode' in short. https://milieudatabase.nl/media/filer_public/89/42/8942d5dd-8d37-4867-859a-0bbd6d9fb574/bepalingsmethode_milieuprestatie_bouwwerken_maart_2022_engels.pdf

[8] https://www.wur.nl/nl/onderzoek-resultaten/onderzoeksinstituten/food-biobased-research/show-fbr/milieu-prestatie-biobased-bouwmaterialen-in-de-nationale-milieudatabase.htm

[9] SGS Search, 2022. 'Voorstel berekeningsmethodiek om koolstofvastlegging in biobased bouwmaterialen te kunnen waarderen', https://www.rijksoverheid.nl/documenten/rapporten/2022/07/29/onderzoek-berekeningsmethodiek-koolstofvastlegging-in-biobased-bouwmaterialen

solutions to address and adapt to climate change. The value of negative CO_2 emissions by temporary yet long term storage of biogenic carbon can be estimated by quantifying the effect of delayed emissions on global warming potential. Models to quantify the effect of delayed CO_2 emissions as presented in literature have been evaluated in chapter 6. Attention is paid to the timing of CO_2 emissions, the relevant period for delaying the CO_2 emissions, and the aspect of bio-based versus fossil-based products (6.4).

Based on the evaluation, a procedure to quantify the GWP benefit as a result of temporary biogenic carbon storage in biobased building materials has been drafted (sections 7.2 – 7.6). This benefit can be credited via an addition to the Determination Method (section 7.1 and 7.7), or through other ways (section 7.1).

2 Quantification of carbon storage in bio-based building products

The amount of biogenic carbon stored in bio-based materials relates to the chemical composition of that material, i.e. the several constituent components of the material and their molecular structure. Many lignocellulosic materials, like wood, mainly consist of so called carbohydrates: cellulose, hemicellulose, lignin, and extractives; and to a slight extent protein. The molecular structure of cellulose is unique, and constant for all lignocellulose materials. The other components each have specific main molecular structure characteristics, however, also showing some variation in details, depending e.g. on type of bio-feedstocks. Result of this variation is that the structures of hemicellulose, lignin, pectin and protein cannot be exactly defined into unique chemical formulas. On the other hand, estimates have been provided in literature.

Box 1. Definition of Bio-based
"Bio-based products are wholly or partly derived from materials of biological origin, excluding materials embedded in geological formations and/or fossilised."[10] The type of organism is not limited to plants; animals and lower forms of life (micro-organisms) are also composed of biomass.[11] This means that all feedstocks addressed in Table 6 to Table 8 are considered bio-based.

Box 2. Definition of Biogenic carbon
Biogenic carbon is carbon derived from biomass which has recently absorbed CO_2 from the atmosphere.

2.1 EN 16449 standard on biogenic carbon content in wood

The standard EN 16449 specifies the "calculation of the biogenic carbon content of wood and conversion to CO_2".[12] For the carbon fraction in wood, the standard sets a default value of 0.5, based on the global chemical composition of wood, mentioned to vary in the ranges 40-55% for cellulose, 12-15% for hemicellulose, 15-30% for lignin and 2-15% for extractives. Based on the molecular masses of CO_2 and carbon, 44 and 12 Da respectively, it can be calculated that 1 tonne of carbon contained in oven dry wood stores 3.67 tonnes of CO_2 absorbed from the atmosphere. According to the default value of 0.5 assumed in EN 16449, 1 tonne of oven dry wood contains 1.84 tonnes of CO_2 absorbed from the atmosphere, and 1 m^3 of oven dry wood having a density of 500 kg/m^3 contains 0.92 tonne of CO_2.

EN 16449 also presents the general formula to calculate the amount of CO_2 absorbed in a bio-based material containing any carbon fraction, and at a certain moisture content:

$$P_{CO_2} = \frac{M_{CO2}}{M_C} * cf * \frac{\rho_\omega * V_\omega}{1+\frac{\omega}{100}} \qquad \text{(equation 1)}$$

Where:
P_{CO2} = amount of CO_2 absorbed from the atmosphere in a volume of bio-based material, in kg
M_{CO2} = molecular mass of CO_2, 44 Da
M_C = atomic mass of carbon, 12 Da
cf = carbon fraction of oven dry bio-based material

[10] https://ec.europa.eu/growth/sectors/biotechnology/bio-based-products_en
[11] https://biobasedeconomy.nl/wp-content/uploads/2019/11/Biomass-for-the-circular-economy-EN-site.pdf
[12] EN 16449: Wood and wood-based products - Calculation of the biogenic carbon content of wood and conversion to carbon dioxide. https://www.nen.nl/nen-en-16449-2014-en-193510

ω = moisture content of bio-based material, in wt.%
ρ_ω = density of bio-based material at that moisture content, in kg/m^3
V_ω = volume of solid bio-based material at that moisture content, in m^3

Nevertheless, the standard does not discriminate on carbon fraction per type of wood, and sets a default value of 0.5 for all wood species, regardless of the type of wood and the actual amount of CO_2 stored in them.

2.2 Carbon content of wood (Literature review)

The chemical composition and carbon content of wood species has been studied since the early 1900's.[13] The vast majority of average carbon contents of about 50 species, reviewed by Matthews in 1993, is in the range 48 – 51%, concluding that broadleaf species tend to cluster around 49% and conifers and tropical species around 50%. A more recent review in 2018 by Ma et al.[14] presents carbon content values of 47.7% (± 2.7%) and 50.5% (± 3.1%) for broadleaf and conifer species, based on 1581 and 502 stem samples, respectively. Roughly speaking, this is in line with the factor 0.5 used in EN 16449.

Some wood species relevant for the Dutch building and construction sector have been listed in Table 1.

Table 1 Some wood species relevant for Dutch building and construction sector (indicated by Centrum Hout).

Name	Density * (kg/m^3)	Applications
Poplar (Populus spp.)	440	Decorative inside (walls, floor, ceiling, furniture) and outside (façade)
Spruce (Picea Abies)	460	Timber construction; Stairs; Window frames; OSB; Particle board; etc.
Meranti (Shorea Species)	640	Exterior doors; Window frames
Sapeli (Entandrophragma cylindricum)	650	Upcoming, for e.g.: Exterior doors; Window frames
Azobé (Lophira alata)	1060	Infrastructure, demanding constructions (e.g. Bridges, Sheet piles)
Massarunduba (Manilkara bidentata)	1050	Infrastructure (less demanding than Azobé)

* Average density as presented in Houtvademecum, at 12% moisture content.[15]

For 3 of these species, carbon content data have been found in public literature. These values are summarised in Table 2.

Table 2 Carbon content (wt.%) in selection of in wood species.[13]

Material	Number of tests	Carbon content, cf	
		Range	Average
Poplar	4	49.6 – 50.3	49.9
Spruce	14	47.2 – 52.7	49.8
Massarunduba	4	49.6 – 50.6	50.2

[13] Matthews, 1993. https://www.forestresearch.gov.uk/research/archive-the-carbon-content-of-trees/
[14] Ma et al., 2018. https://bg.copernicus.org/articles/15/693/2018/bg-15-693-2018.pdf
[15] http://www.houtvademecum.com/

2.3 Carbon content in other bio-based feedstocks (Literature)

Whereas different wood species exhibit varying chemical compositions, other bio-based materials contain further differences in composition. F.i. flax and hemp fibres have higher cellulose content and lower lignin content compared to wood, while also containing pectin. Sheep wool mainly consists of keratin, a polypeptide. The main component in cork is suberin, a polyester.

For a number of feedstocks which store CO_2 absorbed from the atmosphere, direct carbon content data have been found, either because the chemical composition mainly consists of one component (e.g. cellulose or shell), or because carbon content has been presented in literature (sheep wool, bamboo) (Table 3).
For other bio-based feedstocks which are (potentially) relevant for building and construction materials (like flax, hemp, etc.) no direct carbon content data have been found. Therefore, in order to explore the carbon content contained in these materials, a 3 step approach is followed: 1) Estimation of carbon share in each of main constituents (Table 3); 2) estimation of constituent composition in bio-based materials (Table 4); 3) calculation of carbon share in bio-based materials (Table 6).

The (estimated) chemical formulas and share of carbon in the main constituents of bio-based materials are summarized in Table 3. The letters C, H, O, N, P and Ca represent carbon, hydrogen, oxygen, nitrogen, phosphorous and calcium, having relative weights of 12, 1, 16, 14, 31 and 40 g/mole, respectively.

Table 3 Chemical formulas of different components present in bio-based materials (exact for cellulose, and approximations for the other components), and the related share of carbon.

Component	Chemical formula	Share of Carbon, cf (kg/kg)
Cellulose	$(C_6H_{10}O_5)_n$ [16]	0.444
Hemicellulose	$(C_5H_8O_4)n + (C_6H_{10}O_5)_n$ [17]	0.455
Lignin	$(C_{81}H_{92}O_{28})_n$ [18]	0.643
Pectin	$(C_6H_{10}O_7)_n$ [19]	0.371
Protein	Range of amino acid based structures [20]	0.534
Polar extractives, like polysacch. oligomers	Similar to (hemi)cellulose	0.450
Apolar extractives, like fatty acids	e.g. $C_{16}H_{32}O_2$	0.750
Suberin	$(C_{112}H_{203}O_{28})$ [21]	0.674
Ceroid (phospholipid)	$C_{48}H_{103}O_8N_4P_1$ [22]	0.644
Tannin	$C_{76}H_{52}O_{46}$ [23]	0.536
Keratin in Sheep wool	[24]	0.505
Ash		0

Each bio-based feedstock shows variation in the share of its constituent components (also called chemical composition), e.g. depending on crop species and agronomic conditions. Based on literature data and a WFBR internal database, the average share of the main components of a range of bio-based feedstocks, on dry matter basis, is presented in Table 4.

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[16] https://en.wikipedia.org/wiki/Cellulose
[17] https://www.sciencedirect.com/topics/engineering/hemicelluloses
[18] Indicative structure/formula. https://pubchem.ncbi.nlm.nih.gov/compound/Lignin_-organosolv
[19] https://pubchem.ncbi.nlm.nih.gov/compound/Pectin
[20] https://www.pnas.org/content/pnas/89/14/6604.full.pdf Carbon share calculated based on amino acid composition.
[21] https://pubs.acs.org/doi/10.1021/jf400577k
[22] https://www.sciencedirect.com/topics/engineering/phospholipid
[23] https://en.wikipedia.org/wiki/Tannic_acid
[24] https://www.chemistryislife.com/the-chemistry-of-sheep-woo

The number of samples analysed per feedstock, as well as the number of components analysed per sample, vary; for instance, protein and ash content are only analysed occasionally. Further, it should be noted that most chemical composition values are presented as determined, so not normalised to 100%. For the calculation of carbon content, the composition data in Table 4 have been normalized to 100%. Details are presented in Annex 1.

The share of carbon in the materials can then be calculated by summation of the multiplications of share of each component in the material (Table 4) and the share of carbon in the component (Table 3). The total sum of shares of components is normalized to 100%. The share of carbon in the materials is presented in Table 6.

Table 4 ***Estimated average chemical composition (%) of bio-based materials (potentially) used in building and construction.***

Material	Cellulose	Hemicell.	Lignin	Pectin	Protein	Polar extractives	Apolar extractives	Ash
Flax bast fibres	73.3	9.1	3.6	2.8	2.0	5.0	2.9	1.3
Hemp bast fibres	74.4	9.0	3.6	3.7	1.7	4.2	1.1	2.3
Flax shives	38.6	19.3	23.3	3.7	2.8	7.1	3.1	2.1
Hemp shives	40.9	29.7	21.3	2.2	1.5	n.d.	2.4	2.0
Wheat straw	34.5	23.8	22.3	2.7	n.d.	6.5	3.4	6.8
Reed	34.8	20.7	28.1	2.1	n.d.	4.2	3.5	6.6

* n.d. = no data.

Table 5 ***Estimated average chemical composition (%) of cork.***

Cellulose	Hemicell.	Lignin	Pectin	Protein	Suberin	Ceriod	Tannin	Polar extr	Apolar extr	Ash
8.2	7.5	21.7	0.4	2.3	35.9	5.5	4.6	6.1	6.4	1.4

As some building materials like wood, cork and bamboo may be traded and applied per m^3, the share of carbon for these materials has also been translated to volume specific data, through the material density.

Because the CO_2 absorbed from the atmosphere during growing is stored as carbon in bio-based materials, the data and calculations in this section so far relate to biogenic carbon. However, in order to quantify the CO_2 removed from the atmosphere during growth, this value per kg of material is presented in Table 6 as well. Due to the relative weights of carbon and oxygen of 12 and 16 g/mole, the amount of absorbed CO_2 can be calculated by multiplying the amount of stored carbon by a factor of 3.67 (=44/12).

Marine shells mainly consist of $CaCO_3$,[25] in which the carbon was recently extracted from the atmosphere. The values for carbon share and CO_2 removed from the atmosphere for marine shells are also included in Table 6.

Sensitivity analysis

At given composition for wood, the carbon share increases about 0.030 kg C/kg material when decreasing cellulose content by 15 wt.% and increasing lignin content by 15 wt.%.

[25] https://en.wikipedia.org/wiki/Calcium_carbonate

Table 6 ***Share of carbon in bio-based materials (potentially) used in building and construction. The last column presents the amount of CO_2 absorbed in the materials.***

Material	**Share of Carbon (kg C/kg material)**	**Density oven dry[26] (kg/m³)**	**Biogenic Carbon (kg C/m³ material)**	**CO_2 removed from atmosphere (kg CO_2/kg material)**
Cellulose	0.444			1.63
Flax bast fibres	0.452			1.66
Hemp bast fibres	0.443			1.63
Flax shives	0.489			1.79
Hemp shives	0.488			1.79
Wheat straw	0.467			1.71
Reed	0.480			1.76
Sheep wool	0.505			1.85
Cork	0.598	110 – 450 [27,28]	66 – 269	2.19
Bamboo	0.492[14]	650 – 1200 [29]	320 – 590	1.81
Poplar	0.499	393	196	1.83
Spruce	0.498	411	205	1.82
Massarunduba	0.502	938	471	1.84
Marine shells	0.120			0.44

Non-validated tool for estimating carbon content

Centrum Hout has developed a (non-validated) tool based on EN 16449 to calculate how much biogenic carbon is stored in a range of wood species.[30] The numbers are delivered as kg of biogenic CO_2 stored per m^3 of wood. Data for a range of wood species commonly used in the Netherlands have been calculated using this tool and presented in Table 7, along with values derived from literature in the exercise in this section above (Table 6). Data calculated by the online Centrum Hout tool are somewhat lower than the values derived in the present study; the lower values presented by the online calculation tool seem to relate to lower densities assumed than presented in Houtvademecum as used in this study.

Table 7 ***Calculated amount of biogenic carbon stored in a range of wood species: Centrum Hout CO_2-storage calculation tool vs. data derived from literature (this study).***

Material	**Density oven dry (kg/m³)**	**Stored CO_2 via online Centrum Hout-tool (kg CO_2/m³ material)**	**Stored CO_2 derived from this study (Table 7) (kg CO_2/m³ material)**
Poplar	393	685	719
Spruce	411	623	748
Meranti	571	779	879
Sapeli	580	1012	
Azobé	946	1635	
Massarunduba	938	1479	1726

Another non-validated tool to calculate carbon storage in materials can be found here. This tool requires registration.

[26] Houtvademecum, https://houtinfo.nl/hout/nieuwe-houtvademecum-%E2%80%93-kennis-inspiratie
[27] Expanded cork: https://www.groenebouwmaterialen.nl/pro-suber-kurkisolatie.html
[28] Flooring: https://www.apcor.pt/wp-content/uploads/2015/07/Caderno_Tecnico_F_EN.pdf
[29] https://www.moso-bamboo.com/wp-content/uploads/NL-Gevelbekleding_Booklet_Bamboo_X-treme_2021_LQ.pdf
[30] https://opslagco2inhout.nl/

Box 3. Biogenic carbon storage: Short versus long cyclic crops

The amount of biogenic carbon stored in a product is independent of the growing cycle length of the plant, i.e. hemp, Miscanthus and wood store similar amounts of biogenic carbon per tonne of material.

At the same time, annual crops capture CO_2 from the atmosphere each year, while harvested forest has sequestered CO_2 over the past couple of decennia usually. A fast growing tree species like poplar is being harvested after about 30 years, other species will be harvested after e.g. 80 years. However, at sustainable forestry practices, where the amount of harvested wood is basically steady over the years and replanted in equal amounts, the annual average overall CO_2 sequestration from the atmosphere virtually equals the amount of CO_2 stored in the annually harvested trees. Consequently, sustainable forestry comes with the same annual CO_2 capture and emissions as annual crops.

The yield in tonne/ha may differ a lot between forest, perennial and annual lignocellulose crops. Typical yield ranges are 3 – 5, 10 – 25 and 4 – 9 tonne/ha.a for forest, perennials and annual crops, respectively. The growth rate relates to genetics of the species as well as fertilisation (or the absence of it in e.g. forests).

Regarding yield, the optimal moment for harvesting wood is when the growth of trees becomes lower than the average till that moment.

Another aspect is that production of annual crops allows more flexibility in land use compared to trees or perennial species like miscanthus. Trade-off include: yield, demand, technical requirements, flexibility.

2.4 Experimental determination of biogenic carbon content in range of bio-based feedstocks

For a range of bio-based feedstocks the carbon content has been determined experimentally. Samples were grinded using a hammer mill over a 0.5 mm screen, and dried at 70°C until equilibrium. Samples of about 150 mg were analysed for carbon content using an elemental analyser (LECO-CN).

Values for groups of feedstock are presented in Table 8, and range from 428 for cellulose to 685 g/kg for expanded cork. Carbon content increases with increasing lignin content, so values are relatively low for fibrous lignocellulose with high cellulose content, and increasing with increasing lignin content. Cork, high in suberin, exhibits the highest carbon content. Acetylation and thermal treatment, methods to make wood more durable, increases the carbon content of wood from about 500 to 518 and 529 g/kg. All data are presented in Annex 2.

Table 8 Carbon content in bio-based feedstocks, per type of material, based on a selection of analysed samples (Annex 2).

Feedstock	Examples	Range (g/kg)
Fibrous lignocellulose	Flax, hemp, cotton, cellulose	430 - 440
Woody lignocellulose	straw, stalks, reed, shives, and the 'new' crops like Miscanthus, cattail, Sorghum, cup plant, and bamboo	460 - 495
Wood	Softwood, European hardwood, tropical hardwood	495 - 520
Acetylated, thermally treated wood		518 - 520
Sheep wool		473
Mycelium		485
Cork (expanded)		626 - 685

Figure 1 shows there is a fairly good correlation between experimental results and the 'theoretical' values derived/found in section 2.3, i.e. Table 6.

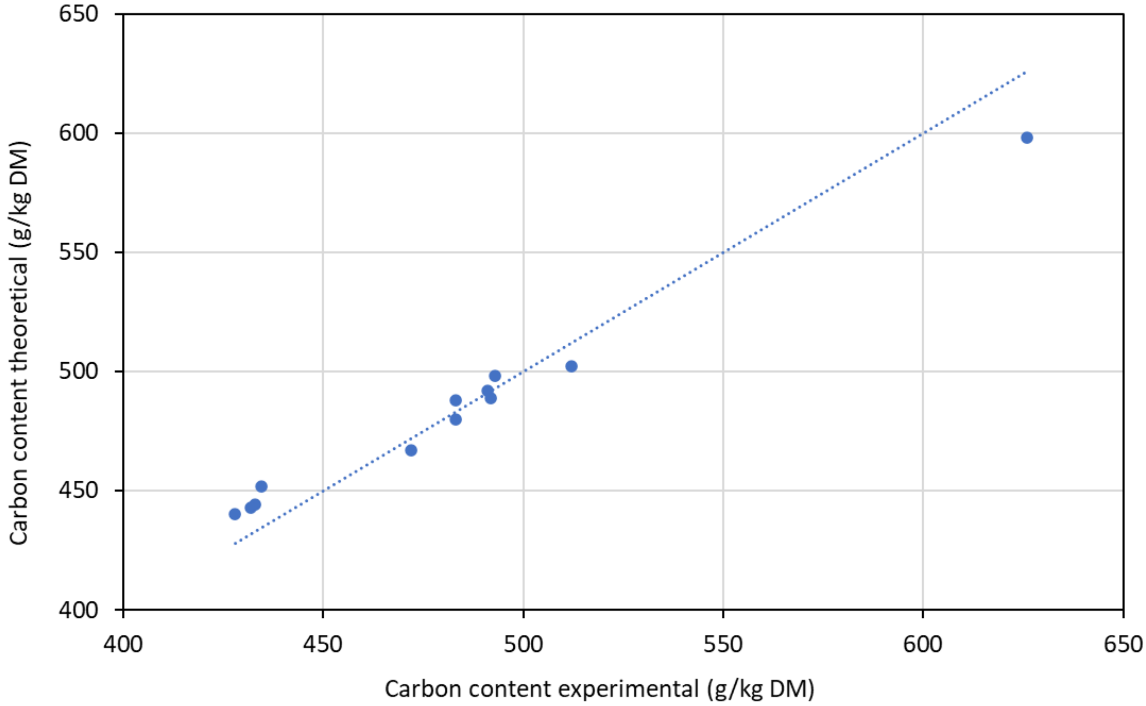

Figure 1 ***Carbon content in wood and lignocellulose crop samples: theoretically derived from literature data (Table 6) versus experimentally determined. Dotted line represents y=x.***

2.5 Conclusions

Carbon content in bio-based building materials relates to the chemical composition: Pectin showing the lowest carbon content, followed by cellulose, hemicellulose, keratin, protein, lignin, suberin (cork) and fatty acids. Consequently, materials with high cellulose content have lower carbon content than materials with high lignin content.
Experimentally determined carbon content of a range of bio-based feedstocks (section 2.4) appears to show good correlation with 'theoretical' values derived/found (section 2.3).

3 Time span of carbon storage in building products – Service life

The service life of building products determines how long biogenic carbon is stored. Default values for the service life of building products have been presented in the SBR publication 'Service life of building products' (Levensduur van bouwproducten), 2011. Most of the building products have an accepted service life of 75 years, except for thatching reed which lasts 30 years.

Reuse and recycling of materials will increase the time span of carbon storage. E.g. consider a wooden beam which after end-of-life is planed and applied as a slightly thinner beam in a second life, which on its turn after end-of-life is converted into particle board. In this example, the fraction planed off after the first life has a carbon storage time of 75 years, the fraction discarded after the second life has a carbon storage time of 150 years, and the amount ending up in the third life could have a carbon storage time of 175 years or more.

4 Sustainable crop management – No carbon debt

A sustainably managed forest can be considered a huge stock of bio-based feedstock from which annually a small amount is harvested and replanted, with a net zero change in the wood stock. As a consequence, certified forest is CO_2 neutral over a longer period of time, which is typically quantified as 25 – 30 years. Accordingly, EN 16760[31] states that sustainably managed forest needs to be modelled as a stable 'unity process': carbon in = carbon out. This means that under sustainable forest management conditions no so called 'carbon debt' arises, i.e. no loss of stored CO_2 in the forest occurs.[32]

For sustainably produced annual crops by definition all stored biogenic carbon is extracted in the year of harvest, i.e. no carbon debt applies. The same holds for multiannual crops which are harvested annually.

[31] EN 16760:2015 Biobased products – Life Cycle Assessment.
[32] SGS Search, 2022. 'Voorstel berekeningsmethodiek om koolstofvastlegging in biobased bouwmaterialen te kunnen waarderen' (p.10-11), https://www.rijksoverheid.nl/documenten/rapporten/2022/07/29/onderzoek-berekeningsmethodiek-koolstofvastlegging-in-biobased-bouwmaterialen

5 Bio-based material origin and application conditions – Net storage

All bio-based materials are based on biogenic carbon, incorporated in plants by extracting CO_2 from the atmosphere. However, long term application of bio-based materials does not automatically contribute to (temporary) negative CO_2 emissions. This requires that the CO_2 removal from the atmosphere has been recent, which holds for sustainably sourced wood and (multi)annual crops (chapter 4). Reuse and recycling of bio-based building materials, however, does not come with recent CO_2 removals, and therefore no negative CO_2 emissions can be credited. The lower impact of reuse and recycled materials itself is credited in standard LCAs already.

Examples of indicated building product categories include:

- Virgin wood based: beams; planks; Glulam; CLT; panels & boards; insulation slabs, panels or blow-in insulation (including cork).
- Reused/recycled feedstock based: Similar to presented for virgin wood, however, based on previously used feedstock.
- Crop based: Panels & boards based on non-wood like cereal straw; reed; Miscanthus; etc. Thermal insulation based on flax, hemp, grass, cereal straw, Miscanthus, cattail, cellulose fibre, sheep wool, etc.

A further requirement is that there is a net increase in biogenic carbon storage, i.e. a net CO_2 removal from the atmosphere. This is the case for new-built houses, extension of houses and replacement of non-carbon based building elements by bio-based building products. These cases can be generally considered to deliver negative CO_2 emissions and may be credited as such.
On the other hand, in case of renovation, the application of virgin wood and crop based building products to replace other bio-based materials does not automatically lead to a net biogenic carbon storage. The net storage for renovation depends on the end-of-life treatment of scrapped material. If the scrapped material is incinerated while the resulting CO_2 is emitted to the atmosphere there is no net increase in biogenic carbon storage, i.e. no net CO_2 removal from the atmosphere and no value to be credited. If the CO_2 emissions are captured and stored (CCS) or utilised again (CCU), an equivalent biogenic carbon storage may be credited. Also, if the bio-based materials taken out for replacement are reused, recycled, or stored by any other method, an equivalent biogenic carbon storage may be credited for the period of time that these new products are applied. So, renovation requires case specific calculations of the net biogenic carbon storage and related net CO_2 removal from the atmosphere, as well as a dedicated procedure of track and trace administration.

In summary, the combination of bio-based feedstock origin and the application conditions determine whether and to which extent biogenic carbon storage may be credited. Table 9 presents the values for the 'net biogenic carbon storage ratio'. These factors can be directly used in the equation to calculate the value of biogenic carbon storage expressed as GWP benefit (section 7.2).

Table 9 Net biogenic carbon storage ratios for specific application conditions.

Building product category	New-built	Extension to house *	Renovation, replacing	
			Bio-based §	Non-carbon based
Wood, Virgin	1.0	1.0	0.0 – 1.0	1.0
Products based on reused or recycled bio-based feedstock#	0.0	0.0	0.0	0.0
Crop based products	1.0	1.0	0.0 – 1.0	1.0

* Including application of additional thermal insulation.

\# Reuse/recycling of bio-based products/materials avoids CO_2 emissions as a result of decomposition, and therefore has the value of delayed emissions. However, reuse/recycling does not involve extraction of CO_2 from the atmosphere, therefore the delayed emissions comprise a different topic.

§ Whether replacement of bio-based building elements by virgin bio-based materials delivers net positive biogenic carbon storage depends on end-of-life treatment of scrapped material.

6 Review of scientific approaches for accounting for biogenic carbon and its storage in bio-based products

An important aspect of the biogenic carbon content stored in a product is the accounting of greenhouse gas (GHG) removals from the atmosphere and emissions to the atmosphere along the life cycle of bio-based products. There are two main approaches for accounting of biogenic carbon removals and emissions which are described in section 6.1. Both approaches consider that the sum of removal and emissions should be about zero. In between removal and emissions, during the service life of the bio-based product, however, CO_2 absorbed from the atmosphere is stored in that bio-based product.

Biogenic carbon storage can be defined as the sequestration of CO_2 from the atmosphere in bio-based products for a certain period of time, resulting in a temporary reduction of the CO_2 concentration in the atmosphere. An important assumption is that harvested biomass used for the products is replanted (sustainable forestry and agriculture, chapter 4). For the duration of a net positive volume of biogenic carbon storage (chapter 5), the corresponding CO_2 is not exerting a radiative forcing (see text box 4), i.e. does not contribute to the GHG effect. Current LCA standards and guidelines make a distinction between carbon that is released within a short-term (temporary storage) and long-term (beyond a longer and specified time-horizon set by convention (also see text box 5), and which is then considered as permanent storage).[33] In section 6.2, a review is made on the relevant LCA standards and guidelines and their recommendations regarding biogenic carbon accounting method and regarding the resulting reduced impact of delayed emissions.

Box 4. Radiative forcing

A variety of physical and chemical changes can affect the global energy balance and force changes in the Earth's climate. These changes are measured by the amount of warming or cooling they can produce, which is called "radiative forcing." Radiative forcing measures how much energy is coming in from the sun, compared to how much is leaving. Energy travels in the form of radiation: solar radiation entering the atmosphere from the sun, and infrared radiation exiting as heat. If more radiation is entering Earth than leaving—as is happening today—then the atmosphere will warm up. This is called radiative forcing because the difference in energy can force changes in the Earth's climate. Radiative forcing is a result of human activities like emitting greenhouse gases, which keep heat from escaping the Earth. But also from natural features like e.g. solar insolation, earth surface characteristics and aerosols in the atmosphere as a result of natural processes.

The application of bio-based products has the potential to win time to mitigate (the speed of) climate change. The effect and benefits are, roughly speaking, proportional to the time of carbon storage. In order to account for the positive effect of temporary carbon storage, several approaches have been proposed. This includes methods provided in LCA standards and guidelines (i.e. PAS 2050[34], ILCD Handbook[35]) as well as methods proposed in literature (e.g. Lashof, dynamic LCA). An overview and short description of these methods is provided in section 6.3. In section 6.4 discussion is provided on the choices that need to be made when accounting for the effect of temporary biogenic carbon storage, as well as on further aspects related to biogenic carbon storage.

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[33] Hoxha, E., et al. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. Buildings and Cities, 1(1), pp. 504–524.

[34] Publicly Available Specification (PAS) 2050:2011 Specification for the assessment of the life cycle GHG emissions of goods and services. British Standards Institution (BSI).

[35] European Commission. Joint Research Centre. Institute for Environment and Sustainability. International Reference Life Cycle Data System (ILCD) Handbook – General Guide for Life Cycle. Luxembourg. Publications Office of the European Union, 2010.

6.1 Accounting for CO_2 removals from the atmosphere and emissions of biogenic carbon to the atmosphere

Two main approaches may be applied for accounting and modelling the potential impact of CO_2 removal from the atmosphere and biogenic CO_2 emissions to the atmosphere related to bio-based products:

1. The CO_2 incorporated in biomass during the growth phase is inventoried as a removal of CO_2 from the atmosphere during the cultivation/growth phase, and as emission when it is released at end-of-life or throughout the life cycle. For as long as the bio-based product is applied in e.g. a building, the incorporated CO_2 may be inventoried as a removal and the so called Characterisation Factor (CF)[36] is then set equal to -1. Whereas emissions of biogenic CO_2 correspondingly have a CF of 1. This is referred to as the '-1/+1 approach'. For this -1/1 approach, EN 16760[31] specifies that a simplified approach may be used to determine the net quantity of atmospheric carbon dioxide fixed in a product, based on stoichiometry or the biogenic carbon content of the product itself.
2. The CO_2 incorporated in biomass during the growth phase and the corresponding emissions throughout the entire life cycle are either not inventoried, or they are inventoried but in the calculation both removals and emissions are characterised with a characterisation factor of zero (biogenic CO_2 is considered to be "carbon neutral"). This is referred to as the '0/0 approach'. Only the biogenic methane (CH_4) emissions is included, due to its higher global warming potential (GWP) compared with CO_2.[37]

The biogenic carbon stored in bio-based products should be equal to biogenic carbon released at end-of-life in case this leads to complete oxidation of the carbon (e.g. during incineration). For this specific case, the net global warming impact result, calculated by summing up the contributions of single stages over the whole product life cycle, is identical with both approaches. However, contributions of individual life cycle stages to the global warming impact will be different (see case study below).

Case study – Global warming impact of a building calculated with the 0/0 and −1/+1 approaches

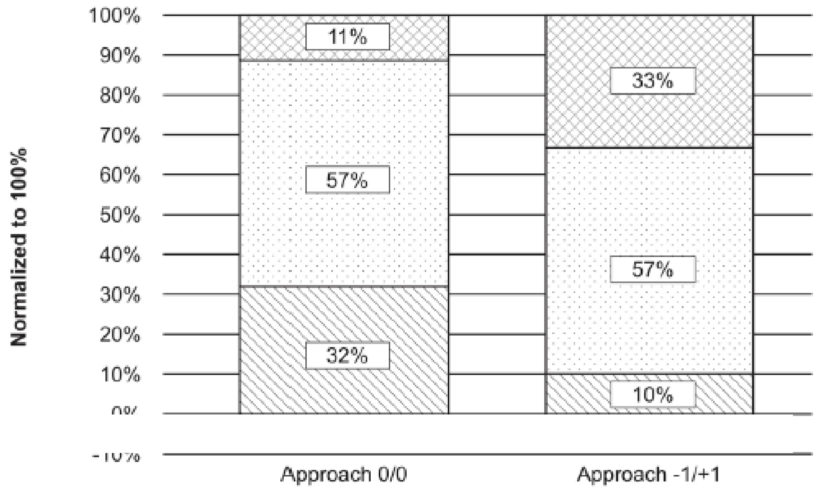
The global warming (GW) impacts[38] of an example timber building obtained using the 0/0 and −1/+1 approaches are presented in Figure 2. Within the end-of-life (C1–C4) stage of the building, the timber-based components are assumed to be incinerated and subsequently biogenic carbon is released as CO_2. Accordingly for this case, the overall impact of the building calculated with the approaches 0/0 and -1/+1 are equal and is 20.7 $kgCO_2eq/m^2$.year. Although the final results are the same, the contribution of the impact of the production stage and the end-of-life stage to the overall impact of the building vary significantly between both approaches.

The impact of the production stage (A1–A3) assessed with the 0/0 approach is 6.58 $kgCO_2eq/m^2$.year (32% contribution of overall impact), while with the −1/+1 approach it is 1.92 $kgCO_2eq$ (10% contribution). The difference of 4.66 $kgCO_2eq/m^2$.year corresponds to the biogenic carbon uptake in the timber-based components, which is counted as a negative emission in the production stage. Thus with the -1/+1 approach, the production stage presents lower values of environmental impacts while the contribution of the end of life stage is higher (33% vs. 11% of 0/0 approach). This way the -1/+1 approach makes explicit that a significant share of the total CO_2 emissions takes place at the end-of-life, i.e. in the future.

[36] Characterisation factors are used to quantify the potential impact of the modelled CO_2 emissions and uptakes (within the GWP impact category).

[37] Global warming potential is a relative measure of the radiative forcing of a unit of a greenhouse gas relative to that of carbon dioxide. It is called 'potential' as it comprises the predicted radiative forcing integrated over time.

[38] Global warming potential (GWP) is widely applied for assessing the contribution of GHGs to climate change and used in Life Cycle Analysis (LCA). It measures the cumulative impact of a given GHG emission on the Earth's radiative forcing relative to the impact of a CO_2 emission, over a fixed and predetermined time horizon (e.g., 100 years).



		GW-score ($kgCO_2e/m^2/yr$) Approach 0/0	GW-score ($kgCO_2e/m^2/yr$) Approach -1/+1
C1-C4	(biogenic CO_2eq release)	0.00	4.66
	(end of life of the building)	2.22	2.22
B6	(operational energy use)	11.89	11.89
B1	(use of installed products)	0.00	0.00
A1-A5	(biogenic carbon uptake)	0.00	-4.66
	(building components production)	6.58	6.58
Total		**20.69**	**20.69**

Figure 2 ***Case study – Global warming impact of an example building calculated with the 0/0 and the −1/+1 approaches.[33]***

6.2 Coverage of biogenic carbon accounting in general LCA guidelines and standards

This section presents a review on how relevant standards and guides on LCA and carbon footprint address and recommend to account for the effect of biogenic carbon in bio-based products and temporary biogenic carbon storage on CO_2 emissions to the atmosphere over time. All the documents listed in Table 10 are based on principles, requirements and guidelines of International Standards on LCA, ISO 14040 and ISO 14044.[39]

There are different standards and guidelines on how to handle biogenic carbon removals from atmosphere and biogenic CO_2 emissions, and any resulting storage of biogenic carbon. There is no full consensus on this topic, which can be due to the fact that the organisations and consortia establishing these standards and guidelines are diverse and may have different goals. An overview of the biogenic carbon accounting approaches adopted in these relevant standards and guidelines, and their key aspects, is presented in Table 11.

Accounting for biogenic CO_2 removals and emissions
Most standards and guidelines (i.e. ISO 14067, PAS 2050, GHG Protocol, ILCD Handbook, ISO 21930 and EN 15804) explicitly or implicitly consider the -1/+1 approach, which implies tracking all biogenic carbon flows over the life-cycle,[33] to be then characterised with characterisation factors equalling -1 for CO_2 removals and +1 for CO_2 emissions. The PEF method currently applies the 0/0 approach, as CFs for biogenic CO_2 uptakes and releases are set to zero. EN 16760:2015 allows both approaches to be chosen.

[39] ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework; ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines

Table 10 Reviewed standards and guidelines

Name of standard/guideline	Short description
ISO 14067:2018 Greenhouse gases – Carbon Footprint of products– Requirements and guidelines for quantification[40]	This international standard specifies principles, requirements and guidelines for the quantification and reporting of the carbon footprint of a product (CFP), This document addresses only a single impact category: climate change.
EN 16760:2015 Biobased products – Life Cycle Assessment[41]	This European Standard provides guidance and requirements to assess impact over the life cycle of bio-based products excluding food, feed and energy, with the focus on how to handle the specificities of the biobased part of the product.
Product Environmental Footprint (PEF) guide, 2013[42,43]	The PEF guide developed by the Directorate General Joint Research Centre (JRC) of the European Commission (EC), provides a harmonised methodology for the calculation of a product environmental footprint. PEF guide provides detailed and comprehensive technical guidance on how to conduct a PEF study, as well as how to create product category-specific methodological requirements for use in Product Environmental Footprint Category Rules (PEFCRs).[44]
PAS 2050, 2011 - Specification for the assessment of the life cycle GHG emissions of goods and services[45]	PAS 2050 developed by the British Standards Institution (BSI) aims to provide a consistent, internationally applicable method for assessing the life cycle of GHG emissions of goods and services. Organisations can use this standard to assess the climate change impact of their activities.
GHG Protocol, 2011 - Product Life Cycle Accounting and Reporting Standard [46]	The GHG Protocol Product Standard is one of a suite of accounting tools developed by the GHG Protocol to encourage users to understand, quantify, and manage GHG emissions. It provides requirements and guidance for companies and other organizations to publicly report GHG emissions associated with a specific product.
ILCD Handbook, 2010[47]	ILCD Handbook provides technical guidance for detailed LCA studies and provides the technical basis to derive product-specific criteria, guides, and simplified tools. The overall objective of the ILCD Handbook is to provide a common basis for consistent and quality-assured life cycle data and robust studies.
ISO 21930:2017[48] Sustainability in buildings and civil engineering works	This global standard provides the principles, specifications and requirements to develop an environmental product declaration (EPD) for construction products and services, construction elements and integrated technical systems used in any type of construction works.
EN 15804:2019[49] Sustainability of construction works—Environmental product declarations	This European standard provides core product category rules (PCR) for environmental product declarations for any construction product and construction service.

EN 16760 also specifies that a simplified approach may be used to determine the net quantity of atmospheric carbon dioxide fixed in a product, based on stoichiometry or the biogenic carbon content of the product itself. All standards and guidelines (including PEF) require to report (or inventory) separately the biogenic carbon removals and emissions.

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[40] ISO 14067:2018 Greenhouse gases – Carbon Footprint of products – Requirements and guidelines for quantification

[41] EN 16760:2015 Biobased products – Life Cycle Assessment

[42] European Commission 2013. PEF Guide, Annex to Commission Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.

[43] Zampori L. and Pant R., 2019. Suggestions for updating the Product Environmental Footprint (PEF) method. Publications Office of the European Union, Luxembourg.

[44] European Commission, 2018. Product Environmental Footprint Category Rules Guidance, Version 6.3 – May 2018.

[45] Publicly Available Specification (PAS) 2050:2011 Specification for the assessment of the life cycle GHG emissions of goods and services. British Standards Institution (BSI).

[46] GHG Protocol:2011. Product Life Cycle Accounting and Reporting Standard. World Resources Institute & World Business Council for Sustainable Development.

[47] European Commission. Joint Research Centre. Institute for Environment and Sustainability. International Reference Life Cycle Data System (ILCD) Handbook – General Guide for Life Cycle. Luxembourg. Publications Office of the European Union, 2010.

[48] ISO-21930. (2017). Sustainability in buildings and civil engineering works—Core rules for environmental product declarations of construction products and services.

[49] EN-15804. (2019). Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products

ISO 21930 makes a distinction whether wood originates from forests sustainably managed or not. Biogenic carbon uptake is characterized with -1 only in the case of sustainable forest management.

Cradle-to-gate, biogenic carbon content reporting

Cradle-to-gate is an assessment of a partial product life cycle from resource extraction (cradle) to the factory gate (i.e., before it is transported to the consumer for actual use). Because for this framework the final application and the type of disposal are unknown and therefore the ultimate fate of the biogenic carbon is unclear, it is complicated to include biogenic as a credit. The default provided in the standards and guidelines is to assign no credit for this.

The biogenic carbon content in (intermediate) products may be provided for information when performing cradle-to-gate studies, when this information is relevant for the remaining value chain. This is explicitly stated in ISO 14067 and provided as a requirement in the PEF method and GHG protocol.

Delayed emissions due to temporary biogenic carbon storage

None of the LCA standards and guidelines includes effects from any delayed emissions due to temporary biogenic carbon storage in the reported carbon footprint value. Some do include stored carbon as a separate additional information.

ISO 14067 prescribes that GHG emissions and removals shall be modelled as if released and removed at the beginning of the assessment period, i.e. at the same point in time, therefore not to be included in the calculation of the carbon footprint. If any carbon storage in products is calculated, it shall be documented separately. A minimum storage time of 10 years is required to account for the effects of temporary storage. No minimum storage time is specified in other standards or guidelines. No time horizon is specified after which carbon in products shall be considered as "permanently" stored. Carbon content in products can be provided as additional information when performing cradle-to-gate studies when this information is relevant for the remaining value chain.

EN 16760, prescribes that where temporal accounting of GHG emissions is relevant (due to e.g. temporary carbon storage), it can be reported separately. An example of the calculation method is provided in Annex B.3 to the standard, which is based on linear discounting following the method described in the ILCD Handbook. A 100-year timeframe is considered in line with the timeframe chosen by IPCC (2014)[50], see text box 5 below for definition of time horizon.

Box 5. Time horizon / Timeframe

GWP measures the warming impacts of a gas compared to CO_2; it basically measures the 'strength' of the greenhouse gas averaged over a chosen time horizon. The choice of a time horizon is a policy decision, not based on scientific methods. Decision makers set time horizons as a means of focusing their efforts on a period that results in productive action, a finite period of time required to be able to influence events. If one sets a short time horizon, say 20 years, the effect is that near-term impacts are weighted very heavily, and that emissions delayed for 20 years would not be counted while the target of net zero GHG emissions by 2050 is likely not yet reached. If one sets a long time horizon, say 1000 years, the effect is that there is little difference between impacts now and several decades in the future, thus not urging to come into action. Several lines of reasoning indicate a figure of around 100 years as a balanced choice for the time horizon for climate response.[51,52] The 100-year time horizon of the GWP (GWP100) is the accounting metric adopted by the Intergovernmental Panel on Climate Change (IPCC)[50] in inventory guidelines. Kyoto Protocol has specified 100 years as the time horizon applying to global warming potentials for comparing different greenhouse gases (UNFCC 1997).[53]

[50] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change IPCC, Geneva, Switzerland

[51] World Meteorological Organization Global Ozone Research and Monitoring Project: Scientific Assessment of Ozone Depletion: 1991 (World Meteorological Organization, Geneva) Report 37, 1992.

[52] Fearnside, P.M. Why a 100-Year Time Horizon should be used for Global Warming Mitigation Calculations. Mitigation and Adaptation Strategies for Global Change 7, 19–30 (2002).

[53] The Kyoto Protocol, Conference of the Parties (COP3) to the United Nations Framework Convention on Climate Change (UNFCCC), 1997.

PAS 2050 also considers a time frame of 100 years to evaluate GHG emissions from products.[45] Any evaluation of the effects of delayed emissions is to be conducted separately. A specific quantification approach is prescribed in the Annex E to the standard.

Table 11 Overview of key aspects of approaches for biogenic carbon accounting adopted in relevant carbon footprint standards and guidelines.

	ISO 14067	EN 16760	PEF	PAS 2050	GHG Protocol	ILCD Handbook	ISO 21930 EN15804
Biogenic carbon removals and emissions to be included in the inventory/modelling	Yes	Yes	Yes ([a])	Yes, except for food and feed	Yes	Yes	Yes
Impact assessment of biogenic carbon emissions and removals	CFs = -1/+1	CFs may be either set to -1/+1 or 0/0	CFs = 0/0	n.s. (-1/+1) ([b])	CFs = -1/+1	CFs = -1/+1	CFs = -1/+1
Biogenic carbon removals and emissions to be reported (or inventoried) separately	Yes	Yes	Yes ([c])	n.s.	Yes	Yes	Yes
Biogenic carbon content in intermediate products to be separately reported	Yes	Not required	Yes	Not required	Yes	Not required	Not required
Delayed emissions due to temporary carbon storage included in the assessment for climate change reported	No. Can be reported separately. Minimum storage time of 10 years is considered.	No. Should be taken into account where relevant, but reported separately.	No	No. Can be reported separately	No. Can be reported separately.	No. Can be taken into account if directly required in the goal of the study.	No. Can be reported separately.
Calculation method for including the effect of delayed emissions specified	No	Yes. Calculation method specified in ILCD Handbook may be followed.	No	Yes	No	Yes	No
'Permanent' carbon storage included in the assessment	n.s. ([d])	No. Can be reported separately.	No	Yes. Carbon storage of >100 years is considered permanent.	Yes. Minimum time period of 100 years considered. ([e])	Yes. Inventoried /reported separately using 100 year time-frame.	No

Notes:
n.s. = not specified
([a]) Unless a simplified modelling approach (where only biogenic CH_4 emissions are modelled) is selected in a specific PEFCR.
([b]) Not explicitly reported in the standard, but it can be inferred from provisions related to other relevant aspects.
([c]) The provision in the PEF method refers to the modelling, not to the reporting. Biogenic carbon emissions and removals shall be modelled separately in the inventory, but not reported (separately) in the PEF results. This applies unless a simplified modelling approach is selected in a specific PEFCR.
([d]) The standard does not report any specific time horizon (or assessment period) after which carbon removed from the atmosphere (e.g. during biomass growth) shall be considered as no longer released, and hence as 'permanently' stored. It may hence be inferred that no permanent carbon storage shall be accounted in the assessment.
([e]) Companies shall report the time period of the inventory. Companies shall report the amount of carbon contained in the product or its components that is not released to the atmosphere during waste treatment and therefore is considered stored.

Regarding temporary carbon storage and delayed emissions, ISO 21930 states that "*Several methodological approaches have been proposed to address delayed emissions in the quantification of the Global Warming Potential (GWP), for example approaches based on discounting or approaches based on time-dependent characterization factors within a predefined reference study period. Since there is no common acceptance of these approaches, such calculations are not part of the quantification of the GWP. If a manufacturer wishes to declare quantitative or qualitative information on delayed emissions within the Environmental Product Declaration (EPD), the information shall be reported under "Additional environmental information not derived from LCA" and the underlying methodology shall be referenced".*

EN 15804 is aligned with ISO14067 where no permanent and/or temporary carbon storage can be accounted for, nor reported as additional information.

Accounting for 'permanent' carbon storage

PAS 2050 explicitly specifies that the portion of removed carbon not emitted to the atmosphere during the default 100-year assessment period is to be treated as if it was no longer released back to the atmosphere, i.e. as 'permanently' stored carbon. Apart from PAS 2050, none of the mentioned standards explicitly specify a fixed time horizon after which carbon removed from the atmosphere (e.g. during biomass growth) is to be considered as no longer released, and hence as 'permanently' stored. ILCD Handbook separately inventories/reports the delayed emissions beyond 100 years as 'Carbon dioxide, biogenic (long term)'.

6.3 Specific methods for accounting for benefits of temporary biogenic carbon storage and delayed emissions

As mentioned in the review above, PAS 2050 and ILCD Handbook specify calculation methods to account for the beneficial effect of temporary biogenic carbon storage on radiative forcing (See text box 4 in chapter 6), i.e. on climate change. There are additional methods proposed in scientific literature, including the Lashof method, which describe the reduced relative impact of sequestration and storage of CO_2 for the number of years it is removed and kept out of the atmosphere. Where 'relative' means: per mass unit of stored biogenic CO_2, and considering a time horizon to be specified (See text box 5 in section 6.2). This reduced impact can be subtracted from the life cycle GHG emissions as a credit. Also, dynamic approaches have been developed in literature (such as DLCA by Levasseur et al. (2010)[54]) which consider use of time dependent characterization factors for the calculation of GWP[54].

The methods accounting for the storage of biogenic carbon make use of a so called time horizon (See text box 5 in section 6.2). The radiative forcing occurring after the adopted time-horizon is not considered (neglected), and the radiative forcing occurring within the defined time-horizon is considered significant, with the relative impact decreasing with storage time. As described above, the most common time horizon used for GWP is 100 years. Figure 3 illustrates the different models proposed in literature to address the reduced impact of temporary carbon storage using a 100-year time horizon. This figure also shows the current LCA practice where there is no benefit of temporary biogenic carbon storage (Fixed GWP method, option 1). Options 2 to 5 show the different methods available to account for lower relative impact with increasing number of years of biogenic carbon storage.

Fixed GWP method (currently applied, no benefit for temporary storage)

The fixed GWP (option 1 in Figure 3) is the method currently applied in conventional LCA methods where there is no benefit assigned to temporarily (up to 100 years) removing carbon from the atmosphere. As provided in Table 10, some guidelines allow for 'permanent' carbon storage to be included in the assessment (when the emissions occur beyond 100 years). This is seen in Figure 3 as a sudden drop of the relative impact of an emission from 1 to 0 at year 100. The flaw in this method is that up to year 99

[54] Levasseur, A., Lesage, P., Margni, M., Deschênes, L., & Samson, R.,2010. Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. Environmental Science & Technology, 44(8), 3169–3174.

no benefit is received from delaying the emissions, so radiative forcing is fully accounted, while further delay to the next year (year 100) no emissions have to be accounted.

Contrarily to what happens traditionally in LCA (with fixed GWP method), where any flux has the same impact regardless of when it happens, the approaches described below (options 2-5) give less weight to fluxes happening closer to the end of the time horizon compared to those happening at the beginning. In this way the timing of the release of the emissions is considered relative to the removal of CO_2 (in year 0).

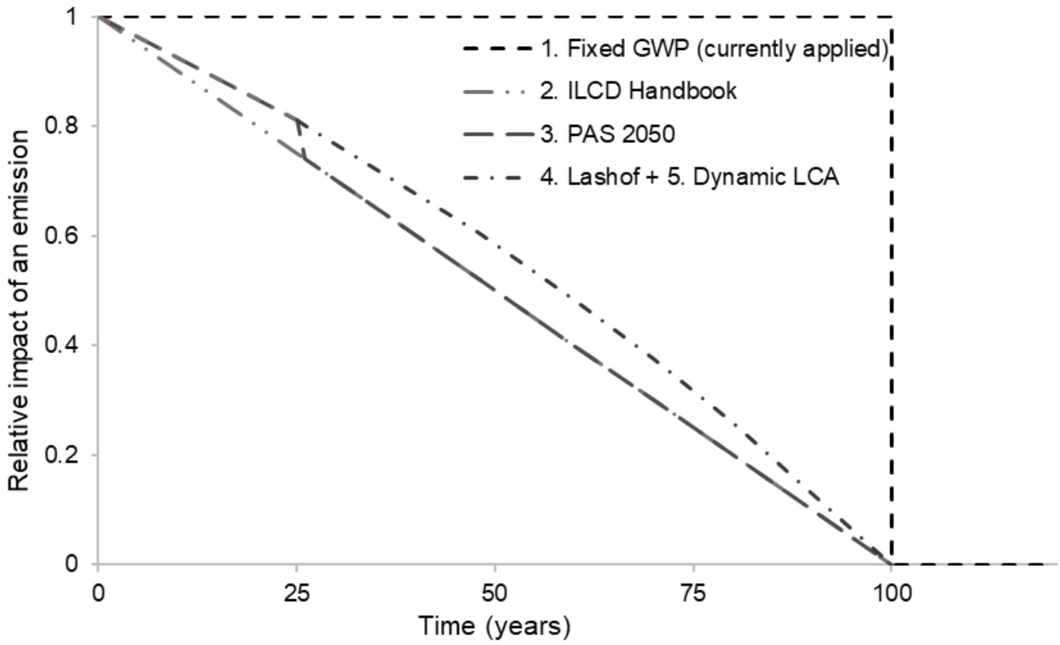

Figure 3 Illustration of different methods for the accounting of the relative impact (decreasing means a potential benefit) versus biogenic carbon storage time for a 100-year time horizon.[55]

<u>The ILCD Handbook method</u>

In the method proposed in the ILCD Handbook (option 2 in Figure 3), the credit value for carbon storage is calculated by multiplying the kg of CO_2eq by the number of years the emission is delayed, up to 100 years, divided by 100 to represent the timeframe of 100 years. This approach is equivalent to a credit factor of 1% per year of storage. Emissions occurring beyond 100 years from the time of the study are inventoried separately as “long-term emissions”, and are not included into the general LCIA results calculation. This method is also adopted in EN 16760[31] and calculation method is provided in Annex B.3 to the standard.

$$CFP_{temp,Storage} = -\sum m_i \times t_s \times GWP_{IPCC,i}/100 \qquad \text{(equation 2)}$$

$CFP_{temp,Storage}$: Carbon footprint of temporarily stored GHG species i
m_i: Mass of GHG i removed

For CO_2: $m_{CO_2} = m_C \times M_{CO_2}/M_C$

For CH_4: $m_{CH_4} = m_C \times M_{CH_4}/M_C$

m_C: mass of carbon stored in a product and released within a 100 yr timeframe
M_{CO_2}, M_{CH_4}, M_C: molecular weight of CO_2, CH_4 and carbon, respectively.
t_s: time of temporary storage in years
$GWP_{IPCC,i}$: IPCC Global Warming Potential (GWP) for 100 year time horizon for GHG i

[55] Brandão M, Levasseur A, Kirschbaum MUF, Weidema BP, Cowie AL, Vedel Jørgensen S, et al. (2013) Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. International Journal of Life Cycle Assessment 18:230–40.

The linear discounting applied does not provide as accurate a representation of the impact of delayed emissions compared to the full representation provided by non-linear decay curves (like Lashof and dynamic LCA methods described below).

The Lashof method

The Lashof method[56] (option 4 in Figure 3) considers that storing biogenic carbon for a given number of years is equivalent to delaying a CO_2 emission until the end of the storage period. The credit is then calculated as the area under the 100-year decay curve of CO_2 in the atmosphere (see text box 6 below) which is beyond the 100-year time horizon as a result of the delay in emissions (see Figure 4). An emission delayed by 100 years or more results in a 100% CO_2 emission credit or compensation.

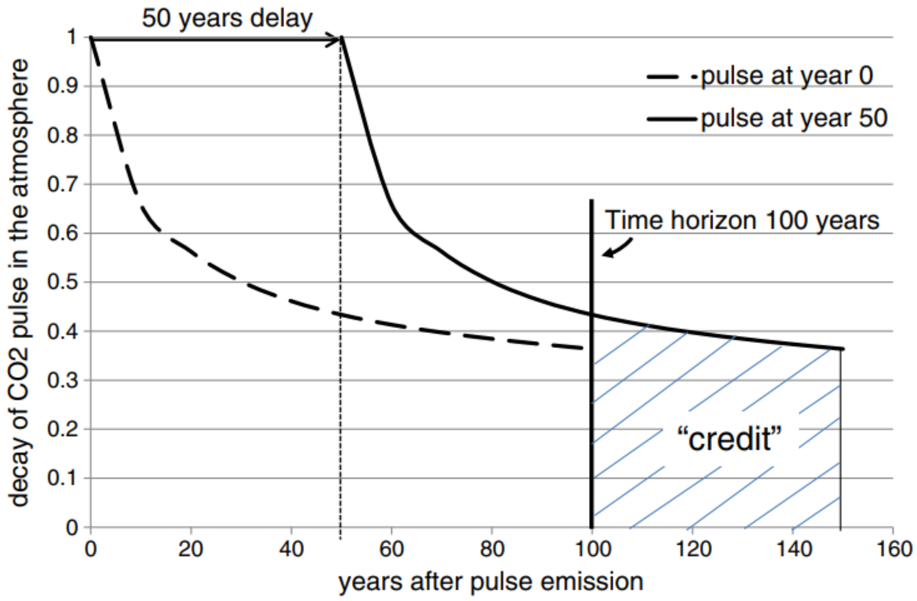

Figure 4 Resulting credit of delayed emissions according to the Lashof method with a 100 year time horizon.[57]

Box 6. Absorption of CO_2 in the atmosphere by oceans and terrestrial ecosystems

CO_2 in the atmosphere is absorbed by oceans and terrestrial ecosystems.[58] The type of response to a pulse CO_2 emission to the atmosphere as a result of uptake by oceans and biosphere is modelled by the so called Bern carbon cycle climate model and illustrated in Figure 4. The actual CO_2 decay depends on the future composition of the atmosphere and feedbacks from climate change.[56] Even if there is discussion about details of the exact CO_2 decay and how it is affected by the effect of climate change, the net decay is not expected to change considerably.[58]

The PAS 2050 method

In PAS 2050 a different approach was proposed (option 3 in Figure 3) to give a credit for delaying emissions.[45] If all the carbon emissions occur within the first year, they are treated as a single emissions event at the beginning of the 100 year assessment period. If all the carbon emissions occur as a single emissions event between 2 and 25 years after the manufacture of the product, the credit factor is 1% per year of storage multiplied by 0.76 (as a linear approximation of the Lashof method).[59] Beyond 25

[56] Fearnside PM, Lashof DA, Moura-Costa P (2000) Accounting for time in mitigating global warming through land-use change and forestry. Mitig Adapt Strateg Glob Chang 5:239–270

[57] Vogtländer, J.G., van der Velden, N.M., van der Lugt, P. (2014) Int J Life Cycle Assess 19: 13-23.

[58] Schimel et al. (1996), 'Radiative Forcing of Climate Change', in J.T. Houghton, L.G.Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.), Climate Change 1995: The Science of Climate Change, Cambridge University Press, pp. 65–131.

[59] Based on Clift R, Brandão M. (2008) Carbon storage and timing of emissions. University of Surrey, Centre for Environmental Strategy Working Paper Number 02. Available from: https://www.surrey.ac.uk/sites/default/files/2018-03/02-08-carbon_storage-and-timing-of-emissions.pdf

years storage time, the linear approximation is no longer valid to approximate the Lashof method. Between 25 to 100 years, the PAS 2050 method has chosen to use the same factor as proposed by ILCD Handbook, i.e., 1% per year of storage. Carbon that is released after 100 years is considered as permanently stored and not counted as an emission.

The method presented in PAS 2050 for short storage times (up to year 25) is a linear approximation of the dynamic LCA approach or the Lashof method (option 4). A linear approximation in PAS 2050 has the advantage of being very simple to use in LCA, as the yearly benefit for delaying an emission is constant. By including this decay rate within the weighting factor formula, PAS 2050 aimed to more accurately reflect global warming potential of CO_2 released at different times, however it leads to a discontinuity. Emission delayed by x years gets a credit of 0.0076x (from 2 years to 25 years) and 0.01x (from 25 years to 100 years). At the same time, applying the linear ILCD calculation between 25 and 100 years ignores the dynamics of delayed emissions of the Lashof method.

The dynamic LCA method

The methods discussed above are based on traditional LCA which linearly accounts for delayed emissions. In addition, the Lashof method accounts for the decay of a CO_2 emission pulse in the atmosphere, i.e. the Lashof method accounts for the atmospheric load integrated over time (Box 6 and Figure 4). The effect of the decay, however, is calculated by a laborious method which calculates the avoided radiative forcing for the chosen time horizon of 100 years by determining the 'credit' surface as illustrated in Figure 4. Levasseur et al. (2010)[54] developed a dynamic LCA (DLCA) method which considers both the timing of an emission as well as the atmospheric load of GHG emissions over time by using time-dependent (dynamic) characterization factors (DCF) to calculate the impact of GHG emissions on radiative forcing at any time. This enables to determine consistently the time-dependent impact of every GHG emission on radiative forcing. The result for the relative impact of a CO_2 emission is the same as derived from the Lashof method for a 100 year time horizon (see option 4 in Figure 3).

The dynamic LCA (DLCA) approach of Levasseur et al. is considered to be the most accurate description of the radiative forcing (GHG effect) of delayed CO_2 emissions by temporary biogenic carbon storage. This is confirmed by recent critical review studies of other authors.[60,61]

Resch method

Yet, dynamic approaches need to be simple enough to allow for wider use by practitioners striking a balance between accuracy and complexity. Therefore, recently Resch et al. (2021)[62] presented a simplification of the DLCA method of Levasseur. Weighting factors were first calculated for every tenth year based on the method of Levasseur, and the analytical function was fitted thereafter. It was found that an exponential decay function of $2 - e^{\frac{\ln 2}{T}y}$ fits the curve which describes the reduction in GWP due to delay in emission in year y for a time horizon of T years. This function can be used for any time horizon making the method easy to apply. The approximated function is calculated to be only 0.2% off from an equivalent impulse response functions calculated in the original relatively complex method of Levasseur et al. (2010) [54] for a 100 year time horizon. This shows that the accuracy is not compromised with this approximation.

6.4 Discussion

Storing biogenic carbon in building products delays release of that carbon to the atmosphere as long as it is in use. GHG emissions that occur later in time have less time to trap heat in the atmosphere, and

[60] Hoxha, E., et al. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. Buildings and Cities, 1(1), pp. 504–524.

[61] Trinomics, VITO, Wageningen University & Research, Technische Universität Graz and Ricardo (2021) Evaluation of the climate benefits of the use of Harvested Wood Products in the construction sector and assessment of remuneration schemes Report to the European Commission, DG Climate Action, under Contract N° 340201/2020/831983/ETU/ CLIMA.C.3, Trinomics BV, Rotterdam.

[62] Resch, E., Andresen, I., Cherubini, F., Brattebo, H. (2021) Estimating dynamic climate change effects of material use in buildings—Timing, uncertainty, and emission sources. Building and Environment 187, 107399.

therefore have lower cumulative radiative forcing, i.e. on climate change, during the coming period. The main criticism of traditional LCA approaches (as illustrated by the 'Fixed GWP' curve in Figure 3) is that they do not consider the effect of timing of CO_2 emissions. For products with long lifetimes, such as buildings, it is important to include time considerations in LCA. Therefore several approaches have been proposed to account for the impact of delayed CO_2 emissions, where emissions happening in the future have a less weight compared to those happening today or tomorrow (illustrated by the other curves in Figure 3).

In the paragraphs below, several aspects related to biogenic carbon storage, its accounting and crediting its benefits are discussed.

6.4.1 Delayed emissions, i.e. future radiative forcing, requires further action

The logic behind accounting for biogenic carbon storage in e.g. bio-based building products is that for the duration of storage the CO_2 is not exerting a radiative forcing. This makes sense in case near-term radiative forcing is considered more relevant than future radiative forcing, as the later re-emitted biogenic CO_2 will still exert its full radiative forcing effect, only later. The delay in CO_2 emissions and the related delay in greenhouse gas effect, i.e. the slowing down of climate change, will give society and ecosystems time to adapt to climate change. Adaptation involves e.g. developing and implementing less CO_2 intensive (energy) production systems, building systems which require less energy for heating and cooling, new technologies to trap CO_2 and its utilization (carbon capture and utilization – CCU), agriculture and nature systems which may thrive with anticipated climate change. In other words: The benefit of delayed emissions comes with the task to adapt to climate change and achieve a real CO_2-neutral society.

The crediting of biogenic carbon storage while simultaneously having to pursue all kind of developments is still worthwhile, because it is expected that steadily developing solutions over the next 25 – 50 years involves less costs than the effects of climate change will cost if we do not delay climate change.

6.4.2 Service life of building product

The timing of the emission at end-of-life relates to the service live of bio-based building product (chapter 3), including the service life of reused and recycled building product. This service life of products is indicated in the environmental product declaration (EPD) of a building product. The service life of biobased building products is typically assumed to equal to the service life of a building; the Determination Method considers a service life of a building of 75 years.

6.4.3 Time horizon – Relevant period for delaying CO_2 emissions

The effect of delayed CO_2 emissions on radiative forcing is scientifically described by models presented in section 6.3. The attributed benefits from biogenic carbon storage are included in the scientific models by a time horizon over which the global warming potential of delayed emissions is considered (text box 5). The time horizon is supposed to provide the perspective of productive action, i.e. leading to application of bio-based materials which reduce CO_2 emissions for a long period of time, and to balance the rewarding of significant delay of CO_2 emissions and avoiding passing on the problem to future generations. The latter is supposed to be achieved by using next decades to develop and implement permanent GHG emission reductions and climate change adaptation measures.

100 Years is often considered such a balanced time horizon. A 100 year time horizon is used in the vast majority of scientific literature on the development of modelling the effects of biogenic carbon storage, and has been adopted for national inventory reporting to the United Nations Framework Convention on Climate Change (UNFCCC). The 100 years balances a clear credit for long term biogenic carbon storage and providing current and next generation time to develop and implement strategies to reduce actual CO_2 emissions, and to 'absorb' residual emissions after this 100 years time period.

More recent discussions in the EU on biogenic carbon storage mention 35 years for 'temporary carbon storage in long-lasting products' such as wood-based building products, and 'several centuries' for 'permanent carbon removal'.[63] A clear link to how these time horizons affect productive action, however, is not explained.

The value choice for the time horizon is ultimately not based on scientific grounds, but is a political choice which gives a value to delayed (temporarily reduced) CO_2 emissions.

It may be noted that, although the 'time horizon' of GWP (mostly set at 100 years) and the 'service life of a building product' (mostly set at 75 years in the Netherlands) have the same order of magnitude, they constitute 2 distinct topics.

6.4.4 Crediting biogenic carbon storage – No double counting

The current LCA methods and the Determination Method based on EN 15804 consider all CO_2 emissions during a products lifetime, from extraction of raw materials to final (waste) processing at end-of-life. Figure 5 presents a schematic representation of the timing of these CO_2 emissions for bio-based and fossil-based building materials: sequestration of CO_2 from the atmosphere for biobased feedstocks, and emissions for raw material extraction, product manufacturing, transportation, and ultimately deconstruction and (waste) processing at end-of-life for both bio-based and fossil-based products. In the Determination Method all these emissions over the lifetime of building products are added up to a grand total, independent of the origin of the raw material.
Contrary to fossil-based products, however, bio-based products have sequestered CO_2 from the atmosphere at t=0 in case feedstock has been sustainably cultivated (chapter 4). This biogenic carbon storage comes with a reduced cumulative radiative forcing (text box 4 at beginning of chapter 6) and a related temporary negative GWP impact. Where 'temporary' in first instance means the duration of the product service life, e.g. 75 years, or more in case of reuse/recycling. This feature is additional to the grand total CO_2 emission arising from standard LCA, and therefore does not involve double counting.
In fact, the period of 'temporary' means until the moment that the net use of biobased products declines below zero, i.e. when the volume (tonne/a) of biobased products released at the end of last life which will be decomposed into CO_2 exceeds the volume that will be newly applied. Ultimately, in case adequate CO_2 capture and storage technologies can be developed and applied, 'temporary' may be extended to 'virtually permanent'.

[63] https://www.consilium.europa.eu/en/press/press-releases/2024/02/20/climate-action-council-and-parliament-agree-to-establish-an-eu-carbon-removals-certification-framework/?ref=ctvc.co

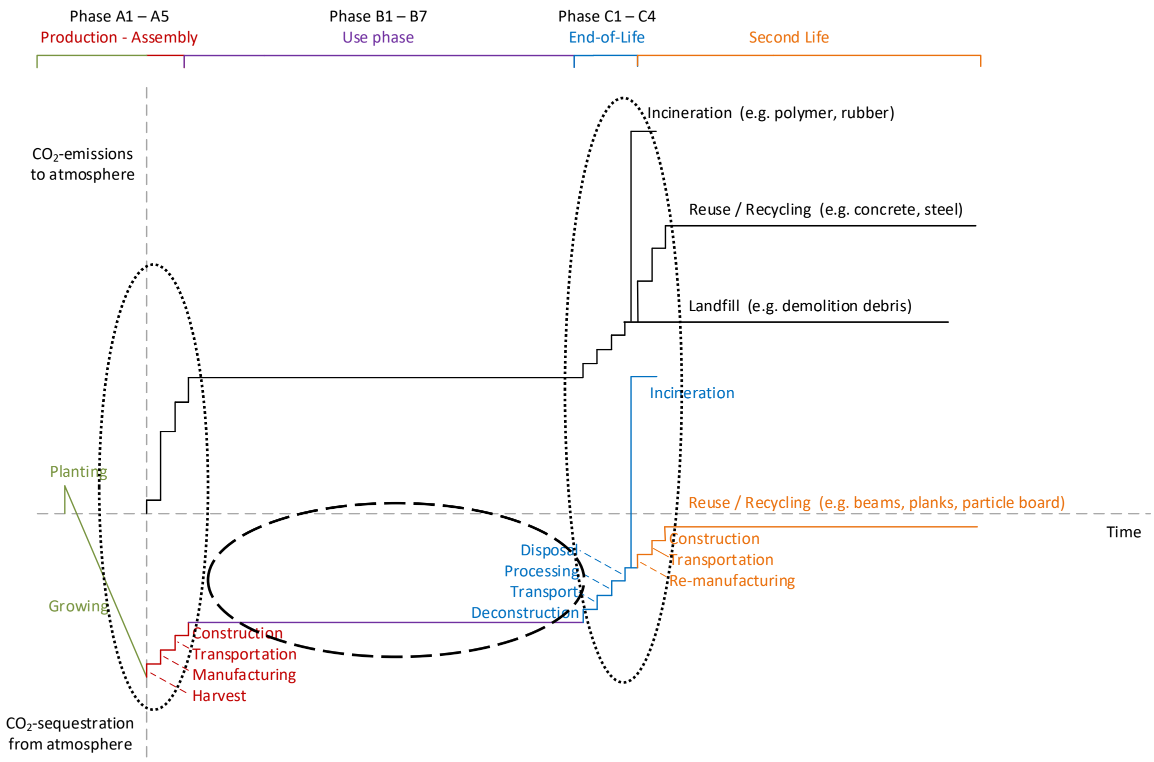

Figure 5 ***Scheme of sequestration of CO_2 from the atmosphere and emissions to the atmosphere for bio-based (coloured) and fossil based (black) building materials taking place over time, from raw material extraction to end-of-life. Impacts 'enclosed' in dotted ovals are addressed in current LCA and MPG methods; the effect 'enclosed' in the dashed oval is topic of this study.***

6.4.5 Crediting biogenic carbon storage – Applies for all building materials

The crediting of biogenic carbon storage originates from the fact that CO_2 has been absorbed from the atmosphere most recently – actually this may be counted in the year of harvest (see box 3 in section 2.3) – thus reducing the CO_2 concentration in the atmosphere and reducing the related GWP impact. For fossil-based products there is no CO_2 sequestration from the atmosphere like for bio-based products, and therefore no reduction in CO_2 concentration and no reduced GWP impact. In other words, the crediting of biogenic carbon applies equally for all building materials, however, bio-based materials do contain a certain content of biogenic carbon, whereas fossil-based materials do not.

6.4.6 Effect of crediting biogenic carbon storage – Example calculation

In order to illustrate the effect of crediting biogenic carbon storage on GWP values and environmental cost indicator (in Dutch 'milieukosten indicator', MKI), an example calculation has been performed for a timber frame construction for a pitched roofing element, consisting of 10.22 kg/m^2 of dry matter wood (considered corresponding to 5.11 kg of biogenic carbon per m^2). Considering a service life of 75 years, the value of biogenic carbon storage can be quantified as proposed in equation 3 in section 7.2. For new-built houses using virgin wood products, the net storage ratio is 100% (Table 9). The specific GWP and MKI values, as well as their effect on total GWP and MKI values, have been presented in Table 12.

For new-built houses using virgin wood, the GWP total values become negative for both EN 15804+A1 and A2 methods. The total MKI value according to EN 15804+A1 (MKI-1) becomes even negative. The total MKI according EN 15804+A2 (MKI-2), using the preliminary weighing factors for set A2[64] becomes nearly 90% lower compared to the current EN 15804+A2 procedure.

[64] https://www.dubocalc.nl/nieuwsbrieven/nieuwsbrief-oktober-2023/

It may be noted that the negative impacts confirm that the crediting mainly has a solid base if in parallel measures are pursued to realise a virtually CO_2 neutral economy by 2050, or certainly no later than 2100.

Table 12 ***Specific and total GWP and MKI values when crediting the biogenic carbon storage in a virgin wood based timber frame construction roofing element in a new-built house with a service life of 75 years, at a 100 years 'time horizon'.***

Environmental impact indictor	Current procedure	GWP benefit	Current procedure + GWP benefit
	EN 15804+A1		
004. GWP (kg CO_2 eq)	5.38	-12.79	-7.41
MKI of 004. GWP (€)	0.2692	-0.6395	-0.3703
MKI-1 total (€)	0.4432		-0.1963
	EN 15804+A2		
051. GWP total (kg CO_2 eq)	6.71		-6.08
053. GWP biogenic (kg CO_2 eq)	1.24	-12.79	-11.55
MKI of 053. GWP biogenic (€)	0.1438	-1.4836	-1.3398
MKI-2 total (€)	1.6713		0.1877

6.4.7 Current biogenic carbon storage relative to fossil CO_2 emitted to and extracted from the atmosphere

The largest sources worldwide for human CO_2 emission are considered to be fossil fuel combustion and cement production, followed by emissions as a result of (tropical) land-use change. The largest absorbers of CO_2 from the atmosphere include oceans, forest regrowth and other terrestrial sinks.[58] Global emissions from fossil fuels and industry are reasonably known based on fossil fuel consumption, amounting about 35 – 37 Gtonnes CO_2/a over the past decade.[65] Uptake by terrestrial biosphere and oceans comes with relatively large uncertainties, and is estimated to be in the ranges 8.4 – 16.5 and 9.2 – 14.3 Gtonnes CO_2/a, respectively.[66,67] Net emissions to the atmosphere are estimated in the range 14.7 – 22.0 Gtonnes CO_2/a over the past decade.
Current biogenic carbon storage in buildings can be derived from the global wood consumption for construction sector, which is about 473 Mm^3/a of sawn wood and 367 Mm^3/a wood-based panels.[68] At estimated average densities of 500 and 700 kg/m^3, respectively, and assuming a content of 0.5 kg carbon per kg of wood, a total of 247 Mtonnes C/a or 0.91 Gtonnes CO_2/a is stored in bio-based building products. This corresponds to about 2.5% of annual global fossil CO_2 emissions, and 23% of CO_2 emissions related to building materials production (which is about 11% of total global fossil CO_2 emissions).

Crediting temporary biogenic carbon storage in bio-based building materials is expected to act as a lever: It is supposed to promote bio-based building in order to substitute concrete and brick building materials, thus reducing radiative forcing by increasing temporary biogenic carbon storage and eliminating the (huge) CO_2 emissions of traditional building materials. Example calculations will be presented in a following report 'Bio-based building products in the Dutch Environmental Database (NMD) – Example calculations on the environmental impact of building materials and buildings'.

Example calculation
Global concrete production is about 14 billion m^3/a.[69] Concrete consumption for buildings in the Netherlands is about 13.6 million tonnes/a.[70] At an average density of 2.3 tonnes/m^3, and at

[65] https://www.statista.com/statistics/276629/global-co2-emissions/
[66] Takahashi et al. (1997) Global air-sea flux of CO2: An estimate based on measurements of sea–air pCO2 difference. PNAS 94:8292– 829.
[67] Global Monitoring Laboratory, CarbonTracker CT2022. https://gml.noaa.gov/ccgg/carbontracker/.
[68] FAO (2021) Global production and trade in forest products in 2020. https://www.fao.org/forestry/statistics/80938/en/
[69] https://gccassociation.org/concretefuture/cement-concrete-around-the-world/
[70] https://www.metabolic.nl/publication/materiaalstromen-milieu-impact-en-energieverbruik-in-de-woning-en-utiliteitsbouw/

about 0.29 tonnes of CO_2 emission for the manufacturing of 1 m^3 of concrete,[71] this multiplies to an emission of 1.7 million tonnes CO_2/a for the Netherlands. Considering 60,000 houses to be constructed in the Netherlands per annum, and assuming the use of 30 m^3 of woody material per building at a density of 500 kg/m^3 and containing 0.5 kg carbon per kg of material, and considering 3.67 kg of CO_2 corresponding to 1 kg of carbon, then scenarios of 50% and 100% bio-based building would translate into 0.8 and 1.7 million tonness of CO_2 (temporarily) stored in these buildings. This means that if 50% of buildings would be constructed in bio-based materials, the CO_2 emissions from the remaining concrete buildings would be (temporarily) compensated by the CO_2 stored in the other 50% bio-based buildings. Considering that also bio-based building materials production comes with a CO_2 emission, the replacement share has to be higher than 50% to achieve this (temporary) compensation.

Alternatively, if the global fossil CO_2 emission of about 36 Gtonnes/a would have to be compensated for by growing forest at an estimated average growth rate of 10 tonnes DM/ha.a, an area of about 2.0 billion ha would be required. Comparing to the existing 4.1 billion ha of forest on the planet of which 1.15 billion ha is managed for the production of wood based products,[72] and considering that trees inevitably will die and decompose into CO_2 emissions again, especially biomass in not-managed areas may be considered to be in a kind of steady state of growing and decomposition, this would mean virtually no harvesting of existing forest. And even if no harvesting would be an option, due to the limited average lifetime of trees this approach is expected to last for a shorter period of time than storing the biogenic carbon as materials in buildings.
If the global fossil CO_2 emissions would have to be compensated by newly planted forest at an estimated average growth rate of 10 tonnes DM/ha.a, an area of 4,400 x 4,400 km^2 would be required; the area of twice the Sahara desert, or the area of the top 10 largest deserts on the world, excluding the Arctic and Antarctica deserts. But also in this case, the storage will be temporarily; ultimately the forests will reach an equilibrium of CO_2 sequestration from the atmosphere by growing biomass and release of CO_2 to the atmosphere by decomposition of the dead biomass.

6.5 Conclusions

The different scientific approaches for determining the effect of biogenic carbon storage on GWP benefit described in literature exhibit only small differences for this GWP benefit at given storage times. The ‘dynamic LCA method’ describes the effects and therefore the GWP benefit the most accurately.

In order to quantify the GWP benefit, a time horizon must be taken into account. This time horizon is a policy decision which needs to be long enough to avoid passing on problems to the future (i.e. long enough to develop adequate solutions to cope with the climate situation by that time) and short enough to achieve productive action now.
Most standards, experts and governments have adopted a time horizon of 100 years.

Biogenic carbon storage presents a GWP benefit which is additional to standard LCA which is used in the Determination Method. Therefore, no double counting is involved when crediting the temporary yet long term biogenic carbon storage.

The GWP benefit arises from the long term reduction of CO_2 concentration in the atmosphere, which is a result of (most recent) sequestration of CO_2 from the atmosphere as biogenic carbon in plant materials and subsequent long term application of this material in e.g. buildings. Therefore, all long term biogenic carbon storage presents a GWP benefit. Bio-based and fossil-based building materials are treated equally when crediting biogenic carbon storage.

[71] https://en.wikipedia.org/wiki/Environmental_impact_of_concrete
[72] https://www.fao.org/global-forest-resources-assessment-2020.pdf

Biogenic carbon storage is a long term yet temporary GWP benefit. Further action is required for the development and implementation of technologies and other measures to achieve permanent GHG emission reductions and climate change adaptation.

7 Proposal to credit biogenic carbon storage in building products

In this section a couple of proposals is presented which, when implemented in combination, allow for the crediting of the benefits of biogenic carbon storage in bio-based building materials. These benefits include: 1) Long term biogenic carbon storage in building products, which can be regarded as temporary negative CO_2 emissions, as well as 2) Replacement of traditional building products like concrete and its high GHG emissions. As a consequence, promotion of bio-based building products by crediting biogenic carbon storage contributes to delaying and reducing GHG effects, thus buying time to adapt to climate change.

7.1 Environmental benefits outside traditional LCA

Long term storage of biogenic carbon in bio-based building materials brings a benefit by delaying and reducing GHG effects, i.e. climate change. This benefit, however, falls outside the regular LCA methodologies. Also, the benefits of such long term biogenic carbon storage are not easily recognised and valued by industry and consumers. Therefore, promoting long term biogenic carbon storage in building products can be an efficient approach to delay and reduce GHG effects as bio-based building products not only store CO_2 recently extracted from the atmosphere, but also replace concrete and its high GHG emissions.

It is proposed to credit the benefits of long term biogenic carbon storage in bio-based building materials via one of several options:

1) In module D of the Dutch Determination Method (see scheme in Figure 6). More details in section 7.7.
2) As an additional parameter in the MPG tool, for consideration otherwise than including in the single score MPG calculation.
3) In carbon credit certification schemes.

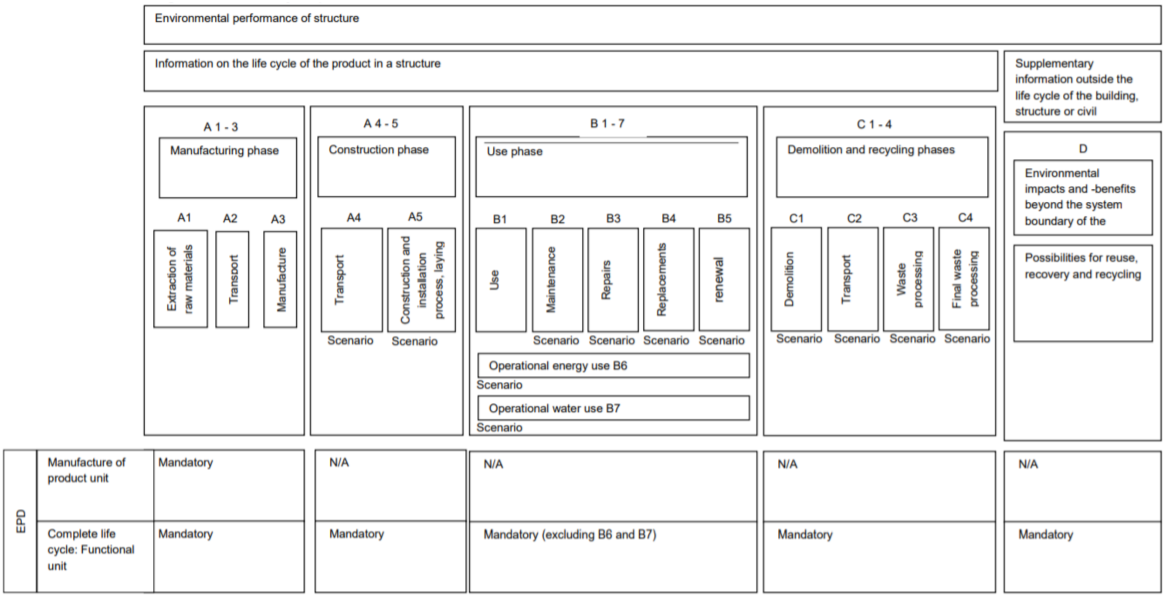

***Figure 6** Life cycle phases addressed in LCA and EPD.*

7.2 Formula to calculate Global Warming Potential (GWP) benefit

The credit of long term yet temporary biogenic carbon storage can be determined as a GWP benefit, GWP_B, expressed in kg CO_2 equivalent, and equals:

$$GWP_B = m * C_C * 3.67 * GWP_{BF,T} * R_{ns} \quad \text{(equation 3)}$$

Where:

m = The amount of bio-based material in the product, in kg. This value should refer to dry matter, i.e. the moisture content has to be clear. Both mass and moisture content to be stated in the LCA/EPD.

C_C = Biogenic carbon content of building material, in kg/kg. To be stated in the EPD, and taken from a list of experimentally determined values or from a dedicated analysis. For details see section 7.3.
In case of a product composed of multiple materials, m and C_C of each component has to be reported.

3.67 = Ratio between the molecular masses of CO_2 and carbon, equal to 44/12.

$GWP_{BF,T}$ = Relative global warming potential benefit factor. This factor is calculated using equation 4 (section 7.4) for a time horizon to be specified by authorities (section 7.5), and at given service life (stated in the EPD).
Once the time horizon has been set, the $GWP_{BF,T}$ versus service life can be listed in a table (section 7.6).

R_{NS} = Net storage ratio for biogenic carbon. This ratio depends on bio-based feedstock origin and the application conditions and is given in Table 9 (chapter 5).
This ratio is 1.0 for sustainably sourced wood and bio-based building materials applied in new-built houses, extension of houses and replacement of non-carbon based building elements. The ratio is in the range 0.0 – 1.0 for sustainably sourced wood and bio-based building materials for renovation of bio-based building elements. The ratio is 0.0 for building materials based on reused or recycled feedstock.

<u>It is proposed</u> that equation 4 is used to calculate the GWP benefit in kg CO_2 eq, together with the to be selected time horizon (section 7.5), and the procedure for determining carbon content in a bio-based building product (section 7.3).

7.3 Biogenic carbon content in bio-based materials

The amount of CO_2 extracted from the atmosphere and stored in a bio-based product directly relates to its biogenic carbon content. The carbon content in bio-based materials exhibits quite some variation, ranging from 430 to 685 g carbon per kg of material (overview in Table 8 in section 2.4; details in Annex 2). The single value of 500 g/kg as presented in EN 16449 does no full justice to this variation.
Biogenic carbon content in fossil based materials is 0 g/kg.

<u>It is proposed</u> that a list of default values for the biogenic carbon content in bio-based feedstocks relevant for building and construction will be established by an independent organisation. This to avoid administrative burden and costs in all stages of the validation chain. The data in Table 8 and Annex 2 provide a good indication, however, data are based on duplicate measurements of mainly single samples only.
For fossil based (parts of) building products the value for biogenic carbon content is 0 g/kg.

Eventually, biogenic carbon content values may be determined by product owners themselves, as costs for experimental analysis of carbon content are small compared to e.g. establishing an LCA.

7.4 Calculating GWP benefit versus storage time as a relative factor

The dynamic LCA (DLCA) approach of Levasseur et al. (2010)[54] is considered to be the most accurate description of the radiative forcing (GHG effect) of delayed CO_2 emissions by temporary biogenic carbon storage. The equation of Resch et al. (2021)[62] provides an accurate representation of this DLCA approach for any chosen time horizon (see paragraph on 'Resch method' in section 6.3).

It is proposed to use the equation of Resch et al. to calculate the benefit of a delayed emission as a 'relative global warming potential benefit factor', $GWP_{BF,T}$. This factor for an emission delayed for y years at a time horizon of T years then equals:

$$GWP_{BF,T} = e^{\frac{ln2}{T}y} - 1 \qquad \text{(equation 4)}$$

The delay time, y, is proposed to be equal to the building product service life as stated in the EPD.
Eventually, this delay time can be extended with the service life of recycled products which can be demonstrated to be made from the initial building product material, also considering recovery and recycling efficiencies.
The values increase from 0 for no delay of CO_2 emissions to 1 when CO_2 emissions are delayed for a time period equal to the selected time horizon.

7.5 Policy decision to set the value of CO_2 storage benefits through a 'time horizon'

A 100 year time horizon is used in the vast majority of scientific literature on the development of modelling the effects of biogenic carbon storage, and has been adopted for national inventory reporting to the United Nations Framework Convention on Climate Change (UNFCCC). The 100 years balances a clear credit for long term biogenic carbon storage, thus providing productive action, and providing current and next generation time to develop and implement strategies to reduce actual CO_2 emissions.

More recent negotiation at EU level on biogenic carbon storage mentions 'several centuries' for 'permanent carbon removal', which may be considered the equivalent of 'time horizon' (see section 6.4.3). However, a clear indication of how this relatively long time horizon is considered to lead to productive action is not (yet) explained.

It is proposed that the Dutch government credits temporary yet long term biogenic carbon storage by setting a value for the time horizon.

7.6 Table with GWP benefit factors

Once the time horizon is chosen, the GWP benefit factor can be calculated using the above mentioned equation 4 for any service life. The values for any service life of a building product for a 100 year time horizon have been presented in Table 13. This table can be easily adapted if another time horizon would be set by the Dutch government.
It may be noted that the time horizon of GWP and the service life of a building product constitute 2 distinct topics.

It is proposed to include such a table for the selected time horizon for broad communication, e.g. in the Determination Method.
For calculation tools, equation 4 may be used.

Table 13 ***Relative global warming potential benefit factor ($GWP_{BF,100}$) versus service life of a bio-based building product at a 100 years time horizon.***

Service life (years)	GWP benefit factor (-)	Service life (years)	GWP benefit factor (-)	Service life (years)	GWP benefit factor (-)	Service life (years)	GWP benefit factor (-)	Service life (years)	GWP benefit factor (-)
1	0.007	21	0.157	41	0.329	61	0.526	81	0.753
2	0.014	22	0.165	42	0.338	62	0.537	82	0.765
3	0.021	23	0.173	43	0.347	63	0.548	83	0.778
4	0.028	24	0.181	44	0.357	64	0.558	84	0.790
5	0.035	25	0.189	45	0.366	65	0.569	85	0.803
6	0.042	26	0.197	46	0.376	66	0.580	86	0.815
7	0.050	27	0.206	47	0.385	67	0.591	87	0.828
8	0.057	28	0.214	48	0.395	68	0.602	88	0.840
9	0.064	29	0.223	49	0.404	69	0.613	89	0.853
10	0.072	30	0.231	50	0.414	70	0.625	90	0.866
11	0.079	31	0.240	51	0.424	71	0.636	91	0.879
12	0.087	32	0.248	52	0.434	72	0.647	92	0.892
13	0.094	33	0.257	53	0.444	73	0.659	93	0.905
14	0.102	34	0.266	54	0.454	74	0.670	94	0.919
15	0.110	35	0.275	55	0.464	75	0.682	95	0.932
16	0.117	36	0.283	56	0.474	76	0.693	96	0.945
17	0.125	37	0.292	57	0.485	77	0.705	97	0.959
18	0.133	38	0.301	58	0.495	78	0.717	98	0.972
19	0.141	39	0.310	59	0.505	79	0.729	99	0.986
20	0.149	40	0.320	60	0.516	80	0.741	100	1.000

7.7 Crediting of GWP benefit in module D

The benefits of biogenic carbon storage in bio-based building materials and products can be credited in module D of the Dutch Determination Method. This can be done in a similar way like the anticipated benefits of avoided impacts in the future by e.g. reusing and recycling of building products at the end-of-life are credited in module D to stimulate the use of materials and products which can be reused/recycled at end-of-life. The GWP benefit may be subtracted from the GWP value in the MPG calculation.

7.8 Other actions required to avoid future impacts of temporarily stored CO_2

Storage of CO_2 in bio-based building materials will be temporarily. Ultimately the bio-based materials will decompose again and the stored CO_2 will be either released to the atmosphere, or captured for storage (CCS) or utilisation as feedstock for new products (CCU).

<u>It is proposed</u> that governments steer and impose actions for the development and implementation of permanent GHG emission reductions and climate change adaptation measures.

Abbreviations

C	Carbon
Ca	Calcium
C_C	Carbon content (kg/kg)
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CF	Characterization factor
CH_4	Methane
CLT	Cross laminated timber
CO_2	Carbon dioxide
DCF	Dynamic characterization factor
DLCA	Dynamic life cycle analysis
EN	European Standard (from German 'Europäische Norm')
EPD	Environmental Product Declaration
GHG	Greenhouse gas
Glulam	Glued laminated timber
GWP	Global Warming Potential (kg CO_2 eq.)
$GWP_{BF,T}$	Global Warming Potential benefit factor at time horizon of T years
GWP_B	Global Warming Potential benefit (kg CO_2 eq.)
Gtonne/a	Gigatonnes per annum (1,000,000,000 tonnes/a)
H	Hydrogen
ISO	International Organization for Standardization
kg/m^3	Kilogram per cubic meter
km^2	Square kilometer
LCA	Life cycle analysis
LCI	Life cycle inventory
m^3/a	Cubic meter per annum
MKI	Environmental cost indicator (in Dutch 'Milieukosten indicator')
MPG	Environmental impact of buildings (in Dutch 'Milieu Prestatie Gebouwen')
MRPI	Milieu relevante product informatie (Dutch equivalent for 'Environmental product declaration', EPD)
Mtonne/a	Megatonnes per annum (1,000,000 tonnes/a)
N	Nitrogen
NMD	National Environmental Database (in Dutch 'Nationale Milieudatabase')
O	Oxygen
OSB	Oriented strand board
P	Phosphorous
T	Time horizon (years)
tonne/ha.a	1,000 kg per hectare per annum
tonne/m^3	tonnes per cubic meter
UNFCCC	United Nations Framework Convention on Climate Change
wt.%	Weight percent
y	Service life of building product (years)

Annex 1 Chemical composition of bio-based feedstock

In the tables below, the chemical composition (wt.%) of a range of bio-based feedstocks is presented: Average value calculated from data from literature and WFBR internal database and standard deviation, number of samples tested, composition normalized to a total of 100 wt.% and standard deviation.

Table A1.1. Chemical composition (%) of <u>flax bast fibre</u>: Average value calculated from data from literature and WFBR internal database; standard deviation; number of samples tested; chemical composition normalized to 100 wt.%.

Component	**Average Composition**			**Average Composition, Normalized to 100 wt.%**	
	(wt.%)	Stdev	n =	(wt.%)	Stdev
Cellulose	72.8	3.2	28	73.8	3.2
Hemicellulose	9.0	1.1	28	9.2	1.1
Lignin	3.5	1.2	28	3.6	1.2
Pectin	2.7	0.9	28	2.8	0.9
Protein	2.0		1	2.0	0.0
Extractives, polar	4.34	2.2	27	4.4	2.3
Extractives, apolar	2.9	0.7	23	3.0	0.7
Ash	1.3		1	1.3	
Total	98.6			100	

Table A1.2. Chemical composition (%) of <u>hemp bast fibre</u>: Average value calculated from data from literature and WFBR internal database; standard deviation; number of samples tested; chemical composition normalized to 100 wt.%.

Component	**Average Composition**			**Average Composition, Normalized to 100 wt.%**	
	(wt.%)	Stdev	n =	(wt.%)	Stdev
Cellulose	75.0	5.9	12	74.7	5.8
Hemicellulose	9.1	2.0	12	9.1	2.0
Lignin	3.7	1.3	11	3.6	1.3
Pectin	3.7	1.2	11	3.7	1.2
Protein	1.7		1	1.7	
Extractives, polar	3.8	2.5	10	3.8	2.5
Extractives, apolar	1.1	0.6	10	1.1	0.6
Ash	2.3	1.6	3	2.3	1.5
Total	100.4			100	

Table A1.3. Chemical composition (%) of <u>flax shives</u>: Average value calculated from data from literature and WFBR internal database; standard deviation; number of samples tested; chemical composition normalized to 100 wt.%.

Component	**Average Composition**			**Average Composition, Normalized to 100 wt.%**	
	(wt.%)	Stdev	n =	(wt.%)	Stdev
Cellulose	41.1	10.9	9	39.7	10.5
Hemicellulose	20.6	7.2	9	19.9	6.9
Lignin	24.8	5.0	9	24.0	4.9
Pectin	4.0	1.2	2	3.8	1.2
Protein	3.0		1	2.9	
Extractives, polar	4.5	5.1	3	4.4	4.9
Extractives, apolar	3.3	0.3	2	3.2	0.3
Ash	2.2	0.8	7	2.1	0.8
Total	103.6			100	

Table A1.4 Chemical composition (%) of <u>hemp shives</u>: Average value calculated from data from literature and WFBR internal database; standard deviation; number of samples tested; chemical composition normalized to 100 wt.%.

Component	**Average Composition**			**Average Composition, Normalized to 100 wt.%**	
	(wt.%)	Stdev	n =	(wt.%)	Stdev
Cellulose	43.0	2.7	4	41.0	2.5
Hemicellulose	31.2	4.1	4	29.7	3.9
Lignin	22.4	1.1	4	21.3	1.1
Pectin	2.3	2.4	2	2.2	2.3
Protein	1.6		1	1.5	
Extractives, polar					
Extractives, apolar	2.5	1.3	4	2.4	1.2
Ash	2.1	0.9	4	2.0	0.8
Total	105.0			100	

Table A1.5. Chemical composition (%) of <u>wheat straw</u>: Average value calculated from data from literature and WFBR internal database; standard deviation; number of samples tested; chemical composition normalized to 100 wt.%.

Component	**Average Composition**			**Average Composition, Normalized to 100 wt.%**	
	(wt.%)	Stdev	n =	(wt.%)	Stdev
Cellulose	33.1	3.0	24	34.5	3.1
Hemicellulose	22.8	2.2	24	23.8	2.3
Lignin	21.4	3.1	24	22.3	3.2
Pectin	2.6	0.9	23	2.7	0.9
Protein					
Extractives, polar	6.2	3.1	24	6.5	3.3
Extractives, apolar	3.3	1.3	24	3.4	1.4
Ash	6.5	0.2	2	6.8	0.2
Total	95.7			100	

Table A1.6. Chemical composition (%) of <u>reed</u>: Average value calculated from data from literature and WFBR internal database; standard deviation; number of samples tested; chemical composition normalized to 100 wt.%.

Component	**Average Composition**			**Average Composition, Normalized to 100 wt.%**	
	(wt.%)	Stdev	n =	(wt.%)	Stdev
Cellulose	30.4	4.9	13	34.8	5.6
Hemicellulose	18.1	3.6	13	20.7	4.1
Lignin	24.5	1.9	13	28.1	2.2
Pectin	1.9	0.4	13	2.1	0.4
Protein					
Extractives, polar	3.7	1.0	13	4.2	1.2
Extractives, apolar	3.0	0.8	13	3.5	0.9
Ash	5.8	1.9	7	6.6	2.2
Total	87.3			100	

Annex 2 Carbon content of bio-based feedstock

In the table below, the experimentally determined carbon content (g/kg) of a range of bio-based feedstocks is presented. Carbon content is based on samples milled to < 0.5 mm, drying till equilibrium at 70°C and using a LECO CN Analyser.

Table A2. Carbon content of biobased feedstock (g/kg).

Feedstock	**C-content (g/kg)**	**Feedstock**	**C-content (g/kg)**
Spruce	493	Reed (annual)	483
Pine	500	Reed (multi annual)	474
Accoya (acetylated Radiata Pine)	518	Verge grass	480
Finti (thermally treated Pine)	529	Miscanthus	476
Mahonie	503	Cattail	480
Meranti	512	Wheat straw	472
Swietenia	508	Sorghum straw	460
Red Grandis	494	Cupplant	458
Sapupira	511	Cupplant (Steam exploded)	483
Sapeli	504	Bell pepper stalk	460
Azobé	520	Bell pepper stalk (2)	344 *
Massarunduba	512	Tomato stalk	330 *
Cellulose Softwood fibre	433	Sheep wool	473
Cellulose Hardwood fibre	434	Cork starting material	626
Cotton	428	Expanded Cork insulation	685
Flax bast fibres	434	Mycelium top layer	485
Flax shives	492	Bamboo	491
Hemp bast fibres	432		
Hemp shives	483		

* Not clear what has caused the low values for these 2 stalk samples. No satisfying explanation could be found so far; samples do not contain significant amount of sand.

To explore the potential of nature to improve the quality of life

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