

SCORELCA

STUDY N° 2022-03

GHG SINKS

DEFINITIONS, CALCULATION METHODS AND USE

SYNTHESIS

November 2023



SCORE LCA is an association that has been created to financially support collaborative research on LCA and related topics. It aims to promote and organize cooperation between companies, institutional and scientists in order to support the evolution of LCA methods and its practical implementation at European and international level.

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- ✓ The information and conclusions presented in this document were established on the basis of scientific and technical data and regulatory and normative framework in force at the date of the publication of documents.

WeLOOP & CyVi have been collaborating with ScoreLCA on Carbon Capture, Use, and Storage (CCU/S) techniques and the methodological challenges of considering these techniques in Life Cycle Assessment (LCA) for practitioners, companies, and institutions.

The objectives of the project are to:

- Establish an inventory of the different types of GHG sinks used and usable by companies to “neutralise their emissions”.
- Propose methodologies for calculating the emissions captured by these different types of GHG sinks.
- Make recommendations.

Desk research and interviews with 10 experts on CCU/S from different countries and sectors (industry, research, public institutions, etc.) provided an overview of CCU/S in practice today.

I. STATE OF THE ART

CCU/S are the techniques used to avoid CO₂ emissions or remove them from the atmosphere, then use or store the carbon in various forms (e.g., GHG sinks). These techniques are necessary to achieve carbon neutrality, to compensate for the surplus of residual emissions once GHG emissions have been reduced as much as possible.

Capture is divided into two categories: natural capture, which takes place in an anthropised natural environment (such as a sustainably managed forest) without any direct energy input, and technological capture, which relies on processes to remove CO₂ from the combustion of fossil or biogenic fuels, from a chemical reaction, or directly from the atmosphere. The technological capture stage alone accounts for 80% of the energy CCS systems consume (the other stages are conditioning, transport, and injection). The most suitable techniques for each application will be determined according to the capture conditions, such as the composition of the gas to be treated, the partial pressure of CO₂, and the energy required by the process. Capture technology is divided into five categories, as illustrated in Figure 1.

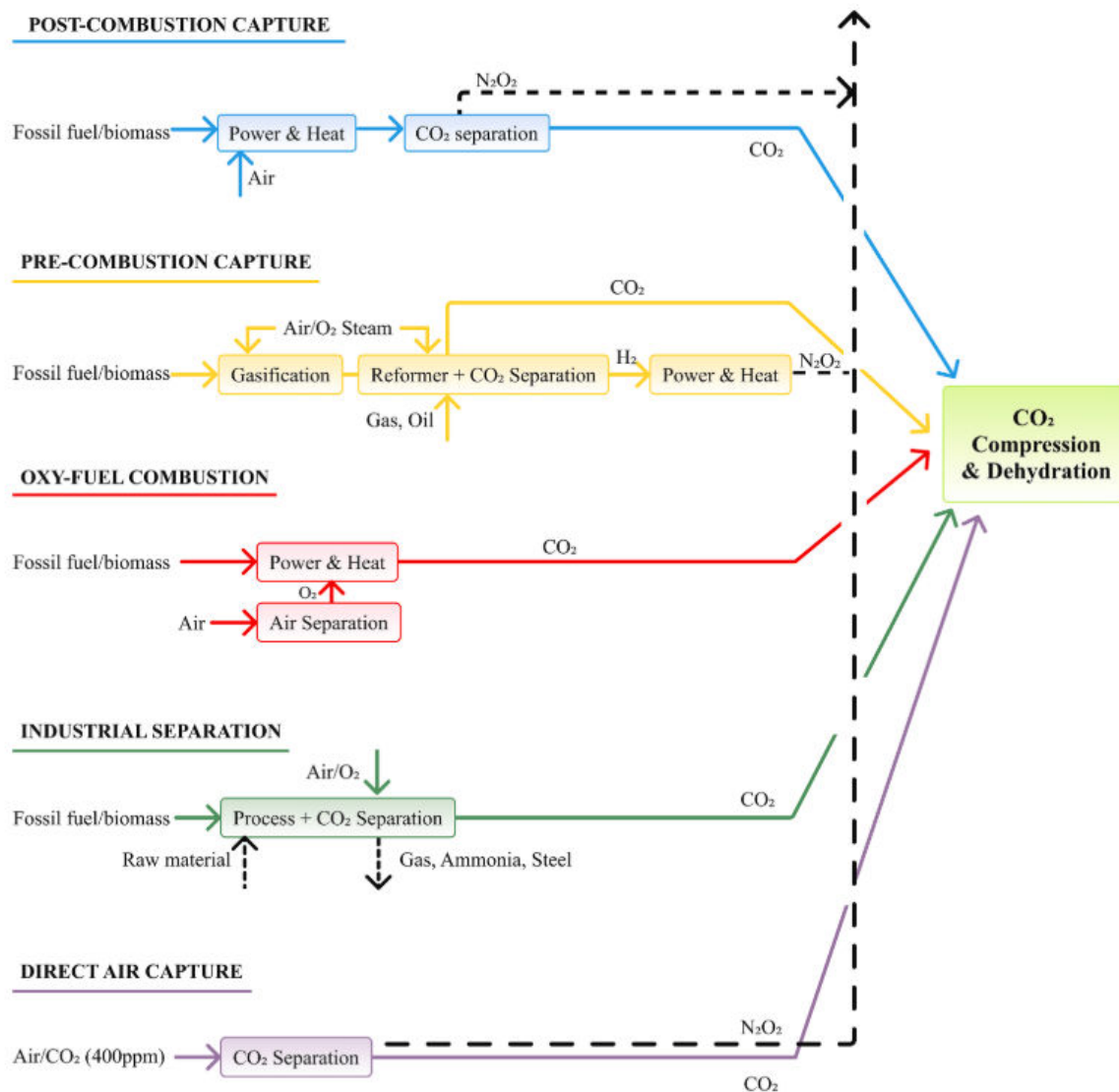


Figure 1 : Carbon capture processes (Dziejarski et al., 2023)

Depending on the capture type, different options are available once the carbon has been conditioned (in liquid form for CO₂, for example) and transported. For example, natural carbon capture, in the form of wood, can be used to make timber frames or stored in the soil as biochar. CO₂ from technological capture, on the other hand, can be used to produce chemical precursors or stored geologically.

Figure 2 shows the various carbon flows and stocks directly influenced by anthropogenic processes. The flows shown are either naturally or technologically captured carbon flows (arrows pointing downwards from the top) or emissions linked to the degradation or end-of-life of anthropogenic carbon sinks, where applicable (arrows pointing upwards from the bottom).

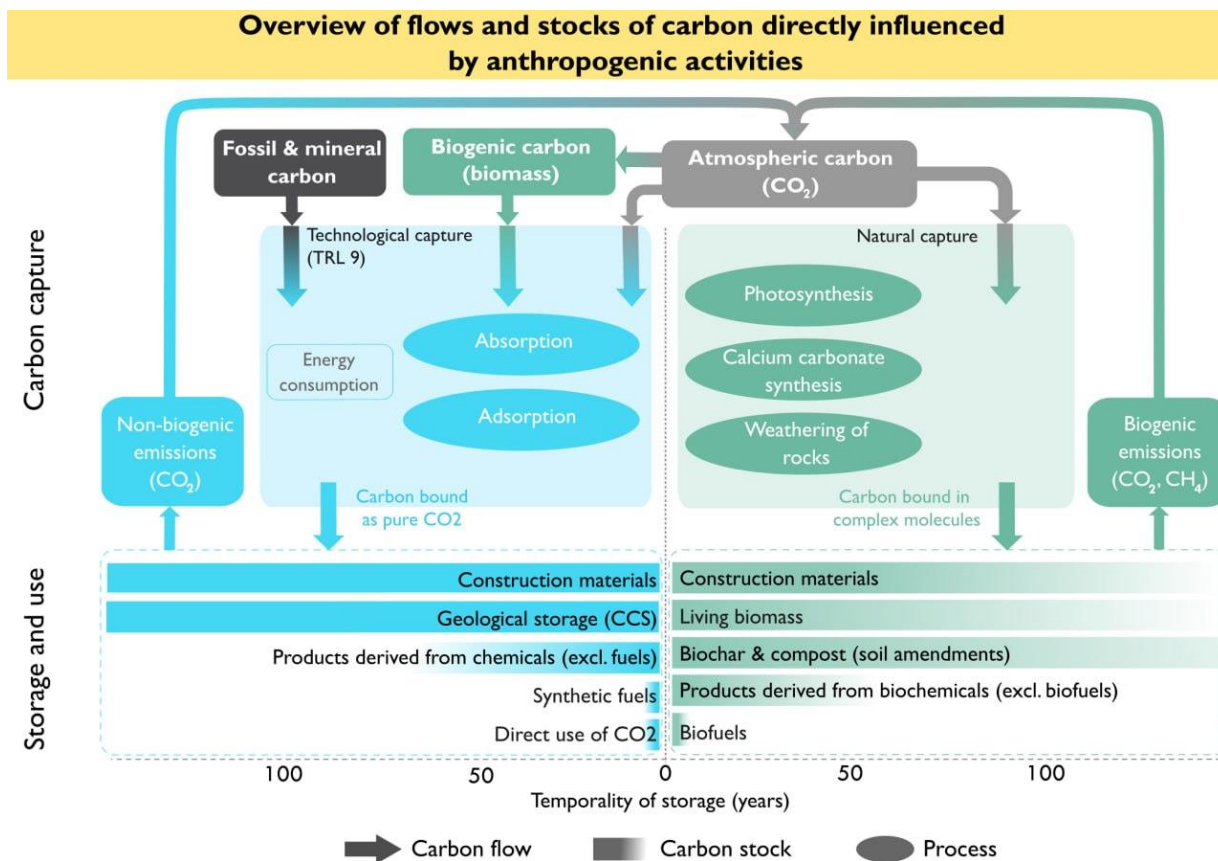


Figure 2 : Carbon flows and stocks directly influenced by anthropogenic processes

The storage times indicated are approximate and cover all potential applications or forms in which carbon is stored (for example, the “living biomass” category includes annual plants and trees that can live for over 100 years). Shading indicates potential variability in storage duration. (image from WeLOOP, 2023)

Finally, in the case of CCU systems, the products' end-of-life (e.g., landfill or incineration) will determine how the carbon remains stored or whether it is released into the atmosphere.

Although more and more CCU/S systems are operational today, many obstacles still prevent their large-scale deployment. The main barriers to their development are the lack of robust concrete implementation cases, the slowness and complexity of setting up projects, and a lack of social acceptability, which must add significant financial difficulties. Figure 3 shows the main obstacles identified by the European Union's Directorate-General for Climate Action.

The lack of robust application cases and the solutions' low technological maturity complicate life cycle impact assessments, not only because of the lack of data but also because of the latter's uncertainty compared with more mature solutions.

The European Commission has identified the need to harmonise and structure CCU/S solutions. Indeed, applications are still limited, and the term CCU/S refers to many solutions involving different techniques at each stage (capture/transport/storage). WeLOOP, therefore, proposes a nomenclature to classify the different solutions available.



Figure 3 : Barriers to the development of UCD/S solutions (European Commission, 2018)

The nomenclature presents solutions in stages, in the form of a tree structure, from carbon capture to destination. The first letter distinguishes natural capture (N) from technological capture (T). The second letter (C) distinguishes capture according to its identifier. The letter T corresponds to transport from T1 to T5. Two or more digits indicate multimodal transport. The capture and transport solutions identified are presented in Table 1.

Table 1 : Summary of available capture and transport solutions, with corresponding identifiers in the nomenclature and compatibility matrix

Step	Name	ID	Compatibility	
			Capture type	
			N	T
Capture	Absorption	C1	Red	Green
	Adsorption	C2	Red	Green
	Membrane	C3	Red	Green
	Carbonate calcium looping	C4	Red	Green
	Chemical loop combustion	C5	Red	Green
	Other technologies	C6	Red	Green
	Photosynthesis	C7	Green	Red
	Carbonate calcium synthesis	C8	Green	Red
	Enhanced weathering	C9	Green	Red
Transport	Truck	T1	Green	Green
	Train	T2	Green	Green
	Barge	T3	Green	Green
	Ship	T4	Green	Green
	Pipeline	T5	Red	Green

Next, the letters U and S distinguish whether the carbon is used or stored. Finally, the letters N, M and L represent carbon storage duration. The number that follows indicates the type of storage. The use and storage solutions identified are presented in the table below:

Table 2 : Summary of available use and storage solutions, with corresponding nomenclature identifier and compatibility matrix

Step	Name	ID	Compatibility						
			Capture type		Use or storage		Storage duration		
			N	T	U	S	N	M	L
Use or storage	Chemical synthesis	1							
	Fuel synthesis	2							
	Direct use of CO ₂	3							
	Construction materials	4							
	Other biobased materials	5							
	Biochar	6							
	Afforestation and reforestation	7							
	Agroforestry	8							
	Rehabilitated peatlands / rewetted	9							
	Forest management	10							
	Increase in soil organic carbon	11							
	Geological storage	12							
	Accelerated carbonation	13							
	Enhanced weathering	14							

Figure 4 shows an example of the classification corresponding to a timber frame used in a house. The compatibility matrix from Table 2 is used to determine the utilization options (U) available for natural capture (N) via photosynthesis (C7), with truck transport (T1): M1, M4, M5, M6, M7 and M8.

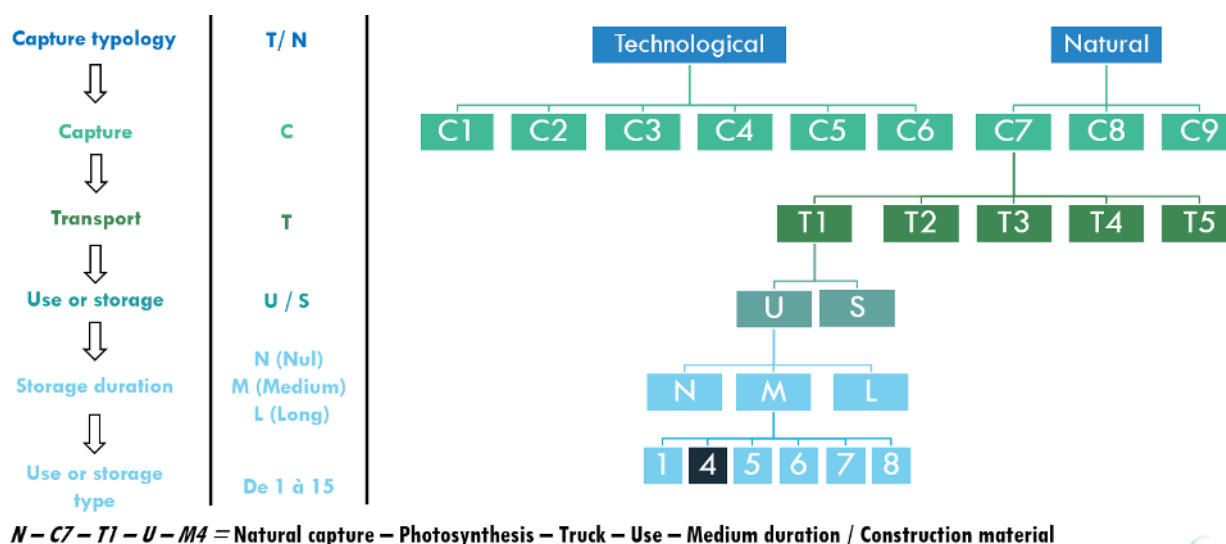


Figure 4 : Nomenclature presentation for a timber frame

II. METHODOLOGY FOR LCA OF CCU/S AND RECOMMENDATIONS

We identified two important issues for LCA of CCU/S:

1. temporality of storage,
2. allocation of impacts & benefits between generating/capturing and the user the CO₂.

How do we consider the temporary carbon storage in wood for 50 years (building applications) compared to the wood used as energy, which releases CO₂ directly?

Who should benefit from the credits (&impacts) associated with CO₂ capture and use?

Other questions remain, such as how to deal with the carbon's "status" (biogenic, fossil) and classify flows. The next section will address these and other issues that arise at every stage of an LCA.

II.1 Goal and scope of the study

Objective of the study

The precise definition of the research question to be answered by the LCA is important since the study's objective will determine its specific methodological choices, such as the definition of the system boundaries and the allocation rules for co-products.

The most common research questions in the literature on different CCU/S solutions concern the environmental profile improvement of a product or service through CCU/S, the hotspots identification of a CCU/S system, or the environmental trade-offs related to CCU/S implementation.

Several types of LCA can be considered depending on the study objectives: consequential LCA, which studies the consequences of a solution's market impact; dynamic LCA, which compares two CCU/S solutions with a temporal vision; or prospective LCA for innovative solutions or those with a low TRL (Technological Readiness Level).

Scope of the study

Apart from hotspots, processes common to the different systems analysed (isoperimetric) can be excluded from the study.

In the case of CCS systems, the system is not multifunctional since only the original product is considered in the functional unit, and the captured CO₂ can be considered as a waste product that is disposed of similarly to waste sent to a landfill. The functional unit must, therefore, quantify the product or service's performance (with or without CCS), ideally specifying where and when it was produced (e.g., "1 kg of steel produced in [year] in [country/continent]").

In the case of CCU systems, the captured carbon is used as an input in another industrial process and thus contributes to a function (and the associated functional unit in the case of an LCA). The system's multifunctionality must, therefore, be considered. When defining the system under study, the functional unit should enable reliable comparison of studies on different CCU systems.

An important point when modelling CCU solutions concerns CO₂ as a product: In LCA terminology, "CO₂" refers to an elemental flow. In the analysis of CCU solutions, this same CO₂ is classified as a final product and must, therefore, be reflected in the functional unit, where the declared unit could be "1 kg of CO₂ captured".

II.2 Multifunctional process management

As explained in the previous chapter, the process of producing CO₂ for a CCS system is not multifunctional. CO₂ captured for use (CCU) always comes from a multifunctional process, as it is co-produced with a main product (cement, for example). Therefore, it is necessary to divide the carbon capture impacts between these products in some cases.

The ISO14040/44 standard provides a mandatory hierarchy to be followed for the distribution of impacts between multifunctional processes, shown in the table below:

Tableau 3 : ISO hierarchy for multifunctional processes

Hierarchy	Name	Description
If allocation is avoidable		
1.	Subdivision	Division of multifunctional processes into sub-processes and distribution of inputs and outputs between the various sub-processes.
2.	System expansion	Inclusion of additional functions in system boundaries followed by substitution to avoid allocation (ISO 14044:2006, Amendment 2, Annex D:2020)
If allocation is unavoidable		
3.	Physical allocation	Inputs and outputs are allocated between sub-processes based on physical relationships (mass or volume).
4.	Allocation based on other criteria	If this is not possible, other relationships are used to allocate impacts to different products (e.g. economic value)

When a subdivision is not applicable, boundary extension must be applied. This involves separating the product and the CO₂ co-product into different functions. This boundary extension involves identifying the product(s) that are replaced by the co-product(s) of the product under study and quantifying the associated impacts (ISO14044, Annex D: 2020). The main limitations of this method are the consequential approach used in attributional modelling, the complexity of identifying the substituted system and the risk of double counting between the CO₂ producer and the user. When allocation is unavoidable, the last two options in the table should be used. The limitation of these allocations is that physical allocation is not always applicable (co-production of electricity and CO₂, for example) or may give inconsistent results (co-production of cement and CO₂, which generates a comparable mass of both) and that the difference between the revenues associated with CO₂ and the main product may be significant, so physical allocation is not recommended. Economic allocation is impossible for two reasons: the price of CO₂ (or of the main product) can vary significantly, and CO₂ is poorly monetised in most markets.

WeLOOP has, therefore, proposed a new method based on supply and demand, illustrated in Figure 5, to allocate impacts between CO₂ producers and users. This approach is simple to implement and aims

to encourage the development of the most efficient solutions possible, freeing us from dependence on fossil fuels.

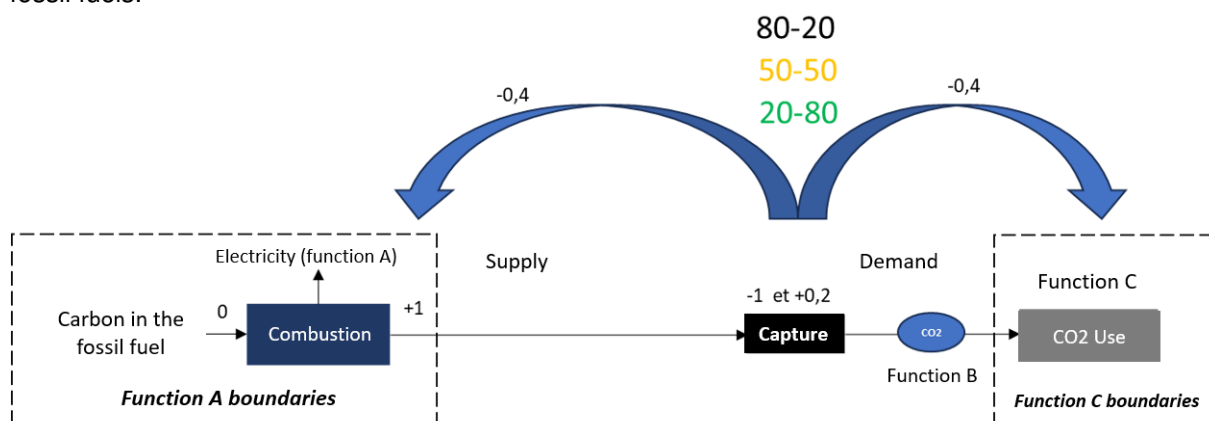


Figure 5 : Supply and demand allocation

The impacts and benefits of capture will be calculated by extending the system's boundaries by substituting the CO₂-generating process and then splitting between the main product and the CO₂ according to an attribution factor set at the political level. This is a hybrid approach, as it combines a boundary extension with an attribution and conservative vision. The substitution system to be chosen is functionally equivalent to the production of the main product without capture. This leads to a vision close to the real impacts of the product, unlike a substitution of the capture system by a Direct Air Capture (DAC), which attributes a large benefit to the CO₂-generating system. In addition, there is no risk of double counting the substitution in applying ISO14040/44.

The allocation factor is set between 0 and 100%, depending on the actual market. At present, the amount of capturable CO₂ is significant, but little CO₂ is captured, resulting in a relatively low supply. 80/20, 50/50, or 20/80 factors could be used to avoid marginal cases where all the impacts and benefits would be attributed to a single system. The main limitations of this method are that it is subjective and political due to the choice of substitution system and attribution factor and that the capture effort may not be sufficiently rewarded in the current context.

II.3 Mass balance approach for CCU/S solutions

The “mass balance—credit method” was proposed as an alternative to the “mass balance—rolling average” method traditionally used in LCA. According to ISO 22095, this value chain modelling consists of attributing credits linked to an industry's virtuous approach to a single part of its production, as illustrated in Figure 6.

For example, a company producing three different products and capturing/storing 10% of its total emissions could, via the mass balance approach, declare 10% of its production (product 1) as carbon neutral and the remaining 90% without any specific mention.

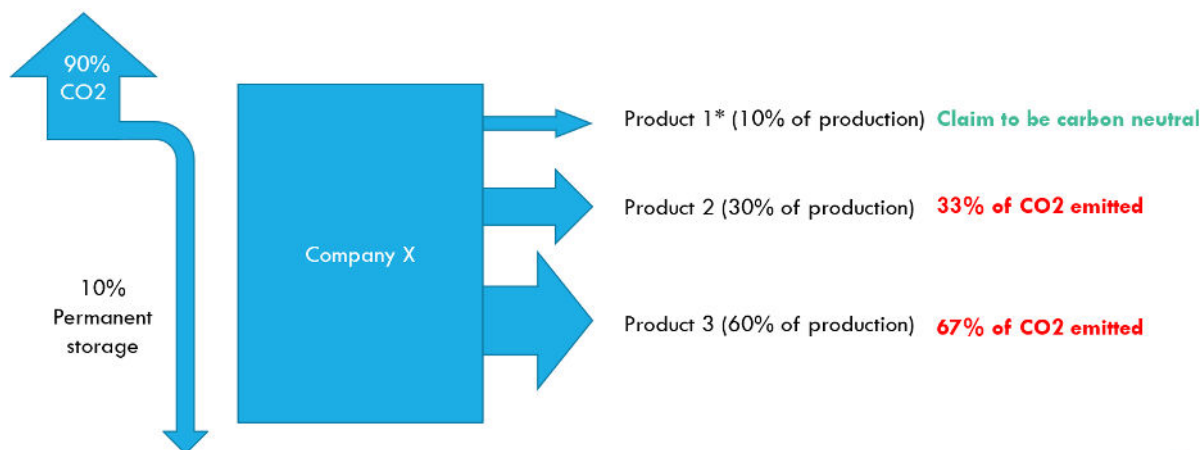


Figure 6 : Mass balance approach for carbon capture and storage

WeLOOP does not recommend the use of the Mass Balance - Credit Method in the LCA of CCU/S solutions. As an emission reduction is not an input-specific characteristic, it cannot be attributed to an output product under ISO 22095. Instead, WeLOOP recommends using the “Mass Balance - Rolling Average” approach, as is conventional in LCA, in which each product benefits from the capture.

II.4 Carbon status, transfer between pools, and temporality of emissions

Carbon status nomenclature and transfer between pools

Carbon can be found in various pools, the main ones being biomass, soil, lithosphere, ocean and atmosphere. Human activities influence the different pool concentrations. Thus, in LCI data, elemental CO₂ fluxes enable us to identify emissions of fossil or biogenic origin or those linked to the transformation of land use. Once in the atmosphere, CO₂ can no longer be differentiated according to its origin. Carbon captured by soil or biomass is identified as “carbon dioxide, to soil or biomass stock”.

Consideration of the carbon cycle is essential for correctly applying the LCA methodology. WeLOOP, therefore, recommends not assigning a status (biogenic or fossil) to the carbon present in the atmosphere, whatever its source. On the other hand, monitoring the carbon status in the product and its possible transfer of status will enable long-term effects to be correctly considered. Status changes are possible, for example, with the mineralisation of biogenic carbon contained in common industrial waste (CIW).

Emission timing

LCA, as it is mostly practised, is “static”: absorptions and emissions have the same impact whether they occur today or in the future (this is a requirement of ISO 14067, for example). This corresponds to the matrix structure of conventional LCA and facilitates life-cycle inventory, calculation, and interpretation.

Regarding emissions temporality, the problem lies in the fact that the actual impact varies with time and that the political agenda defines targets with a fixed time horizon, such as carbon neutrality by 2050 for France. LCA guidelines and standards propose different approaches for considering the temporality of emissions (they are mentioned in ISO 14067). Temporal effects are not considered due to the methodological difficulties involved in considering temporality in LCA and the uncertainty regarding climate change's evolution and the impact of emissions over the medium and long term.

Table 4 presents the methodological choices for the main LCA standards and guidelines.

Table 4 : Summary of temporality treatment according to methodologies

Temporality	ISO 14040/44	ILCD	PEF	EN 15804 A2 EN 15978
				RE2020
Short term 0-100 years	-	Correction factor Additional information	No differentiated flow according to time frame. Storage is not authorised, and carbon is re-emitted artificially.	- Dynamic modelling at the building scale
Long term 100 < < ∞ years	Unspecified	Additional elemental flux Long-term CO ₂ No impact		No timeframe specified for permanent storage
Quasi-permanent permanent ∞	Waste No impact	Waste No impact		Biogenic carbon re-emitted, credit/storage for fossil carbon

WeLOOP recommends following the ILCD guidelines for a proper assessment when the context of the requirements in which the calculation is performed does not impose another rule. All short-term (0-100), long-term (100-infinite) and permanent (infinite) flows should be accounted for separately. This approach enables these flows to be considered in the studies according to the set objectives. Temporary storage must only be considered if the products have a medium or long lifespan (e.g over 5 years). This way, a characterisation of carbon flows in products with temporary storage capacity could be set up. It is also recommended that temporary storage effects be reported separately in the results.

II.5 Life cycle impact assessment methods

There are two indicators, the Global Warming Potential (GWP) and the Global Temperature Potential (GTP), and three timeframes (20, 100 and 500 years) for assessing the impact of GHGs on climate change (as well as two types of effect: direct and indirect). GWP uses radiative forcing as an indicator, while GTP uses temperature change, and both are expressed in kg of CO₂ equivalent. The advantage of a measure reflecting temperature change is that it is closer to actual impacts than radiative forcing, even if its quantification using flux characterisation factors is more uncertain than GWP.

Using different time horizons and the GTP would enable a more in-depth analysis of study results and more accurate conclusions. The addition of new indicators should also be based on the study objectives and the GHGs emitted. If methane is emitted in large quantities, it makes sense to use several indicators. This is not the case if the only GHG is CO₂.

WeLOOP recommends using PRG100 for studies aimed at a non-expert audience to limit the risk of misinterpretation: this is the conventional indicator used (ISO 14067 requires that the latest characterisation factors provided by the IPCC be used to date those in the AR6 report). Complementary indicators can be used for decision-making purposes for a study aimed at an expert audience.

II.6 Dynamic modeling

Unlike conventional “static” LCA, dynamic LCA considers the temporality of delayed emissions. The temporary storage of carbon in products can, therefore, be considered in impact assessment. In theory, this could lead to an assessment closer to reality. Indeed, the impact of CO₂ emissions over 100 years

after a 75-year lifespan (i.e., over the period T+75 to T+175) is not the same as the impact of emissions considered at time 0 (T0 to T+100). For the impacts generated by the two emissions to be comparable, it would be necessary to compare the result of the first calculation from T+75 to T+175 for the emission taking place at T75 with the calculation from T0 to T+175 for the emission taking place at T0. Nevertheless, modelling dynamic impacts is complex, and the lack of knowledge of the future climate context makes assessing delayed impacts uncertain. Furthermore, dynamic modelling of a single impact category (climate change in this case) may lack coherence within the LCA framework.

The ILCD and RE2020 approaches incorporate a dynamic approach specific to the climate change indicator. It is integrated from the Life Cycle Impact Assessment (LCIA) stage onwards. For ILCD, a linear correction factor is applied in the additional information from 0 to 100 years, with a credit from 0 to 100 years. RE2020 has a similar correction factor, but it is applied at the building scale, not the product scale like ILCD.

II.7 Issues related to CCU/S solutions

Because of their low TRL and/or limited large-scale deployment, certain issues are more pressing for CCU/S solutions: leakage and stability of the various carbon storages, and emissions from the data considered to model CCU/S processes.

Transport is the biggest source of leakage for technologically captured carbon, while it is negligible for CO₂ captured naturally. The Innovation Fund provides estimates of leakage (European Commission, 2020). There is an identified need for evaluation or prediction methods for the future.

The calculation of process-related emissions from CCU/S solutions, and in particular the electricity mix used in the modelling, is a subject of debate in the interviews that have been carried out. Electricity often has a major impact on CO₂ capture processes and can also have a major impact on its use and/or storage. For example, the GWP of methanol production from CO₂ can decrease by 90% depending on the mix used (Ana Villa-Zaragoza et al., 2019).

WeLOOP, therefore, recommends carrying out a sensitivity analysis for the electricity mix, with one mix representative of the current situation (depending on site location, for example) and several prospective mixes.

III. CASE STUDIES

Calculation results between different products were obtained using four methodologies or standards: ILCD, PEF, EN15804:A2 and ISO14040/14044. Case studies were carried out on 2nd generation biodiesel (produced from wood and straw), wood pellets, and wood wool insulation (with two possible end-of-life: incineration or landfill) to compare the storage associated with different uses and on different types of cement to compare the geological storage of the same product.

This work does not result in an environmental claim concluding on the superiority of one product over another (according to ISO 14044). Pellets and wood wool were put into perspective to display the storage potential of products using the same raw material and the influence of end-of-life on storage. Three different types of cement were used: CEM I cement, data taken from Ecoinvent, and two types of cement whose carbon is captured and then stored. The difference between the latter is that one uses solid recovered fuels (SRF, biogenic carbon status), while the other uses fossil fuels for clinker production.

Figure 7 shows the results for wood products. Pellets are used as a reference because there is no storage effect; the result obtained is, therefore, the same for all methodologies. It can be seen that ILCD encourages the longest possible storage, with landfill valorisation, i.e. -2.1 kgCO₂eq/kg, compared with -0.7 kgCO₂eq/kg for incinerated wood wool and 0.1 kgCO₂eq/kg for pellets. For PEF and EN15804, there is almost no variation between the different products, as storage is not considered. ISO14040 allows permanent storage to be considered, with no dynamic effect, which gives a result equal to pellets for incinerated wood wool and negative for landfills.

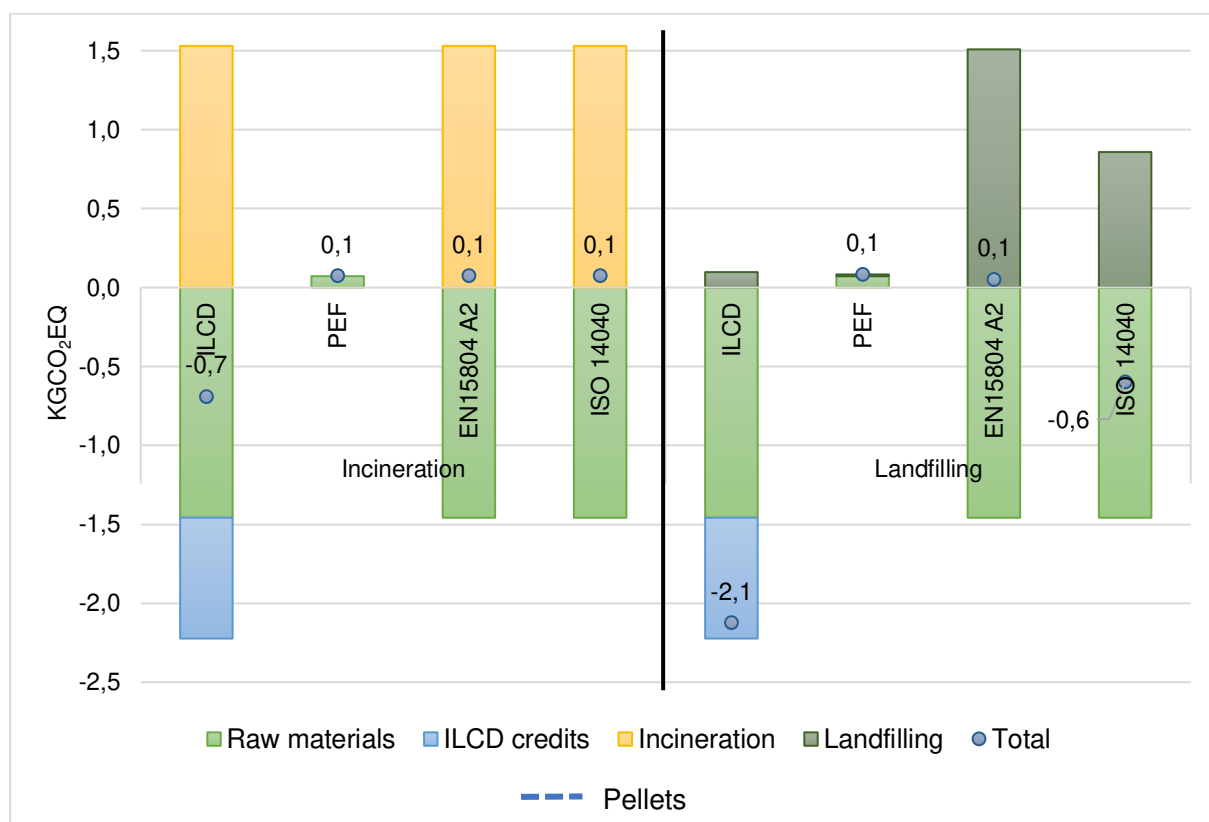


Figure 7 : GHG emissions by method for 1 kg of wood wool incinerated (left) or landfilled (right) at end of life

Figure 8 shows the results for the different cements. When ILCD is used, the results for fossil cement and SRF are equal, i.e., 0.01 kgCO₂eq/kg, as SRF has the status of waste and, therefore, has no benefit associated with the biogenic carbon captured. The ILCD credit is summed with the results, but in reality, it is displayed separately. For PEF, the use of SRF is valorised, with 0.99 kgCO₂eq/per kg for SRF cement and 1.15 kgCO₂eq/kg for fossil cement, but the total impact is more significant than that of CEM I (0.9 kgCO₂eq/kg), as permanent storage is not allowed, and so the extra input required for capture is not rewarded. EN15804 allows fossil carbon storage but not biogenic carbon, resulting in higher impacts for SRF cement (0.01 kgCO₂eq/kg and 0.17 kgCO₂eq/kg, respectively). For ISO, the results are equal to ILCD as there is no temporary use effect.

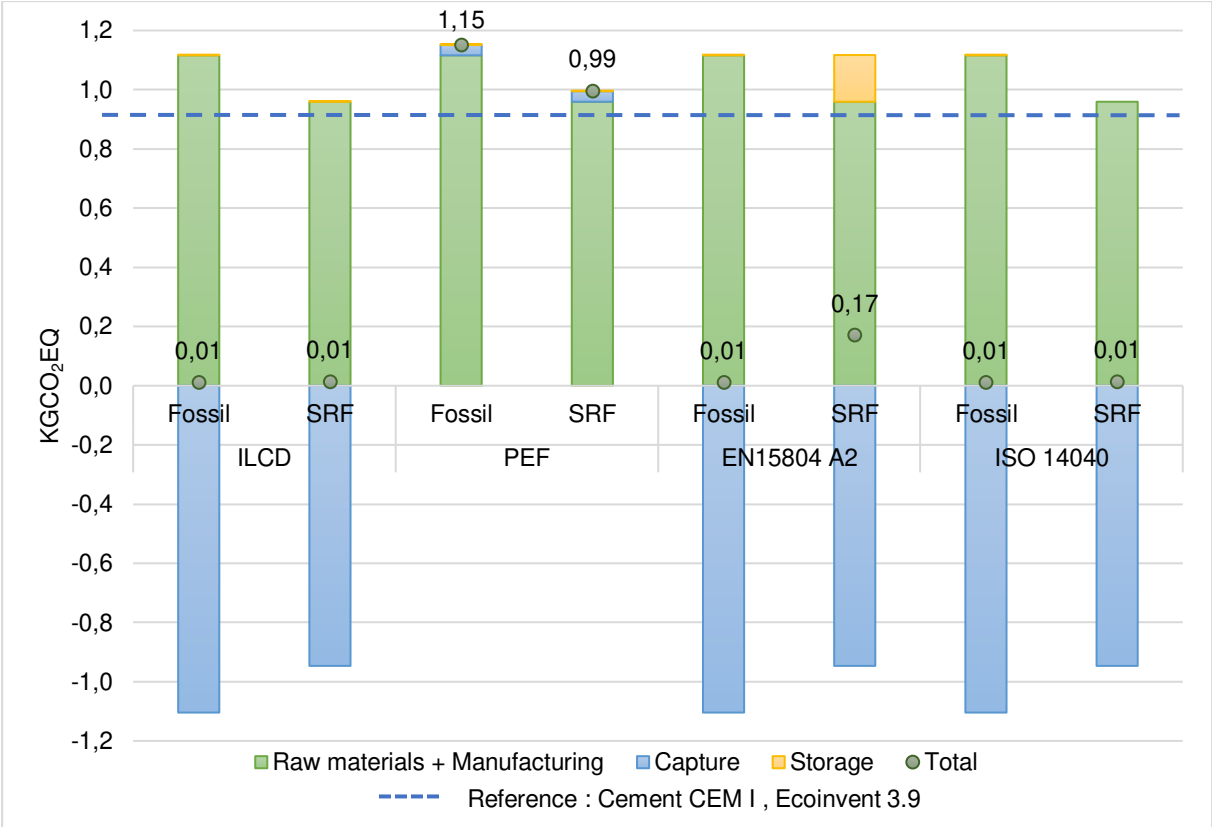


Figure 8 : GHG emissions by method for 1 kg of cement