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Life Cycle Assessment of Carbon Dioxide Supply Chains: State of the Art and Methodology Description

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Abstract: Due to the increase of carbon dioxide emissions, a target for their reduction has been defined in the Paris Agreement for 2030. This topic is extremely important, and urgent actions are required so that the attention of the scientific community is mainly focused on emission reduction. In this context, carbon supply chains have an important role because they can help in carbon dioxide mitigation. In fact, in these systems, carbon dioxide is captured to be stored or used to produce valuable products. However, carbon supply chains involve many energy consumptions during the operation (causing carbon dioxide emissions and resource depletion), and an analysis of the environmental impact of the system is required. Different green metrics exist but the most effective is the life cycle assessment. The methodology of the life cycle assessment is presented in this work, with particular considerations for its application to carbon supply chains. An overview of the research presented in the literature is also considered here, with suggestions for future analyses.

Keywords: life cycle assessment; carbon capture and storage supply chains; carbon capture and utilization supply chains; carbon capture utilization and storage supply chains

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1. Introduction

Continuous greenhouse gas (GHG) emissions from human activities have been one of the most severe environmental problems for decades [1]. In fact, worldwide carbon dioxide emissions were 35.34 Gton in 2021, while carbon dioxide concentration was about 414 ppm [2], and it is foreseen that this parameter will rise to 450 ppm in 2035 if proper actions are not taken [3]. On the other hand, due to the importance of this problem for all humanity, the research community has agreed to keep the carbon dioxide concentration value below 350 ppm for safe considerations [4]. In this context, the European Commission decided to reduce greenhouse gas emissions of 40% by 2030 and 80% by 2050 compared to the level of 1990 [5]. In this way, the increase in temperature should be kept below 2 °C, as signed by 200 parties in the Paris Climate Agreement conference held in 2015 (COP21) [6], and climate neutrality should be the objective to be achieved.

To achieve this purpose, carbon supply chains have an important role and can be considered a strategic solution because they contribute to carbon neutrality by facilitating extensive carbon emission reductions. In fact, the reduction in carbon dioxide emissions requires not only a transition toward renewable energy supply but also the implementation of carbon supply chains. Among these systems, it is possible to have a carbon capture and utilization (CCU) supply chain, carbon capture and storage (CCS) supply chain, and carbon capture utilization and storage (CCUS) supply chain. In these frameworks, respectively, carbon dioxide is captured at the source with different capture technologies, and after its transportation, it is used to produce valuable products (i.e., oil and gas recovery, fuels and chemicals such as methanol, methane, ethanol, urea, polymers, etc., and carbon dioxide can be used for mineralization); it is stored; and it is stored and/or used in the last case (Hasan et al., 2015; Hasan et al., 2014).

The importance of carbon supply chains for carbon dioxide emission reduction has been underlined by the International Energy Agency (IEA) predicting, particularly, that the CCUS system can contribute to 19% reduction in GHG emissions by 2070 by reducing 6.9 $\text{Gton}_{\text{CO2eq}}$/year [7]. Considering specifically the European Union (EU), the CCUS supply chain can contribute to an emission reduction with values of 20–604 Mton_{CO2}/year in 2030, 140–1570 Mton_{CO2}/year in 2040, and 430–2230 Mton_{CO2}/year in 2050, respectively [8]. It is evident that the achievement of carbon neutrality by the mid-21st century will be impossible without CCUS frameworks (Chen et al., 2022). Moreover, the Intergovernmental Panel On Climate Change (IPCC) estimates that achieving global climate goals would be 138% more expensive without the CCUS deployment—incorporating CCUS technologies into decarbonization packages reduces the overall cost of decarbonization [9].

Due to the importance of carbon supply chains, inside the scientific community, it has been suggested to evaluate their environmental impact and verify if they are really favorable from an environmental viewpoint. In fact, despite the benefits underlined above, the overall system also consumes a lot of energy (with a consequent environmental burden) while reducing carbon dioxide. To conduct this evaluation, several ‘green’ metrics can be considered: atom economy, E-factor, EQ-factor, and life cycle assessment (LCA) [10]. Among them, the life cycle assessment is a holistic methodology that transforms all inputs and outputs of a considered process into impact categories considering the entire life. The environmental impact developed considering all life of a process is one of the most important methodologies and by considering a holistic perspective, the method is recognized as the most favorable green metric for an environmental analysis of a system. The life cycle assessment, then, allows for verifying that carbon dioxide emissions are not reduced at the expense of other impact categories and that a net mitigation of carbon dioxide is achieved.

Moreover, inside a carbon supply chain, the life cycle assessment is able to verify if the carbon dioxide utilization section provides more emissions compared to the carbon dioxide storage section; if there are compromises between different impact categories, it allows to evaluate processes with higher emissions and environmental impact and the environmental impact of materials used in the supply chain.

A clear analysis, composed of four phases according to the International Standards Organization (ISO), provides the environmental burden of a carbon supply chain that can be analyzed through the system expansion or function-specific methodology. However, different methodological considerations and details should be considered in the life cycle assessment of carbon supply chains if a transparent and consistent analysis is needed.

In the literature, research about the life cycle assessment of carbon supply chains has been presented discussing what has been undertaken and suggesting that the use of the life cycle assessment in carbon supply chains is rapidly expanding.

An overview of the environmental analysis of carbon frameworks with technical considerations on how to use the LCA in these particular systems is missing in the literature and this presented work is aimed at overcoming this gap. In particular, in this work, a description of the life cycle assessment methodology is presented with considerations that should be kept in mind for its application to carbon supply chains. An overview of the literature analysis about the life cycle assessment of CCUS, CCU, and CCS supply chains is carried out.

2. Literature Analysis about the Life Cycle Assessment of Carbon Supply Chains

Carbon supply chains require a lot of energy during the operation, contributing to an additional environmental impact. In fact, the increased and required energy in terms of fuel consumption per kWh in the presence of carbon dioxide capture is between 24 and 40% for new supercritical pulverized coal plants, 11 and 22% for natural gas combined cycle plants, and 14 and 25% for coal-fired integrated gasification combined cycle systems compared to the respective system without capture plants [11].

To be sure that the considered supply chain reduces carbon dioxide emissions and other environmental impacts a life cycle assessment should be developed optimizing its design with the minimum burden. Different works are present in the literature about the life cycle assessment of carbon supply chains.

2.1. Life Cycle Assessment of Carbon Capture Utilization and Storage Supply Chains

CCUS supply chains not only reduce carbon dioxide emissions but also produce valuable compounds. In the literature, the LCA of carbon capture utilization and storage supply chains is mainly regarding systems that have enhanced oil recovery in the utilization section. The environmental burden and benefits of this carbon supply chain have been reported. According to Lacy et al. [12], the CCUS supply chain with carbon dioxide-enhanced oil recovery in Mexico has an environmental impact of 250.6 $\mathrm{kg_{CO2eq}}$/bbl. Hertwich et al. [13] carry out a hybrid life cycle assessment analysis for the supply chain with enhanced oil recovery in the utilization section, set in Halten (Norwegian sea). In the system, carbon dioxide from a combined cycle power plant is captured by post-combustion amine absorption, and then an emission reduction of 80% is obtained. Aspen Hysys is used for the environmental analysis evaluating the global warming and acidification impact.

Other studies about the life cycle assessment of supply chains with enhanced oil recovery in the carbon dioxide utilization section are carried out by Rhodes et al. [14], Cooney et al. [15], Hussain et al. [16] Hornafius and Hornafius [17], and Laude et al. [18] showing the environmental advantages of this system. Among these studies, Cooney et al. [15] develop a life cycle assessment for the carbon supply chain with enhanced oil recovery considering different system boundaries: gate to gate, cradle to gate, and cradle to grave. In the first case, impacts associated with carbon dioxide sources and the use of the produced crude oil are not considered. In the second case, natural carbon dioxide sources and transportation to the utilization sites are considered. In the last case, anthropogenic carbon dioxide sources, transportation of crude oil to the refinery, the refining step to produce gasoline, and its combustion are considered inside the boundaries. The results show that the crude recovery ratio (how much crude is recovered for a fixed amount of purchased carbon dioxide) is a critical parameter, and a reduction in emissions only for natural carbon dioxide is ensured when this parameter is increased. In Hussain et al. [16], different sources of carbon dioxide are considered for enhanced oil recovery. The results show that all sources of carbon dioxide derived from the integrated gasification combined cycle or natural gas combined cycle plants have about 25% and 60% lower net carbon dioxide emissions per barrel of oil recovered compared to the natural carbon dioxide source. Better performances of a CCUS supply chain for oil recovery are suggested by Hornafius and Hornafius [17], where the system could be carbon neutral or negative if the used carbon dioxide is from the fermentation emissions from an ethanol plant. However, in these studies, the life cycle assessment is not fully integrated.

Abotalib et al. [19] develop a life cycle assessment evaluating greenhouse gas emissions for a carbon supply chain with enhanced oil recovery in the utilization site in the United Nations. Three different carbon dioxide sources are considered: ethanol, coal-fired, and natural gas-fired power plants. In this analysis, system boundaries include carbon dioxide capture and compression, carbon dioxide transportation, carbon dioxide injection (including the recovery and the transportation to a refinery), oil treatment in the refinery, and its combustion end use and displacement credit. The results show that the supply chain using carbon dioxide from ethanol plants is the best alternative that could ensure a reduction in carbon intensity up to $-1.6\ \mathrm{ton_{CO2eq}}$/bbl compared to the conventional crude recovery. Also, the authors find that the environmental analysis depends on a specific crude recovery rate. Different carbon dioxide sources are also considered in the work of Jiang et al. [20] developing a life cycle assessment for a carbon capture utilization and storage supply chain with enhanced oil recovery. In particular, the following sources of carbon dioxide are considered: integrated gasification combined cycle, pulverized coal plants, and oxyfuel plants. The results show, respectively, the following emissions: 114.69–121.50 $\mathrm{Mton_{CO2eq}}$, 222.95–236.19 $\mathrm{Mton_{CO2eq}}$, and 49.09–51.96 $\mathrm{Mton_{CO2eq}}$.

A reduction in carbon dioxide emissions in a supply chain for enhanced oil recovery is obtained in the work of Thorne et al. [21]. Here, the carbon dioxide is captured in an oxyfuel power plant located in Poland and transported in an oil field located on the Norwegian Continental Shelf in the North Sea. The results show that the system is able to reduce 71% of emissions compared to the conventional production of oil and electricity. Environmental benefits obtained by using a CCUS supply chain for oil recovery are also suggested by Liu et al. [22]: the net carbon dioxide emissions of producing one metric ton of crude oil are −1675.15 kg_{CO2eq}, suggesting how the use of this technology is important for China's contributions to climate change. In Zhang et al. [23], the carbon supply chain for oil recovery and carbon dioxide storage is able to reduce emissions by 50% compared to the reference system, although the framework emits 37.108 $Mton_{CO2eq}$/year. In the analysis, carbon dioxide capture and transportation stages are the major contributors, contributing to 42% and 38%. Carbon dioxide capture and transportation have the highest impact on total emissions of the supply chain also in the work of Zhang et al. [24].

Different utilization routes are considered for carbon dioxide in the literature. In the utilization section, carbon dioxide can be used also for algae cultivation. Yue et al. [25] develop a mathematical model to conduct an environmental analysis of the carbon supply chain with algae cultivation for biofuel production, as in Figure 1. The analyzed supply chain is set in Texas. In particular, environmental and economic analyses are developed by using a mixed integer non-linear programming model. The results show that with the system, 64% of greenhouse gas emissions can be avoided and carbon dioxide can be captured and sequestered at a cost of \$45.52/ton_{CO2}.

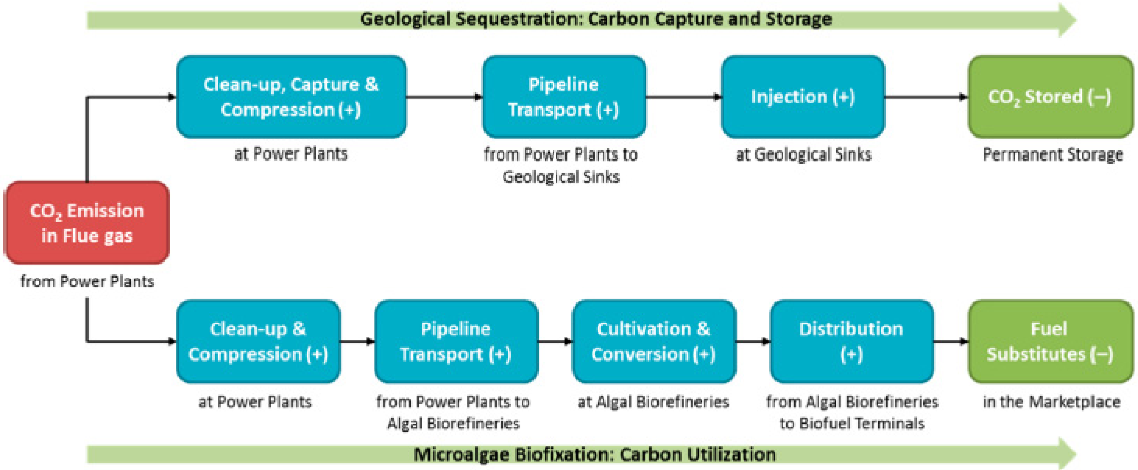


Figure 1. Life cycle stage of carbon capture utilization and storage supply chain [Reprinted with the permission of David T. Allen from Yue et al. [25]].

A life cycle assessment for carbon capture utilization and storage supply chain in refineries producing dimethyl ether and polyol is developed by Fernandez-Dacosta et al. [26]. Overall, a comparison with a carbon capture utilization supply chain shows that the carbon capture utilization and storage system allows a higher carbon dioxide reduction compared to conventional production.

Other products could be produced in a carbon supply chain. An interesting LCA for a CCUS supply chain in Italy and Germany was developed by Leonzio et al. [27] with GaBi software. In the supply chain in Italy, carbon dioxide is used to be stored or to produce methane while, in the CCUS of Germany, carbon dioxide is used to produce concrete, wheat, lignin, calcium carbonate, polyurethane, methanol, and urea, or to be stored. The results show that the annual global warming potential for these supply chains in Italy and Germany are, respectively, 9.62×10^{10} $kg_{CO2\text{-}eq}$ and 1.94×10^{11} $kg_{CO2\text{-}eq}$, which would help enable these countries to achieve the carbon dioxide reduction target fixed by European environmental policies.

Environmental advantages of a CCUS supply chain where the captured carbon dioxide is used for mineralization are found by Ostovari et al. [28]. The system is able to avoid up to 130 $Mton_{CO2eq}$/year in Europe even with the current energy supply system. Moreover, combining the direct air capture technology and low energy emission supply, the framework can provide negative emissions at a rate of 136 $\mathrm{Mton}_{\mathrm{CO2eq}}$/year. However, the critical steps toward achieving the large potential of carbon dioxide mineralization in Europe are (1) scaling up the carbon dioxide mineralization technology to the industrial level and (2) exploiting large-scale mineral deposits.

An important product obtained from carbon dioxide is methanol, and a CCUS supply chain producing this compound is analyzed by Nie et al. [29]. The results show that for each ton of carbon dioxide-derived methanol produced, the supply chain has 1.05 ton of carbon dioxide emissions and requires 1.375 ton of carbon dioxide in input. Consequently, the net emission per carbon dioxide-derived methanol produced is $-0.325\ \mathrm{ton}_{\mathrm{CO2}}$.

From the above analysis, it is evident that the LCA of CCUS supply chains has been conducted in the literature: a benefit of this framework is reported, although the global warming potential is the main investigated impact category. Other impact categories should be analyzed in future research.

2.2. Life Cycle Assessment of Carbon Capture and Utilization Supply Chains

Life cycle assessment has been developed also for carbon capture and utilization supply chains, finding some environmental benefits for the produced compounds and potential hot spots.

Pan et al. [30] carry out an environmental analysis of a carbon capture and utilization supply chain producing calcium carbonate used as a green cement material in Taiwan. In the system, basic oxygen furnace slag and alkaline cold-rolling mill wastewater, produced by the steelmaking manufacturing process, are used as the sources of calcium that is carbonated by carbon dioxide captured from flue gas, thus producing calcium carbonate. The analysis is developed by using Umberto 5.6 software including the stage of raw material extraction, capture, mineralization, transportation, and use of produced compounds. The results show that by removing 97–98% of carbon dioxide from flue gas, the energy consumption is 345 $\mathrm{kWh/ton}_{\mathrm{CO2}}$. From the perspective of environmental benefits, carbon dioxide emission from the cement industry could be indirectly avoided by roughly one ton of $\mathrm{CO}_{2\text{-eq}}$/ton of slag due to the utilization of carbonated products. The results show also that the proposed supply chain can reduce not only carbon dioxide emissions but also environmental impacts on ecosystem quality, human health, and resource depletion.

Other products can be obtained from carbon dioxide. Han and Lee [31] develop an environmental analysis for a carbon capture and utilization supply chain, where carbon dioxide is used to produce polymers and bio-butanol. The system is located in Korea and should satisfy the reduction target established for 2020. In particular, a multiple optimization problem is analyzed considering different levels: techno-economic, environmental, and technical safety. Uncertainties in input data regarding emissions, costs, and technical accidents are also considered in a stochastic model. The results show that in order to reduce environmental impact and technical loss, it is better to reduce gas monoethanolamine capture systems. The use of carbon dioxide to produce polymers is also considered by Kaiser et al. [32]: the whole supply chain, from the carbon dioxide source to the market-ready product has a significant reduction in emissions for every considered product (i.e., high-density polyethylene, low-density polyethylene, polypropylene, polyvinylchloride, polyoxymethylene). Compared to the fossil-based production route, for polyethylene and polypropylene, a reduction of 73% is possible, while the maximum values for polyvinylchloride and polyoxymethylene are 61% and 56%.

In previous studies, only a mathematical model is developed to carry out the environmental analysis. A more detailed study should be developed. In this context, Von der Assen and Bardow [33] conduct a life cycle assessment for a carbon capture and utilization supply chain, where carbon dioxide is used for polyol production in the polyurethane industry. Gabi software is used for this scope, in the cradle-to-gate analysis. Carbon dioxide is captured by lignite power plants. This sustainable process is compared with one producing polyols in a conventional way. In particular, in the sustainable process, it is supposed that polyol is produced at 10% wt, 20% wt, and 30% wt by carbon dioxide. Global warming impacts, fossil resource depletion, eutrophication, ionizing radiation, ozone depletion, particulate matter formation, photochemical oxidant formation, and terrestrial acidification are considered categories of impact. The results show that greenhouse gas emissions are mainly due to the production of epoxides. Also, the production of polyols at 20% wt of carbon dioxide can reduce greenhouse gas emissions by 11–19% and save fossil resources by 13–16%. A reduction is obtained for the other impact categories.

Environmental benefits for a CCU supply chain are also reported by Khoo et al. [34], where carbon dioxide is captured from flue gas and converted into solid carbonates or sand, which can then be used for purposes such as land reclamation in Singapore. The results show that the carbon dioxide mineralization technology abates 115.78 $kg_{CO2\text{-}eq}$ per ton of CO_2 in input. The results also indicate that the major sources of emissions are from the land and sea transportation of serpentine mineral feedstock, the thermal activation of the feedstock, and carbon capture processes. However, despite the use of fossil fuel-based energy for the transportation of serpentine and ammonia, and the generation of electricity consumed by the carbon dioxide mineralization processes, the technology still has a net positive carbon abatement.

In addition to these works, Cuellar-Franca and Azapagic [35] review different utilization systems already analyzed. The life cycle assessment analysis is developed for carbon capture and utilization supply chains, where carbon dioxide is used to produce diesel from microalgae [36–44], to produce dimethyl carbonate [45] or formic acid [46] and it is used for mineral carbonation [30,47–49]. However, the authors show that global warming potential values are lower for a carbon capture and storage supply chain, characterized on average by 276 kg_{CO2eq}/ton_{CO2} removed, even if they could have higher values for other categories of impact. This consideration about the better performance of a CCS in terms of carbon dioxide reduction is also reported in Aldaco et al. [46]. However, compared to CCS systems, CCU has a better economic potential and lower fossil consumption.

Worse conditions for a CCU supply chain are on the other hand suggested by Passell et al. [42]. where carbon dioxide is used to produce diesel from microalgae: the global warming potential is in fact higher compared to the conventional petroleum-based route (2.9 $kg_{CO2eq}/1$ MJ of combusted fuel compared to the petroleum diesel with 0.12 $kg_{CO2eq}/1$ MJ of combusted fuel). However, the environmental analysis is conducted considering a very low algal productivity (3 $g/m^2/day$), while a much higher productivity (20–30 $g/m^2/day$) is reported in other sources.

From the above analyses, it can be seen that CCU supply chains could reduce not only carbon dioxide emissions but could ensure the reduction in other impact categories. However, the good scale of the production plant should be considered.

2.3. Life Cycle Assessment of Carbon Capture and Storage Supply Chains

A first picture of the environmental analysis developed for carbon capture and storage supply chains is presented by Nie [50], considering the power generation site, carbon dioxide capture technology/material, carbon dioxide transportation, and making some considerations about carbon dioxide storage and life cycle inventory.

It is evident that a few works consider a complete carbon supply chain, also with a carbon dioxide storage and transportation section. Some aspects that should be considered within the storage are wells, carbon dioxide storage geological formations, geological zones surrounding the carbon dioxide storage formations, and potential carbon dioxide leakages from the storage. Geographical differences of power plants have not always been considered.

In another work, Khoo and Tan [51] (2006) develop a life cycle assessment for a carbon capture and storage supply chain, considering different capture technologies (chemical absorption, membrane separation, cryogenic, pressure swing adsorption). In addition, different storage options in ocean and geological sequestration are evaluated. SimaPro software is used to analyze the following eight environmental impact categories: global warming potential, acidification, human toxicity to air, human toxicity to water, eutrophication, ecotoxicity, wastes, and fossil fuels. The condition with a lower environmental impact is ensured by using chemical absorption as the capture technology.

A comparison of different capture technologies is also reported by Pehnt and Henkel [52] The authors develop a life cycle assessment of the carbon capture supply chain located in Germany (Lausitz region), storing carbon dioxide in a depleted gas field. A lignite power plant is a carbon dioxide source. Post-combustion, pre-combustion, and oxyfuel capture technologies are compared and analyzed. The results show that in the carbon capture and storage supply chain with post-combustion capture technology, there is a sharp increase in all categories of impact, except for acidification. In the carbon capture and storage supply chain with pre-combustion capture technology, there is a decrease in all categories of impact. In the carbon capture and storage supply chain with oxyfuel capture, there is a near-zero emission if carbon monoxide is captured. The considered categories of impact are the following: cumulative energy demand, global warming, summer smog, eutrophication, acidification, and health impact. The environmental advantages of a CCS supply chain are reported in other works in the literature. Koornneef et al. [53] consider a life cycle assessment for a carbon capture storage supply chain. The author considers three pulverized coal power plants with/without post-combustion capture and storage. This capture system allows a reduction in global warming potential of about 70%, but an increase in human toxicity, ozone layer depletion, and freshwater ecotoxicity is obtained. Other analyses with similar results are carried out by Corsten et al. [54] and Gładysz and Ziebik [55]. In Corsten et al. [54], a CCS results in a net reduction in the global warming potential of power plants through their life cycle in the order of 65–84% (pulverized coal-fired power plant), 68–87% (integrated gasification combined cycle), 47–80% (natural gas-fired combined cycle), and 76–97% (oxyfuel). The benefits of a CCS framework in the transition to net-zero energy systems beyond emission reduction are reported by Shu et al. [56] considering the German (as a representative highly-developed economy) energy system until 2045. Through a mathematical optimization evaluating the cost and environmental impact of the supply chain, the authors find that increasing carbon dioxide storage beyond the minimum amount significantly lowers cost and environmental impacts in up to 13 out of 16 impact categories (only resource use minerals and metals, land use, and ozone depletion increase while climate change, particulate matter, ionizing radiation, photochemical ozone formation, acidification, terrestrial eutrophication, aquatic freshwater eutrophication, aquatic marine eutrophication, human toxicity cancer effects, human toxicity noncancer effects, ecotoxicity freshwater, water scarcity, and resource use energy carriers decrease).

A first more detailed life cycle assessment for these supply chains is proposed by Petrescu et al. [57], considering a cradle-to-grave analysis with Gabi software. Carbon dioxide is captured with different systems from a supercritical pulverized coal process, using amine, aqueous ammonia, and calcium looping. Then, the considered supply chains are compared. The system boundaries include (a) power plant feed by coal; (b) upstream processes such as extraction and processing of coal, limestone, and solvents used in capture technology, as well as power plant, coal mine, and carbon dioxide pipeline construction and commissioning; (c) downstream processes: carbon dioxide compression, transport, and storage as well as power plant, carbon capture and storage units, coal mine, and carbon dioxide pipeline decommissioning. The results show that amine technology has a lower value for global warming potential but not for all environmental categories: acidification potential, eutrophication potential, or other categories related to human toxicology are better for aqueous ammonia technology. Other impact categories such as ozone depletion potentials are better for calcium looping.

Cuellar-Franca and Azapagic [35] (2015) propose a review of the life cycle assessment works for these kinds of systems. The results suggest that carbon dioxide emissions in a power plant can be decreased by 63–82% per unit of produced electricity. However, there is an increase in acidification and human toxicity. A reduction in global warming potential is also reported by Volkart et al. [58]: it is 68–92% for fossil power plants and 39–78% for cement plants.

From the above analyses, it is evident that LCAs of CCS supply chains have been conducted in the literature considering different impact categories and not only the global warming potential. However, in this case, a CCS is not able to ensure a reduction in all impact categories and a trade-off should be achieved.

3. Life Cycle Assessment Methodology

Life cycle assessment is a quantitative methodology used to evaluate the environmental impact of systems or services, and it is used in different fields related to a process and a product (policy, marketing, design, etc.). Life cycle assessment takes into consideration the energy and material balances that a process exchanges with the environment, and it is standardized by the ISO. As reported in Figure 2, this methodology is composed of four phases, regulated by ISO 14040 [59] and ISO 14044 [60]. These phases are interdependent and are goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation phase.

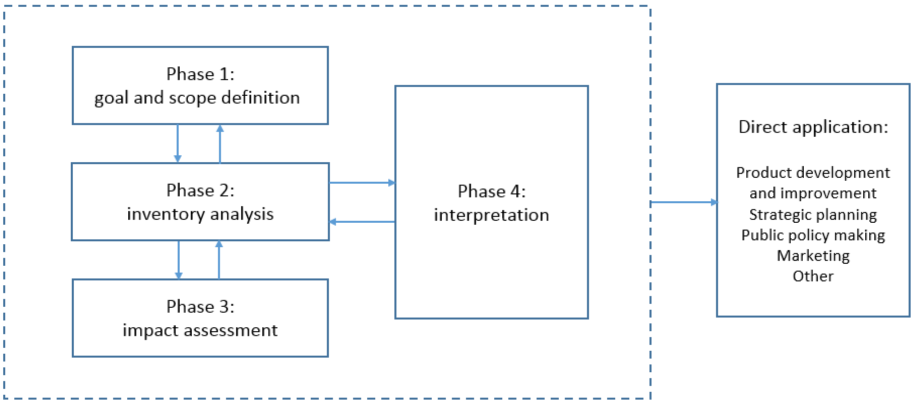


Figure 2. Stages of a life cycle assessment analysis according to the ISO standards (ISO 14040, 2009 [61]; ISO 14044, 2006). Phase 1: Goal and scope definition; Phase 2: Inventory analysis; Phase 3: Impact assessment; Phase 4: Interpretation [modified after von der Aßen [62]].

3.1. Goal and Scope Definition

This phase is data-free and question-oriented and not quantitative as an overall methodology. Goal and scope explanations are provided by ISO 14040. The goal should define “the willful application of the analysis, the motivations to develop the analysis, the willful audience of the analysis and if the obtained results should be used in comparative statements revealed to the public”. Then, it is necessary to explain the reason for the conducted analysis. The scope, instead, should define what is investigated in the analysis and how this analysis is going to be carried out.

In addition to satisfying the above questions, the system boundaries of the analyzed system and functional unit are defined in this phase. System boundaries separate the technosphere from the ecosphere and border all processes considered in the life cycle analysis. Among the mentioned areas, the technosphere contains all analyzed and considered processes while the ecosphere is related to the environment. The interaction between the ecosphere and the technosphere is described by elementary flows (emissions and resources). On the other hand, flows inside the technosphere and between processes are called process flows or economy flows (valuable products or unwanted wastes) [63] From these considerations, it is evident that elementary flows are the inputs and outputs of the system boundaries, while process flows are inside the system boundaries, as shown in Figure 3. To be more precise, ISO 14040 says that elementary flows are in the input and output of “the analyzed system without previous or succeeding human transformations” (ISO 14040, ISO 14044).

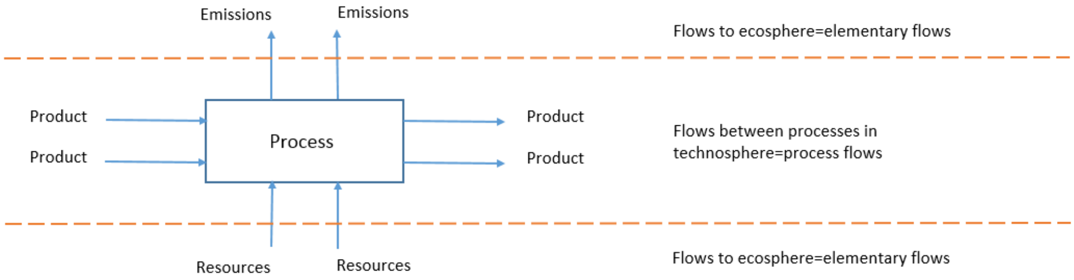


Figure 3. Definition of ecosphere and technosphere, elementary (flows exchanged between the technosphere and ecosphere) and process flows (flows inside the technosphere) [Modified after von der Aßen [62]].

According to the selected system boundaries, different life cycle assessments can be developed: cradle to grave: a complete life cycle assessment considering the resource extraction (cradle), use phase, and disposal phase (grave); cradle to gate: a not complete life cycle assessment considering the resource extraction (cradle) but not the use and disposal phases; cradle-to-cradle: a particular cradle-to-grave analysis for which the disposal phase is a recycling process to produce new, identical, or different products; gate to gate: a not complete life cycle assessment regarding only one process of the overall chain; well-to-wheel: a particular life cycle assessment used for the transportation of fuels and vehicles in order to evaluate energy consumptions and efficiencies and emission impacts.

Another element that is defined in the goal and scope definition phase is the functional unit. The functional unit quantifies the performances of a system or service and it is the reference to relate all inputs and outputs, allowing a comparison of different case studies. Also, the functional unit establishes if the analyzed functions (defined as in Section 2.2) are evaluated jointly or separately, and it is defined by the scope of the study.

3.2. Life Cycle Inventory Analysis

In the life cycle inventory analysis, an inventory of all input (such as material, energy, resource flows) and output (such as product, waste to treatment, emission flows) data for all processes inside the system boundaries is set and as a result, a list of elementary flows (resources and emissions) is provided. Generally, process data are protected by companies; then, other different methods can be used, with differences in accuracy and data/time requirements (time is an important parameter because it is necessary to reduce the time to complete a life cycle assessment) as reported in Figure 4. Here, in addition to real plant data, the following sources can be used: database (method 0), process simulation tools (method 1), advanced process calculations (method 2), basic process calculations (method 3), stoichiometry (method 4), molecular structure models (method 5), and proxy data (method 6). In some cases, data can be omitted (method 7).

In method 0, data are provided by manufacturers, environmental product declarations, company sustainability publications, industry associations, or life cycle inventory databases. In method 1, data can be provided by process simulation software such as Aspen, Hysys, Chemcad, Pro II, etc. The disadvantages of this method are the greater required time, skills in modeling, the use of modeling tools, and the fact that the quality of the life cycle inventory depends on the detailed level of the developed simulation. In methods 2 and 3, inventory data are provided by correlations, Perry and NIST databases, and process encyclopedia. These methods are used if the usable data are not enough for the application of simulation tools but can be used to set material and energy balances and quantify emissions. In method 4, data are provided by chemical reactions and stoichiometry from online databases and literature. It can be used in the absence of any process data. Although the energy requirement can be estimated by the heat of the reaction, the stoichiometric approach does not consider different factors such as the use of material and energy balances in addition to emissions, process conditions, heat losses, yields, and particular operations while it can be useful for fast calculations and in comparing different processes. In method 5, the FineChem web model is used to take relevant data, for example, molar weight, functional groups, and chiral centers to various measures of the environmental impact of its production. Method 6 uses the environmentally extended input-output analysis: it uses the life cycle inventory data of similar processes. In method 7, the omission of data can be used in the presence of the cut-off (an input is very low compared to others), and the irrelevant flow is not included inside system boundaries. Generally, flows are considered when their relative mass, energy content, or price is more than 1% of all flows in the analyzed process.

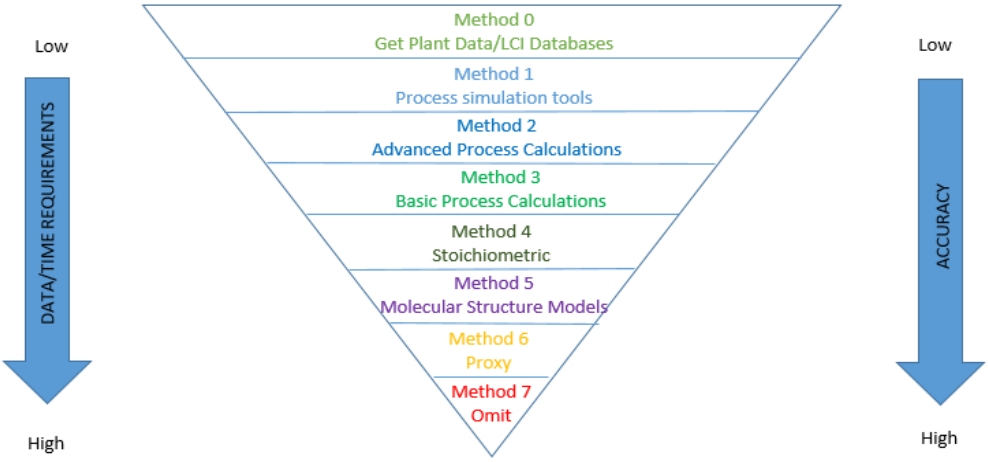


Figure 4. Hierarchy of eight methods used in the life cycle inventory generation of chemicals with respect to the data/time requirements and accuracy (LCI = life cycle inventory) [Modified after Parvatker and Eckelman [64]].

In the life cycle inventory phase, multifunctionality can be treated when two or more functions are present where a function is a valuable product in output or an unwanted waste in input [63]. Multifunctionality occurs for the combinations of the following: the co-production of more valuable products in multiple outputs; the combination of multiple unwanted wastes in multiple inputs; and the recycling of unwanted wastes into valuable products.

The problem in this case is how to allocate the environmental impact of this multifunctional process to different functional flows. In this case, functions can be analyzed in a joint or separate way as established in the functional unit that can contain all functions in a joint evaluation or where many functional units have one function each in a separate analysis, as in Figure 5. In the first case, the system expansion methodology is used: the functional unit is expanded to consider all functions and it is defined as a basket of products. The environmental impact is then evaluated for the overall considered system and products. In the second case, a product-specific methodology is used such as the avoided burden or allocation methods. Among these two specific methods, in the avoided burden, the by-product is the credit and the methodology considers the environmental impact v of another process producing the same by-product, which is in this way avoided. To obtain the specific environmental result, the avoided burden v is subtracted from the overall impact u of the main analyzed process: the main product has an environmental impact equal to $u-v$. The avoided burden is generally suggested for a comparison with another process. On the other hand, in the allocation methodology, the environmental impact is allocated to individual products based on particular properties (mass or volume, energy, exergy, and cost). It is important to consider that the allocation is not undertaken for emissions but only for valuable products and process flows.

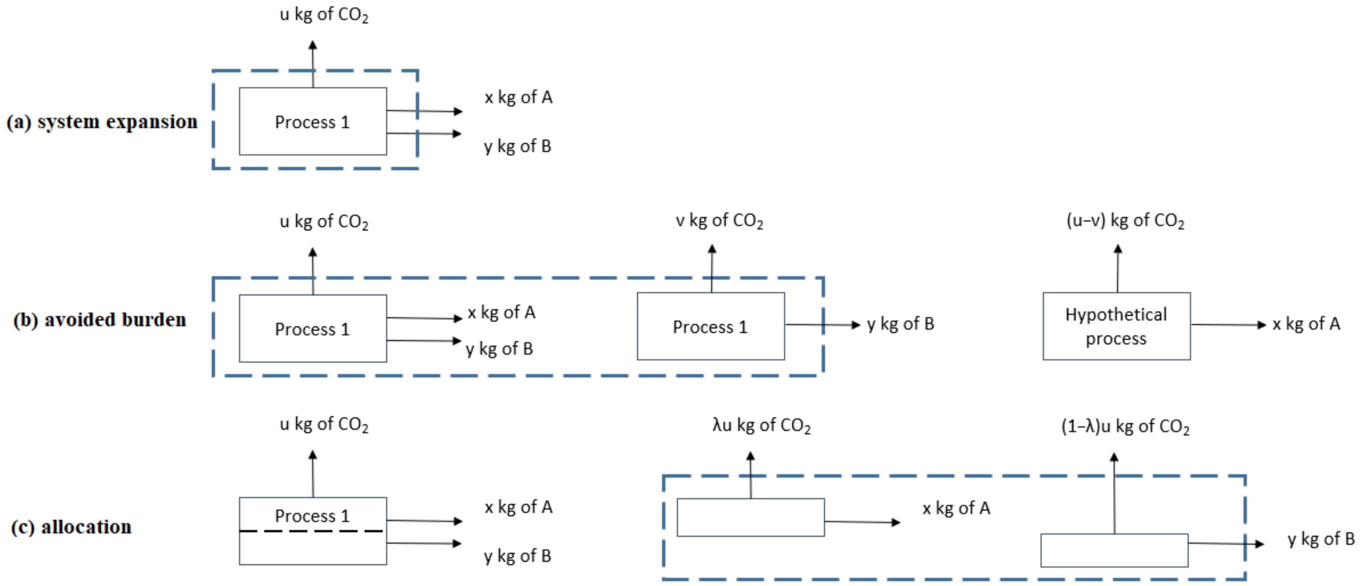


Figure 5. Suggested methodologies for co-products in the life cycle assessment analysis: (**a**) system expansion with the environmental impact of u kg of CO_2 for x kg of A and y kg of B; (**b**) avoided burden with the environmental impact of (u−) kg of CO_2 for x kg of A; (**c**) allocation with the environmental impact of u kg of CO_2 for y kg of B. [Modified after von der Aßen [62]].

In the first analysis, ISO 14040 and ISO 14044 recommend the system expansion methodology in multifunctionality, even if it is not specific to a single product of the process. However, if function-specific results are required or it is impossible to use the system expansion methodology because system boundaries should consider a huge amount of chemicals that can lead to very large baskets of products, then communication and interpretation are difficult. Generally, the choice of one methodology depends mainly on the scope of the life cycle assessment and the analyzed process. However, ISO 14044 suggests the following points: to avoid the allocation by creating sub-processes of the main process and collecting the needed environmental burden data and/or expanding the system boundaries including co-product functions; if the allocation is required, it is better to use an allocation methodology based on physical relationships; if the allocation based on physical relationships can not be considered, other allocation methodology should be used. If an allocation method is used, it is suggested to undertake a sensitivity analysis testing different allocation methods.

3.3. Life Cycle Impact Assessment

The life cycle inventory results are used for the following phase as the life cycle impact assessment, where the magnitude of environmental burden is evaluated through four different steps: classification, characterization, normalization, and weighting. According to ISO 14040, classification and characterization are obligatory while the last two steps are discretionary.

In the classification step, life cycle inventory results (in particular, elementary flows) are combined and organized into impact categories. For example, carbon dioxide, nitrogen dioxide, methane, chlorofluorocarbons, hydrochlorofluorocarbons, and methyl bromide are combined in the global warming impact category.

In the following step, in the characterization stage, a characterization factor is used to translate the life cycle inventory results into comparable impact indicators, so that a comparison can be carried out. For one of them, global warming, the characterization factor is the global warming potential while the impact indicator is evaluated in kg_{CO2eq}. The most used characterization methods convert inventory flows into impact category indicators at the midpoint level because they evaluate the potential impact of the analyzed system differently from the conversion at the endpoint level that measures the damages to human health and the ecosystem. In particular, midpoint indicators are intermediate measures of environmental impact that reflect the changes in the natural environment caused by emissions or resource use. On the other hand, endpoint indicators are final measures of environmental impact that reflect the damage or benefit to human health, natural resources, or biodiversity caused by emissions or resource use. Midpoint indicators are often easier to calculate and understand than endpoint indicators, as they are closer to the source of the impact and less affected by uncertainties and assumptions. However, midpoint indicators may not capture the full consequences of environmental changes for human well-being or ecosystem services, and they may not reflect the relative importance or severity of different impact categories.

LCIA can convert the inventory results into what is referred to as the 'areas of protection' of the LCIA. These areas of protection represent the entities that society wants to protect by using the LCA. Different characterization methods are used for analysis at the midpoint and endpoint, as reported in Tables 1–4 [65].

Table 1. Midpoint-oriented LCIA methodologies [65] (CML = Centrum voor Milieukunde Leiden; EDIP = Environmental Development of Industrial Products; TRACI = Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts).

Methodology	Midpoint Impact Categories	Areas of Protection
CML	**Obligatory impact categories:** Depletion of abiotic resources, land competition, climate change, stratospheric ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photo-oxidant formation, acidification and eutrophication. **Optional impact categories:** Loss of life support function, loss of biodiversity, freshwater sediment ecotoxicity, marine sediment ecotoxicity, impacts of ionizing radiation, malodorous air, noise, waste heat, casualties, lethal, non-lethal, depletion of biotic resources, desiccation, and malodorous water	Human health, natural environment, man-made environment, human resources
EDIP 2003	Global warming, ozone depletion, acidification, terrestrial eutrophication, aquatic eutrophication, photochemical ozone formation, human toxicity, ecotoxicity, and noise	Human health, ecosystem and resources
TRACI	Ozone depletion, global warming, smog formation, acidification, eutrophication, human health cancer, human health noncancer, human health criteria pollutants, ecotoxicity, and fossil fuel depletion	Human health, ecosystem and resources

Table 2. Endpoint-oriented LCIA methodologies [65] (EI99 = Eco-Indicator 99; EPS 2000 = Environmental Priority Strategies in Product Design 2000; JEPIX = Environmental Policy Priorities Index for Japan).

Methodology	Damage Categories (Endpoint Categories)	Areas of Protection
EI99	Climate change, ozone layer depletion, acidification, eutrophication, carcinogenic, respiratory effects, ionizing radiation, ecotoxicity, land use, mineral resources, fossil resources	Human health, ecosystem and resources
EPS 2000	Life expectancy, severe morbidity and suffering, morbidity, severe nuisance, nuisance crop production capacity, wood production capacity, fish and meat production capacity, base cation capacity, production capacity for water, share of species extinction, depletion of element reserves, depletion of fossil reserves (gas), depletion of fossil reserves (coal), depletion of fossil reserves (oil), and depletion of mineral reserves	Human health, ecosystem production capacity, biodiversity and abiotic stock resources

Table 2. *Cont.*

Methodology	Damage Categories (Endpoint Categories)	Areas of Protection
Eco Scarcity	Ozone depletion, photochemical oxidant formation, respiratory effects, air emissions, surface water emissions, radioactive emissions, cancer caused by radionuclides emitted to the sea, emissions to groundwater, emissions to soil, landfilled municipal (reactive) wastes, hazardous wastes (stored underground), radioactive wastes, water consumption, gravel consumption, primary energy resources, endocrine disruptors, and biodiversity losses (Damage categories are determined according to the political agenda of the corresponding country or region)	Human health, ecosystem and resources
JEPIX	Ozone depletion, photochemical oxidant formation, respiratory effects, air emissions, surface water emissions, radioactive emissions, cancer caused by radionuclides emitted to the sea, emissions to groundwater, emissions to soil, landfilled municipal (reactive) wastes, hazardous wastes (stored underground), radioactive wastes, water consumption, gravel consumption, primary energy resources, endocrine disruptors, and biodiversity losses (Damage categories are determined according to the political agenda of the corresponding country or region)	Human health, ecosystem and resources

Table 3. Combined midpoint and endpoint-oriented LCIA methodologies [65].

Methodology	Impact Categories (Midpoint Categories)	Damage Categories (Endpoint Categories)	Areas of Protection
RECIPE	Climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral resource depletion, fossil fuel depletion	Damage to human health, damage to ecosystem diversity and damage to resources availability	Human health, ecosystem and resources
LIME	Ozone layer depletion, global warming, acidification, photochemical oxidant formation, regional air pollution, human-toxic chemical, eco-toxic chemical, eutrophication, land use, waste landfill, resource, and consumption	Cataracts, skin cancer, other cancer, respiratory disease, thermal stress, infectious disease, hypo alimentation, disaster causality, agricultural production, forestry production, fishery production, loss in land use, energy consumption, user cost, terrestrial ecosystem, aquatic ecosystem	Human health, social welfare, net primary production and biodiversity.
IMPACT 2002+	Human toxicity, respiratory effects, ionizing radiation, ozone depletion, photochemical oxidant formation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic eutrophication, terrestrial eutrophication and acidification, land occupation, global warming, non-renewable energy and mineral extraction	Damage to human health, damage to ecosystem quality, damage to climate change and damage to resources	Human health, ecosystem quality, climate change and resources

Table 4. Other LCA methodologies [65] (MEEup = Methodology study for Ecodesign of Energy-using Products; BEES = Building for Environmental and Economic Sustainability; EDP = Environmental Product Declaration; IPCC = Intergovernmental Panel on Climate Change; CED = Cumulative Energy Demand; CExD = Cumulative Exergy Demand; CExC = Cumulative Exergy Consumption; CEENE = Cumulative Exergy Extracted from the Natural Environment).

Methodology	Impact Category
MEEup	Energy consumption, water consumption, materials in use, waste and to incinerator), hazardous waste generation, emissions to air
BEES	Global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, smog, ecotoxicity, ozone depletion, and human health
Ecological footprint	Five types of direct land occupation are considered: cropland, pasture, forest, built-up area, and hydropower area, and two indirect land occupations: fossil fuels and nuclear energy
USEtox	Ecotoxicity
EDP	Land occupation, land transformation, and biodiversity
IPCC	Climate change
CED	Fossil resources, such as hard coal, lignite, peat, natural gas, and crude oil, and for nuclear and other renewable resources as well such as biomass, water, wind, and solar energy
CExD	Fossil resources, such as hard coal, lignite, peat, natural gas, and crude oil, and for nuclear and other renewable resources as well such as biomass, water, wind, and solar energy. Non-energetic resources such as water, minerals, and metals.
Energy	Renewable and non-renewable resources, waste, soil loss, human labor, and water use
CExC	Fossil resources, such as hard coal, lignite, peat, natural gas, and crude oil, and for nuclear and other renewable resources as well such as biomass, water, wind, and solar energy
CEENE	Fossil resources, such as hard coal, lignite, peat, natural gas, and crude oil, and for nuclear and other renewable resources as well such as biomass, water, wind, and solar energy. Non-energetic resources such as water, minerals, and metals. Land use.

In the normalization step, indicator results are divided by a reference value so that they are converted into a dimensionless number that can be compared with other impact categories. It is a methodology introduced by ISO in order to compare different impact categories. In the weighting step, normalized results are multiplied by a weighting factor expressing the relative importance of the impact category. Weighted results have the same unit so that they can be summed providing an overall environmental impact indicator that can be used to compare different systems.

3.4. Interpretation Phase

The last stage of LCA is the interpretation phase. Here, according to ISO 14040, results are interpreted to "achieve conclusions, find limitations and suggest recommendations". To this aim, it is necessary to find "significant issues" (ISO 14044), where significant issues are processes or substances that have a higher influence on the overall result. At this stage, uncertainties due to system boundaries, data in the inventory phase, and characterization factors should also be considered with sensitivity analysis. Conclusions and recommendations should be provided and discussed at this stage.

4. How Should We Treat the Multifunctionality of a Carbon Supply Chain in the LCA?

Before starting a life cycle assessment for a carbon supply chain, it is recommended to have in mind some important considerations where, generally, the aim of this analysis is to find the contribution of different single processes to the overall environmental impact (finding hot spot points with a higher impact); in the case of different products, it is possible to find the route or product process with the lowest environmental impact, compare different carbon dioxide sources, and compare processes with and without carbon dioxide capture with equivalent products.

In a carbon supply chain, if the compressed carbon dioxide is used as a feedstock, then it is a relevant input flow (process flow that remains inside the technosphere) that must be distinguished from carbon dioxide emissions. According to this, the carbon dioxide capture process can be considered as the production process for the feedstock carbon dioxide that is the product of a human transformation. For this reason, system boundaries should contain all upstream processes starting at the carbon dioxide sources that are the production center of the feedstock carbon dioxide. Together with the feedstock carbon dioxide, considered as the main valuable product, another product such as electricity or ammonia or similar is always co-produced.

As shown in Figure 6, different kinds of carbon dioxide sources (non-biogenic, biogenic, air) exist. Power plants and industrial processes are non-biogenic point sources. On the other hand, plants for the production of biogas or bio-ethanol using biomass sources are biogenic point sources. For these two cases, a valuable product such as electricity, ammonia, bio-ethanol, etc., is co-produced in a production process in addition to the feedstock carbon dioxide. In another case, if carbon dioxide is captured by air, then no other products are obtained because the scope is only to capture carbon dioxide from the ambient air. In the first case, positive carbon dioxide emissions are present, while in other cases, carbon dioxide emissions can be positive or negative.

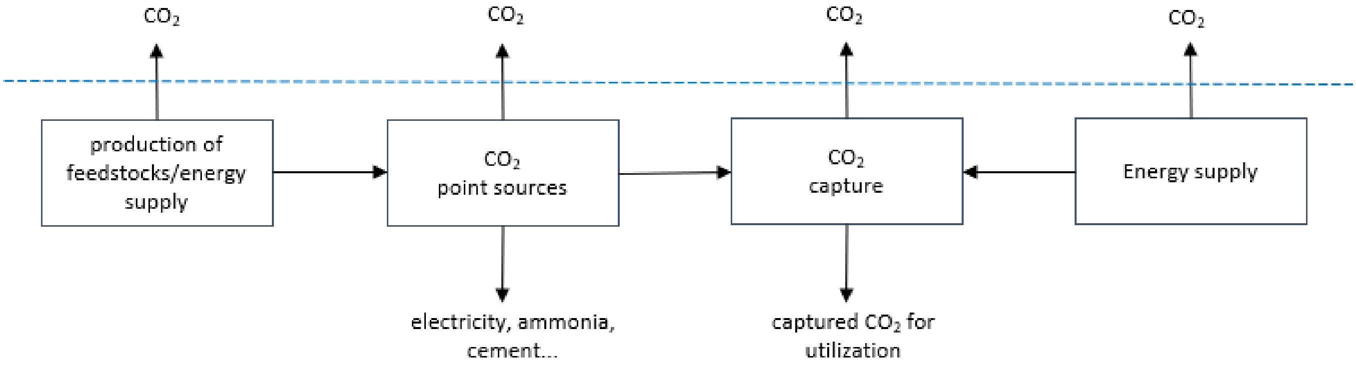
Then, the upstream processes of a carbon supply chain contain many co-products that should be considered inside system boundaries and then in the life cycle assessment. If carbon dioxide is used in the supply chain, two products are present: the product at the source that is co-produced with carbon dioxide and the carbon dioxide product in the utilization section. Overall, the carbon supply chain system is multifunctional. However, if carbon dioxide is captured from the air, the supply chain is mono-functional.

In the case of multifunctionality, if the scope allows a joint evaluation, it is possible to operate by applying a system expansion methodology with the relative functional unit. In fact, the system expansion methodology is suggested by ISO due to the equivocal characteristic of allocation methodology. On the other hand, the allocation methodology will be used if system expansion is impossible because it should include the entire chemical industry or product-specific results are required, finding the emissions produced by a single product. It is important to underline that for a product-specific calculation, the avoided burden is not suggested for a carbon supply chain because the environmental benefit is totally assigned to a single product [10]. Furthermore, it is possible to use an economic allocation when prices are known: an economic allocation is suggested as a baseline method, and results can be verified with a sensitivity analysis.

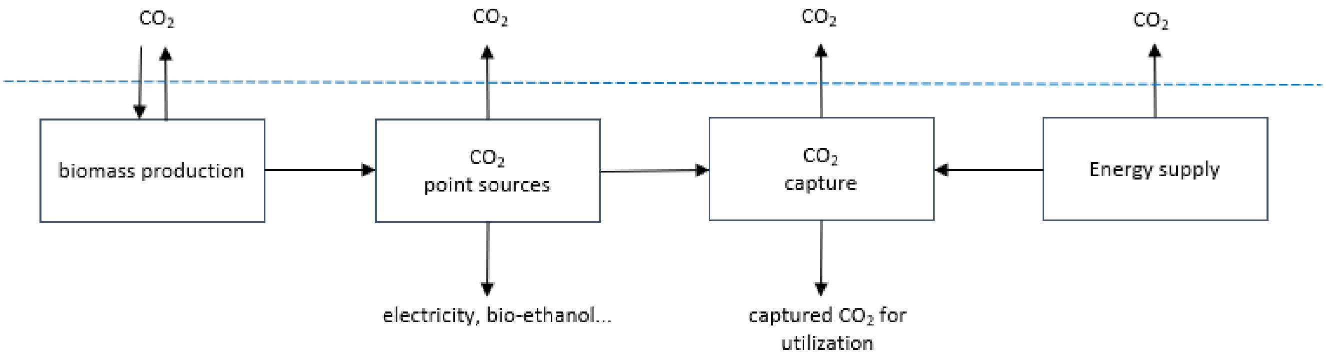
In order to understand the differences between these methods, these methodologies are applied and compared to measure the environmental impact of a carbon capture and utilization supply chain with methanol synthesis through carbon dioxide hydrogenation, capturing carbon dioxide from a power plant. Figure 7 shows the application of the system expansion methodology for the considered supply chain with and without methanol synthesis.

If system expansion is applied, the functional unit considers both the production of 1000 kg of methanol and 1273 kW of electricity from the power plant. The total global warming potential impact is 153 (from the power plant) + 418 (from methanol synthesis) + 188 (from the eolic plant for electricity production and water electrolysis) = 759 $\mathrm{kg_{CO2eq}}$, while for the conventional system, the global warming potential impact is 1090 (from the power plant) + 745 (from methanol synthesis) = 1835 $\mathrm{kg_{CO2eq}}$. Emissions are reduced by 59% and the environmental benefit of the carbon supply chain is evident. The system expansion methodology allows a simple evaluation overcoming equivocal doubts raised with the multifunctionality.

(a) non biogenic point source



(b) biogenic point source



(c) air capture

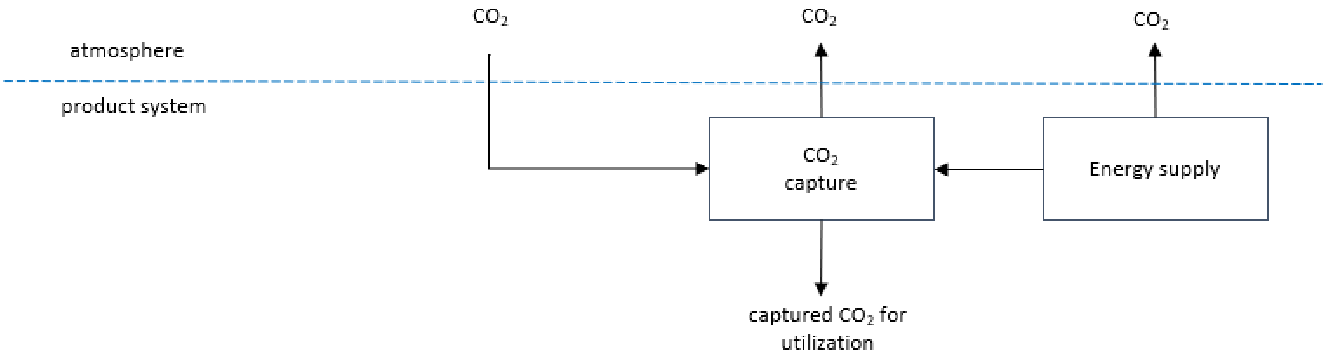
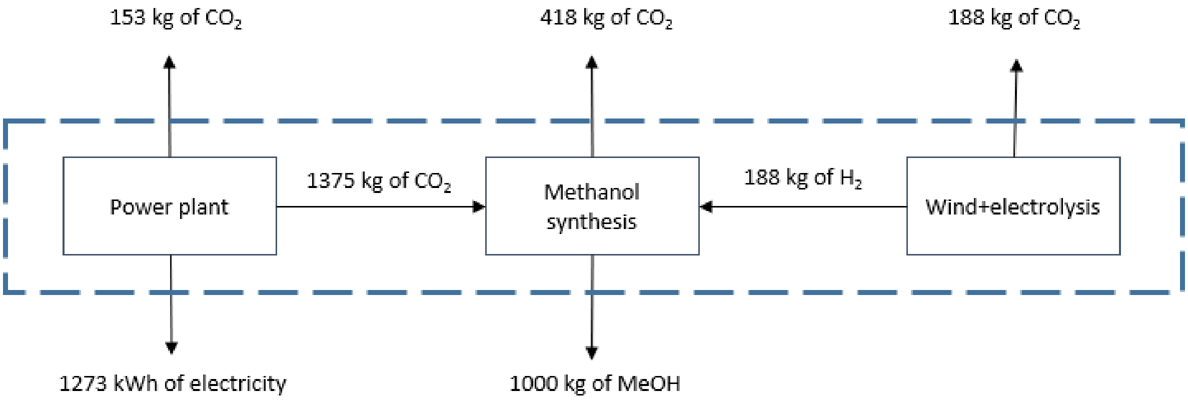


Figure 6. Classification of carbon dioxide sources: (**a**) carbon dioxide capture from non-biogenic point sources includes capture from power plants and industrial processes; (**b**) carbon dioxide from biogenic point sources includes biomass production; (**c**) carbon dioxide capture from ambient air [Modified after von der Aßen [62]].

(a) CCU system



(b) non CCU reference system

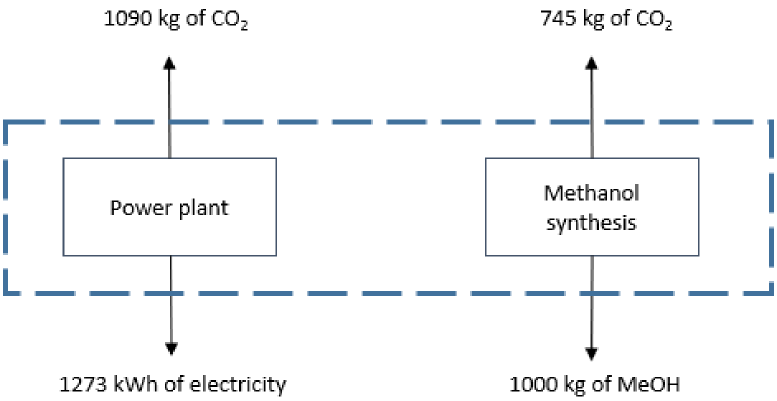
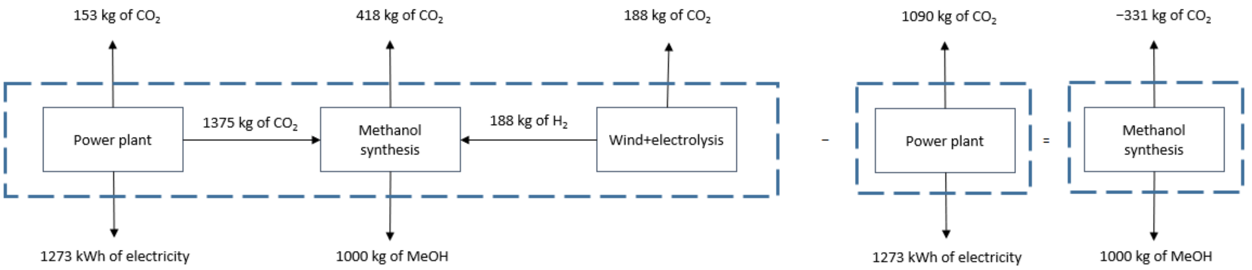


Figure 7. Flow-chart and flow quantities (**a**) for carbon capture utilization system producing electricity and methanol (system expansion methodology) with the environmental impact of 153 + 418 + 188 = 759 kg_{CO2eq} and (**b**) for the non-carbon capture utilization reference system with traditional, non-carbon dioxide-based technologies and with the environmental impact of 1090 + 745 = 1835 kg_{CO2eq} (CCU = carbon capture utilization) [Modified after von der Assen et al. [10]].

For a product-specific analysis, with the avoided burden applied to the considered supply chain, Figure 8 can be considered, where two products such as electricity (1273 kW) and methanol (1000 kg) are present. The main function of the system can be either electricity (considering the electricity producer point of view), as in Figure 7b, or methanol (considering the methanol producer point of view), as in Figure 7a.

From a methanol perspective in the system, a surplus of electricity is present that can be avoided by a coal power plant without carbon dioxide capture. The same consideration is when electricity is the main function. In the first case, according to the avoided burden approach, the global warming potential is 1090 kg_{CO2eq} with the defined functional unit for electricity and −331 kg_{CO2eq} with the defined function for methanol. In the second case, from an electricity-produced perspective, according to the avoided burden approach, the global warming potential is 14 kg_{CO2eq} with the defined functional unit for electricity and 745 kg_{CO2eq} with the defined functional unit for methanol.

(a) methanol producer perspective: avoided burden (=credit) for surplus electricity



(b) electricity producer perspective: avoided burden (=credit) for surplus methanol

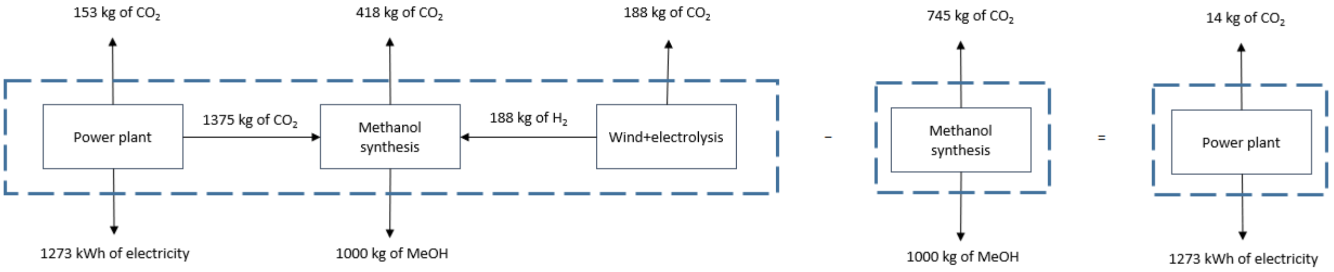


Figure 8. Product-specific global warming impact values for carbon capture utilization systems using avoided burden processes for a surplus of (**a**) electricity (methanol producer perspective) and (**b**) methanol (electricity producer perspective) [Modified after von der Assen et al. [5]].

From these results, it is evident that this methodology is inappropriate because a negative value of global warming potential can be confused with a greenhouse gas sink, although the overall system releases emissions.

The allocation methodology can be developed according to exergy and economic criteria, and results are reported in Figure 9 for the considered carbon supply chain. If methanol is the functional unit, the environmental impact is 135, 66, 187, and 153 kg$_{\mathrm{CO2eq}}$, respectively, for an exergy allocation, an economic allocation where carbon dioxide has a value as a product, as waste, or if it is for free. On the other hand, if electricity is the functional unit, the environmental impact is 624, 693, 572, and 606 kg$_{\mathrm{CO2eq}}$, respectively, for an exergy allocation, an economic allocation where carbon dioxide has a value as a product, as waste, or if it is for free.

These analyses show clearly that an LCA for a carbon supply chain could be carried out through system expansion or allocation methods.

The selection of impact categories is related to the goal and scope of the analysis. However, global warming potential and fossil resource depletion should be in any case considered because a carbon supply chain is used to reduce carbon dioxide emissions and it uses carbon dioxide to reduce the alternative carbon sources.

In carbon supply chains, uncertainties are due to some missing data. Elaboration of uncertainties is carried out in the interpretation phase in order to provide life cycle assessment studies that are reliable and transparent. In this case, it is possible to check the input data with database or literature works. Also, a sensitivity analysis can be developed to see the effect of some parameters on life cycle assessment results. Then, if allocation criteria are used, the effect of different assumptions can be evaluated.

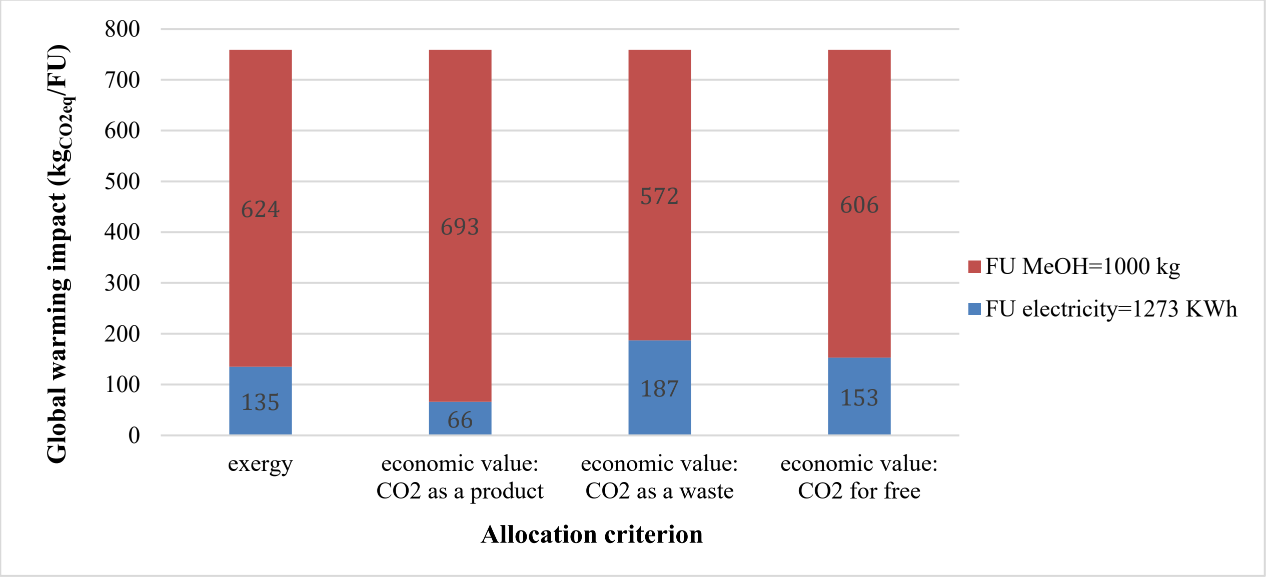


Figure 9. Different allocation methodologies for the carbon supply chain producing electricity and methanol considering the exergy and economic value of CO_2 as a product, as waste, and as free (FU = functional unit) [Modified after von der Assen et al. [5]].

5. Conclusions

An overview of the life cycle assessment methodology is here suggested for carbon supply chains. It is important for these systems to evaluate the environmental impact due to the high energy consumption while reducing carbon dioxide emissions. After the description of the LCA methodology, a literature analysis regarding its use in carbon capture utilization and storage supply chain, carbon capture and utilization supply chain, and carbon capture and storage supply chain is presented.

All co-products should be considered in the life cycle assessment of carbon supply chains, through system expansion or allocation methodologies, which are recommended to be used.

From all reviewed articles, it can be concluded that the employment of carbon supply chains not only significantly reduces carbon dioxide emissions but could also increase other environmental burdens such as acidification, eutrophication, and ecotoxicity depending on the used carbon capture method, energy penalty, and the rate of NOx emitted. This is especially verified in CCS supply chains while for CCUS frameworks, the analysis of different impact categories is not investigated a lot, and it is a point that could be developed in future studies.

Some suggestions for future research are required. If many data are outdated, then more accurate data should be considered also with uncertainties. The life cycle assessment should be developed in a nonstatic sense and at a large scale, considering a benchmark assessment including greenhouse gas emissions, water use, air emissions, and material use.

Research should be developed to implement new tools for analysis able to overcome the limit of static conditions and with considerations at a large scale. In fact, the most crucial limitation of the investigated LCA approach is the absence of time-dependent carbon dioxide emissions data in the life cycle inventory and life cycle assessment stages [46,66]. As a result, due to continuous changes in carbon dioxide emission regulations, the environmental impact of all the relevant processes with these emissions cannot be accurately measured.

Moreover, the environmental analysis should be studied for the new carbon dioxide utilization technologies, with a system boundary including all steps of the carbon supply chain. An LCA of carbon supply chains considering endpoint impact categories is strongly recommended.

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