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Article

Development of Specific Rules for the Application of Life Cycle Assessment to Carbon Capture and Storage

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Abstract: Carbon Capture and Storage (CCS) is a very innovative and promising solution for greenhouse gases (GHG) reduction, *i.e.*, capturing carbon dioxide (CO_2) at its source and storing it indefinitely to avoid its release to the atmosphere. This paper investigates a set of key issues in the development of specific rules for the application of Life Cycle Assessment (LCA) to CCS. The following LCA-based information are addressed in this work: definition of service type, definition of functional unit, definition of system boundaries, choice of allocation rules, choice of selected Life Cycle Inventory (LCI) results or other selected parameters for description of environmental performance. From a communication perspective, the specific rules defined in this study have been developed coherently with the requirements of a type III environment label scheme, the International EPD® System, according to the ISO 14025 standard.

Keywords: life cycle assessment; carbon capture and storage; product category rules; carbon dioxide; greenhouse gases; LCA; CCS; PCR; EPD

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1. Introduction

Carbon Capture and Storage (CCS) is an integrated suite of technologies that are able to prevent large quantities of carbon dioxide (CO_2) from being released into the atmosphere. As the name implies, the technology captures the CO_2, typically from large industrial processes, before it is emitted into the atmosphere; then the CO_2 is transported to a carefully selected and safe storage site, where it can remain permanently stored away from the atmosphere. CCS technologies are globally recognized as a viable option—and in some cases, the only viable option—for reducing emissions from large-scale point sources and have the potential to help reduce to almost zero the emissions to atmosphere from power plants and factories [1].

Significant efforts have been registered recently in the field of research and development of CCS technologies, and governments around the World have committed funds to demonstration projects at large scale. The International Energy Agency (IEA) concluded that, in order to achieve the required emissions reductions in the most cost-effective manner, carbon capture and storage will need to contribute around one-fifth of total reductions in emissions by 2050. With this target, it would be necessary to deploy around 100 CCS projects by 2020, and over 3000 projects by 2050 [2,3]. Such rapid expansion and scale-up of these technologies raises a number of assessment issues that must be addressed in parallel with ongoing efforts to demonstrate the technical, safety and environmental viability of industrial-scale CCS projects. With regard to this, the implementation of appropriate regulatory frameworks for CCS is required to underpin performance and associated incentive schemes, support commercial transactions relating to CCS operations, build public confidence in the technology and public acceptance [4].

In this context, the need to report the environmental performance of such mitigation systems in a transparent manner is emerging. Lack of knowledge on environmental impacts may postpone the actual implementation of CCS projects; at the same time, vagueness in the reporting methodology for the communication of results may spoil public understanding and confidence. A series of key issues regarding the assessment of CCS activities have been summarized in [5], highlighting the need of identifying a set of significant environmental indicators. A life cycle approach is able to provide comprehensive evaluation of the environmental effects of the considered technologies "from cradle to grave" along the whole system, thus Life Cycle Assessment (LCA) has been proved to be a helpful tool to investigate the environmental consequences related to the introduction of CCS [6].

This research is motivated by the need of setting a methodological framework in order to address this and further issues that LCA practitioners might face when analyzing CCS systems, as nowadays evidenced by the scientific community [7]. The aim of the present study is to investigate the development process a specific rules, *i.e.*, Product Category Rules (PCR) according to the ISO 14025 standard [8], for a robust and objective application of LCA to CCS. In particular in this paper a set of five issues are discussed in order to set up such a specific methodology aimed at reporting and disseminating the results to the scientific community and stakeholders, from a communication perspective such as a Type III environmental declaration framework. In order to address and discuss such issues, this paper focuses on the analysis of weaknesses and strengths of the state-of-the-art as concerns the application of LCA to CCS.

2. General Methodological Framework

2.1. Life Cycle Assessment

In the field of environmental sustainability, Life Cycle Assessment (LCA) represents an environmental management tool that is widely recognized by the scientific community for objectively measuring the evaluating the effects of a product or a service on the environment. Widening the perspective in designing activities permits to consider all the environmental aspects along the entire product/service life cycle, without transferring the impacts from one phase to the successive ones.

LCA methodology is in fact an objective assessment process of the environmental burdens related with a product or a service, through the identification and quantification of energy and material inputs and outputs over the entire period of its life: from the extraction and processing of the raw materials from which it is made, through the manufacturing, packaging and marketing processes, the use, re-use and maintenance of the product, and on to its eventual re-use, recycling and/or disposal as waste at the end of its useful life. Emissions and consumption of resources are evaluated at every stage of the life cycle, in order to address the environmental impacts from the entire life cycle of products and services.

The elaboration of a LCA study, as stated in the ISO 14040 standard [9], is based on the evaluation of four phases:

(a) Goal and scope definition: identification of the purpose of the study (e.g., a comparative evaluation of systems that are functionally equivalent), the functional unit (*i.e.*, a measure of the function of the studied system, that provides a reference to which the inputs and outputs can be related) and the system boundaries;
(b) Inventory analysis: data collection, assessment of the procedures for the calculation of the inlet/outlet fluxes from/to the system, including the resource utilization and air emissions, waterborne effluents and solid waste;
(c) Impact assessment: procedure to evaluate the effects of the compounds identified in the inventory phase on specific impact categories, such as global warming, ozone layer depletion, acidification, ground-level ozone creation, eutrophication;
(d) Interpretation: combination of the results obtained in the inventory phase and in the impact assessment phase, in order to draw conclusions and formulate recommendations.

LCA allows designers to identify possible areas where a good or service could be improved by lowering its environmental impact and reducing resource consumption throughout its life cycle. Besides, LCA represents a key stepping stone on the path to sustainable growth in Europe. By providing clear and verifiable information to policy-makers, LCA is able to help shape sustainable consumption and production policies. In its Communication on Integrated Product Policy [COM (2003)302] [10], the European Commission concluded that Life Cycle Assessments provide the best framework for assessing the potential environmental impacts of products currently available. Information from LCA can also support eco-design criteria setting, such as contributing to performance targets within the Environmental Technology Action Plan (EcoAP) [11] and providing the methodological basis for Type III environmental declarations.

2.2. Methodology for Type III Environmental Declarations

Type III environmental declarations, like the Environmental Product Declaration (EPD), are communication tools providing environmental data on products and services using pre-determined parameters based on the ISO 14040 standard [9] and, where relevant, additional environmental information. They are developed in accordance with the ISO 14025 standard [8].

Systems for ISO 14025 Type III environmental declarations [8] are gradually becoming more known and operational on the market. The so-called International EPD® system is one of these programmes operating on the market in several countries, which has considerably gained importance during the last decade. As stated in its General Programme Instructions (GPI) [12], the main objective of the system is to support organisations in any country to disseminate verified product-related information for a number of market applications. With this purpose, the International EPD® system supports other environmental declaration programmes in seeking cooperation and harmonisation and helping organisations to broaden the use of their environmental declarations on an international market.

One of the main purposes of an EPD is to provide the basis for a fair comparison between goods and services having the same principal function based on their inherent environmental performance. Moreover, EPDs can communicate and add up relevant environmental information along a product's supply chain as well as to reflect the continuous environmental improvement of products and services over time. With this perspective, the system is based on so-called attributional LCA studies, describing the environmentally relevant physical flows to and from one product system and its subsystems. Although sometimes the underlying data for upstream and manufacturing processes are referred to "historic data", they have the form of a "book-keeping system" being traceable and documented, and representative to reflect the present situation to the best extent possible. Besides, in case of downstream processes (especially end-of-life), data often reflect future scenarios, depending also on product life span and the modelling assumptions. This approach is aimed to meet specified data quality assurance criteria, that are especially important for a credible updating and verification process [13].

Since an EPD is aimed at ensuring objectivity, comparability and credibility in communicating the environmental performance within clearly defined and classified product categories and service types, it has to meet and comply with specific and strict methodological prerequisites. ISO 14025 describes the procedure necessary for preparing the declarations, how to develop consistent and comparable data sets [14], according to common rules, *i.e.*, Product Category Rules (PCR) [15]. As defined in the GPI of the International EPD® system [12], the PCR shall define the criteria according to assigning a product to a specific category, which parameters are set out to prepare the EPDs, the data quality requirements and the collection and calculation rules for data to be included in the EPD, as well as what kind of information suitable to convey to the primary audience of the EPD.

3. Discussion of the Specific Methodological Choices

This research work identified a set of five key issues, illustrated in Figure 1, that must be rigorously considered by practitioners when assessing of the environmental performance of CCS through LCA methodology in a communication perspective such as the EPD framework. The following methodological choices are addressed in this work: specification of the service, definition of functional unit, definition of system boundaries, description of allocation rules, and selection of environmental performance indicators to be communicated. The proposed rules shall be integrated in the classic structure of PCR for CCS within the aforementioned International EPD® system according to ISO 14025 standard. The discussion of the methodological choices inspiring the rules is addressed by the analysis of a range of LCA studies available in literature as concerns CCS systems (Tables 1 and 2).

Table 1. Aspects covered by LCA studies for CCS systems: Goal and scope—inventory.

Study	Year	Plant(s)	Capture technology			Functional unit	System boundaries [1]	Storage site	CO_2 leakage in storage site
			post-combustion	*pre-combustion*	*oxyfuel*				
Waku *et al.* [16]	1995	Fossil fuel PP [2]	✓	✓		1 kWh	C-T-S	geological /ocean	no
Lombardi [17]	2003	Fossil fuel PP	✓	✓	✓	1 MJ	C	n.a.	n.a.
Benetto *et al.* [18]	2004	Fossil fuel/ biomass PP	✓			414 GJ	C	n.a	n.a.
Spath and Mann [19]	2004	Fossil fuel/ biomass PP	✓			1 kWh	C-T	n.a.	n.a.
Khoo and Tan [20]	2006	Fossil fuel PP	✓			1 MWh	C-S	geological /ocean	yes
Viebahn *et al.* [21]	2007	Fossil fuel PP	✓	✓	✓	1 kWh	C-T-S	geological	yes
Hertwich *et al.* [22]	2008	Fossil fuel PP	✓			1 MWh /1 m^3 (oil)	C-T-S	geological	n.a.
Koorneef *et al.* [23]	2008	Fossil fuel PP	✓			1 kWh	C-T-S	geological	no
Odeh and Cockerill [24]	2008	Fossil fuel PP	✓	✓		1 kWh	C	n.a.	n.a.
Bouvart and Prieur [25]	2009	Fossil fuel PP	✓	✓		1 kWh	C-T-S	geological	no
Korre *et al.* [26]	2009	Fossil fuel PP	✓			1 MWh	C	n.a.	n.a.
Pehnt and Henkel [27]	2009	Fossil fuel PP	✓	✓	✓	1 kWh	C-T-S	geological	no
Schreiber *et al.* [28]	2009	Fossil fuel PP	✓			1 kWh	C-T-S	n.a.	n.a.
Modahl *et al.* [29]	2011	Fossil fuel PP	✓			1 TWh	C-T-S	n.a.	n.a.
Nagashima *et al.* [30]	2011	Fossil fuel PP/ Oil refinery/ Paper mill/Ironworks	✓			1 ton (CO_2)	C-T-S	geological	no
Nie *et al.* [31]	2011	Fossil fuel PP	✓		✓	1 MWh	C-T-S	geological	no
Singh *et al.* [32]	2011	Fossil fuel PP	✓	✓	✓	1 kWh	C-T-S	geological	no

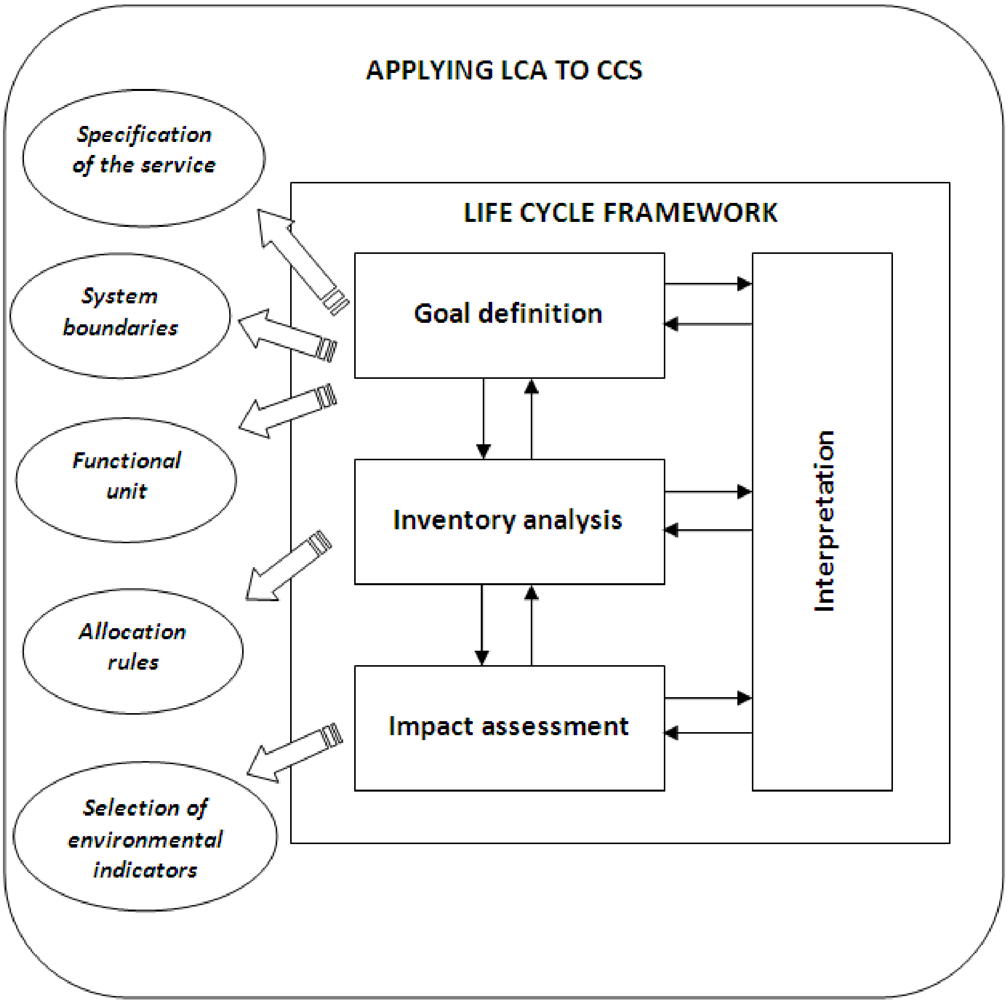
[1] C = capture; T = transport; S = storage; [2] PP = power plant.

Table 2. Aspects covered by LCA studies for CCS systems: Impact assessment.

Study	**GWP** [1]	**AP** [2]	**ODP** [3]	**POCP** [4]	**EP** [5]	**Energy**	**Exergy**	**ADP** [6]	**Toxicity**	**Waste**	**Damage categories**
Waku *et al.* [16]	✓					✓					
Lombardi [17]	✓						✓				
Benetto *et al.* [18]	✓	✓	✓	✓	✓			✓	✓		✓
Spath and Mann [19]	✓					✓					
Khoo and Tan [20]	✓	✓		✓	✓			✓	✓	✓	
Viebahn *et al.* [21]	✓	✓		✓	✓	✓					
Hertwich *et al.* [22]	✓	✓									
Koorneef *et al.* [23]	✓	✓	✓		✓			✓	✓		
Odeh and Cockerill [24]	✓					✓					
Bouvart and Prieur [25]	✓					✓					
Korre *et al.* [26]	✓	✓	✓	✓	✓			✓	✓		
Pehnt and Henkel [27]	✓	✓	✓	✓	✓				✓		
Schreiber *et al.* [28]	✓	✓		✓	✓	✓			✓		
Modahl *et al.* [29]	✓	✓		✓	✓	✓					
Nagashima *et al.* [30]	✓										
Nie *et al.* [31]	✓	✓	✓	✓	✓			✓	✓		
Singh *et al.* [32]	✓	✓							✓		

[1] GWP = Global Warming Potential; [2] AP = Acidification Potential; [3] ODP = Ozone Depletion Potential; [4] POCP = Photochemical Ozone Creation Potential; [5] EP = Eutrophication Potential; [6] ADP = Abiotic Depletion Potential.

Figure 1. The LCA structure defined by ISO 14040: Application to CCS.



3.1. Specification of the Service

Within the goal and scope definition phase, an unequivocal identification of the service must be assured when starting the activities of assessment and when reporting the results in the declaration format. This issue represents a fundamental element in the development of the specific rules, as the details of this definition will unequivocally orient the focus of entire procedure.

Since the aim of the developed PCR is to assure the widest applicability in the whole spectrum of technological scenarios, CCS was here considered as an end-of-life process, so that it can be integrated to whatever industrial plant that is an anthropogenic source of carbon dioxide. On the other side, when analyzing the effect of CCS on integrated systems such as combustion technologies based on fossil and renewable fuels and peat equipped with CCS, the specific PCR for electrical energy, steam and hot water [33] shall be considered.

A hierarchic approach has been followed according to an UN-based product classification scheme, *i.e.*, Central Product Classification (CPC) [34], in order to facilitate a well-structured and easy to communicate product identification. The product category was therefore defined under ISIC–CPC's classification:

- Section: 9—Community, social and personal services
- Division: 94—Sewage and waste collection, treatment and disposal and other environmental protection services
- Group: 949—Other environmental protection services n.e.c.

Although in literature several studies focused on the capture stage only (Table 1), the here proposed methodology must cover the whole CCS process chain with a modular structure. Therefore the product category was defined as a system of technologies that integrates three stages: carbon dioxide (CO_2) capture, transport and storage services. The definition of the three stages was drawn up in order to cover every feasible management option:

Capture is based on capturing carbon dioxide from large point sources, such as large fossil fuel or biomass energy facilities, industries with major CO_2 emissions, natural gas processing, synthetic fuel plants and fossil fuel-based hydrogen production plants, by three different types of technologies: post-combustion, pre-combustion, and oxyfuel;

Transport includes the transfer operation of captured CO_2 to suitable storage sites by high-pressure pipeline networks or by other means;

Storage includes geological storage (gaseous storage in various deep geological formations, including saline formations, oil and gas reservoirs and deep unminable coal seams), mineral storage (solid storage by reaction of CO_2 with metal oxides to produce stable carbonates) and biological storage (e.g., carbon dioxide storage using micro-algal systems).

The storage process involved a series of particular investigation elements. Storage options are different and variegated. For instance, a clear definition of geological storage was necessary as suggested by EU and US regulation [35–37]. Besides, some exclusions must be appointed, in fact in this work, the developed rules do not apply to afforestation/reforestation process, as considered to be out of the scope. Finally, even if ocean storage (*i.e.*, liquid storage in the ocean) was assessed in some LCA for comparative assertions [16,20], this option has been excluded from the range of processes covered by these rules, since the chronic effects of direct CO_2 injection into the ocean on ecosystems over large ocean areas and long time scales have not yet been deeply studied [38].

3.2. Functional Unit

In Life Cycle Assessment, the functional unit is defined as the reference unit used to quantify the performance of a product system [9]. In fact, its main purpose is to provide a reference to which the inputs and outputs can be linked. The functional unit is important as a basis for collection, handling and calculation of LCA data, aimed to ensure the possibility to add up information from EPDs in the supply chain and to be able to compare EPDs within a given product category.

As concerns assessments of services, the basic rule is to declare the expected functional outcome of the service provided. End-of-life systems, such as waste treatment systems, usually consider the disposal as function, so that the functional unit is the quantity entering into the treatment system [39,40]. Nevertheless, in CCS case the function is to capture *in order to store*. The captured quantities that are not stored are out of the system purpose. Therefore the functional unit was defined as the *storage* of 1000 kg (1 ton) of *captured* carbon dioxide (CO_2).

This choice was built in coherence with the goal settings and scope of the study, described in the specification of the service. As noticeable in Table 1, almost all the assessments screened in the literature regarded in particular the effects of the integration of carbon capture in fossil fuel or biomass fired power plants. Since the aim was to measure the difference in performance with or without the capture facility, the different functional units all concerned electricity generation. Only a single study [30] performs an analysis of model cases that include further CO_2 generation sources than thermal power stations such as ironworks, paper mills and oil refineries, where the results are reported per ton of CO_2 rather than per energy generated. The use of energy as a functional unit is useful for understanding the implications at a power plant level, but it is not fruitful for considering large scale effects and for indicating the output of the overall system. In fact this research work was aimed to develop a set of rules that can be applied to whatever anthropogenic source of CO_2. The selection of an amount of CO_2 captured in order to be stored as functional unit for such an end-of-life chain is analogue to the selection of an amount of waste to be treated when setting the rules for solid waste disposal services. It must be also precised that CCS is not a typical waste treatment service as the implementation of the service can have an important impact on upstream processes, e.g., the so-called "fuel penalty" for a power plant.

3.3. System Boundaries

The definition of the system boundaries is a particularly delicate point of investigation as it determines the unit processes to be included in the study and what type of upstream data and downstream data that could be omitted. The international EPD® system has adopted a LCA procedure which is separated into three different life cycle stages: *upstream module*, *core module* and *downstream module*. This separation is based on a modularity approach; moreover, in this way it is possible to differently perform the LCA-based calculations for the separate LCA stages due to various types of background assumptions, different data availability, different accuracies of the calculated data and different needs for data representativeness and quality.

For EPDs of goods, the core module is usually equal to the manufacturing processes, while as concerns EPDs of services, the "production of the service" is regarded as the core module. In the case of CCS, coherently with the final target of the service and the choice of functional unit, the core module covers CO_2 transport and storage phases. Capture phase is consequently considered to be the necessary upstream process, while leakage represents the downstream phase. The lifecycle boundaries that were defined for CCS are described in Figure 2.

3.3.1. Upstream Module

After a screening of the currently feasible technological options for carbon capture, the processes that were considered to be included are listed below:

(a) CO_2 capture (taking into account CO_2 formation and capture efficiency), e.g., by:

- Post-combustion capture technology (e.g., including CO_2 separation from flue gas stream through amine-based or ammonia-based solvents, membrane separation, chemical looping and solid adsorption processes);

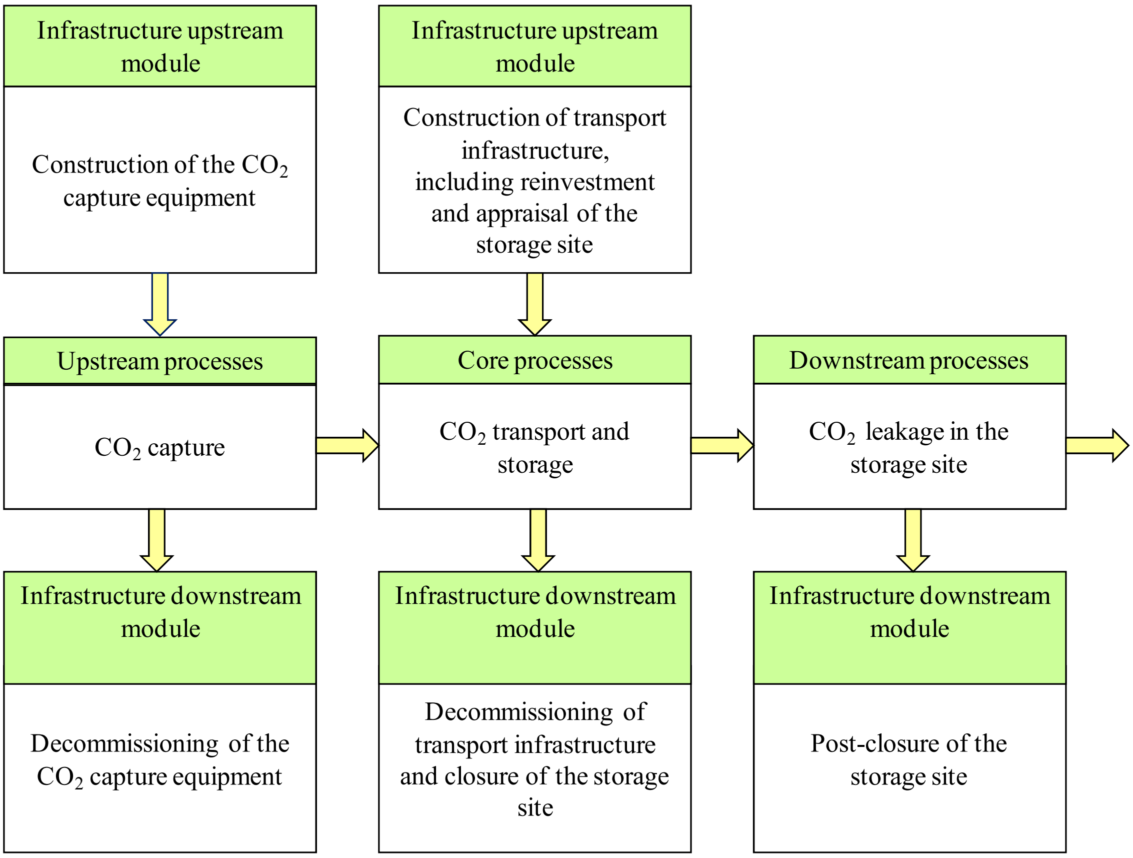
- Pre-combustion capture technology (e.g., including Integrated Gasification Combined Cycle (IGCC)—plants, involving the partial oxidation of solid fuel feedstock in a gasifier to produce a mixture of hydrogen and carbon monoxide, then treated in a shift converter and a physical adsorption unit);
- Oxyfuel (*i.e.*, combusting fossil fuels in recycled flue gas enriched with oxygen).

(b) CO_2 purification/separation.

(c) CO_2 compression to high-pressure supercritical conditions (when performed).

The upstream infrastructures that were listed in the selection included specific equipments such as CO_2 absorber, air separator, compressor, *etc.* It is important to higlight that plants modifications (e.g., retrofitting of existing plant) and power plants efficiency losses have to be taken into account in the calculations. For combustion technologies based on fossil and renewable fuels and peat equipped with CCS, the related PCR [33] shall be considered.

Figure 2. System boundaries.



3.3.2. Core Module

The processes that were considered to be compulsory included as core processes are listed below:

- CO_2 transport through pipelines or mobile transport facilities;
- Operation stage (including CO_2 injection, site monitoring, CO_2 reaction with metal oxides);
- Handling/treatment/storage of process-related emissions and waste (including CO_2 leakage during transport and operation stage).

As concerns the infrastructures, the methodological approach opted for only including those facilities that are specifically linked to transport and storage processes. This selection included the following operations:

- Construction of new and dedicated infrastructure such as CO_2 pipelines systems, road, railways or modification of existing infrastructure, such as oil and gas pipeline (including main transports and reinvestment). As mobile transport facilities are often used not only for the purpose of CO_2 transport, the construction of the means of transport might be negligible with respect to resource use during the lifecycle and shall be included only if they are exclusively dedicated to CO_2 transport;
- Storage site appraisal (e.g., well drilling and completion);
- Construction of injection station or other facilities such as platforms, *etc.*;
- Dismantling of dedicated transport infrastructure (dedicated CO_2 pipelines, roads, railways); Dismantling of transport facilities shall be included only if they are exclusively dedicated to CO_2 transport;
- Site closure (including infrastructure removing, wells plugging and main transports).

3.3.3. Downstream Module

According to the modularity principles adopted, the following items shall be included in the LCA calculations for downstream processes:

- Site post-closure (including site management, remediation and main transports);
- Data about CO_2 leakage.

The analysis of the LCA studies selected for this research highlighted that the inclusion of leakage phase of stored CO_2 is not easy to handle. Some authors did not include this stage as they explicitly consider it insignificant [23,32], or otherwise leakage was assumed to be negligible in the relevant time horizon although declaring that this represented a main uncertainty of high concern [27], or alternatively it was firstly omitted but deserving a sensitivity analysis [21]. In fact the IPCC report states that "if continuous leakage of CO_2 occurs it could at least in part offset the benefits of CCS for mitigating climate changes" [38].

In the here proposed rules the chosen approach followed the current European regulatory framework. According to this approach, CO_2 leakage, associated with capturing 1,000 kg of carbon dioxide, shall be modeled for a time period of 20 years from site closure, in accordance to the requirements about transfer of responsability stated in the EU CCS Directive, Article 18 [35].

3.4. Allocation Rules

Allocation is the partitioning of input or output flows of a process or other product systems to the product system under study [9]. Thus, the inputs and outputs shall be allocated to the different products according to clearly stated procedures. As a general rule, allocation between different products and co-products shall be based on physical relationships. If physical relationships cannot be established or used, allocation can be based on other relationships, e.g., economical allocation.

Allocation always implies valuation and the main goal for the allocation choices made for this product category is to keep the allocation methodology rather simple but transparent and maintain comparability between EPDs. Other allocation choices than the mandatory one listed below may be reported and discussed in the EPD under the section of additional environmental information.

In fact the studied system is a multi-output process that delivers CO_2 treatment services (CCS) together with steam, hot water and/or electricity production. The allocation between service and products follows the International EPD® system instructions regarding waste treatment [41]. The burdens of equipment and processes needed to produce heat, process steam or electricity shall be declared in the EPD per kWh of these products, whereas the CO_2 capturing, transport and storage processes shall be allocated to the CO_2 treatment service and be declared per ton of CO_2 captured. This approach is based on the application of the Polluter-Pays (PP) allocation method [42], which separates interlinked product systems at the pointing in the life cycle where they have their lowest market value.

3.5. Environmental Performance Indicators

The two internationally recognized operational approaches to Life Cycle Impact Assessment (LCIA) are problem-oriented and damage-oriented, respectively addressing mid-point and end-point indicators [43]. The analysis of the selected LCA studies confirms that the first approach has been preferred as more reliable, even if its results are not always easy to interpret for an audience of non-LCA practitioners.

The environmental performance-related part of an EPD always includes LCA-based information about the use of resources, energy consumption, polluting emissions from the life cycle inventory work (when relevant) and the resulting potential environmental impacts. According to the GPI of the International EPD® system [12], the following parameters were identified: use of non-renewable/renewable material and energy resources; water and electricity consumption; potential environmental impacts as global warming, acidification, ozone depletion, photochemical oxidant formation, eutrophication; waste generation, land use and toxic emissions. These categories well match the selection of parameters for most of the studies analyzed in Table 2. In addition to the identified standard parameters, the following specific ones were added:

- LCI emissions of CO_2 captured;
- LCI emissions of CO_2 leakage;
- Ratio between the CO_2 permanently stored and the CO_2 emitted from the considered source.

In this way the methodology allows the audience to directly evaluate a set of relevant inventory data for capture and storage activities, together with a measure of the performance of the entire process. Moreover, further information that is not part of the LCA but identified as an important environmental aspect of the product or information asked for by customers and other stakeholders, were identified to be declared. According to this perspective, the following issues should be addressed:

- Soil pollution;
- Impacts on biodiversity;
- Risk and safety assessment.

The biodiversity theme is meant to focus on direct regional impacts e.g., concerning nature conservation issues and visual impact connected to land use. Besides, some qualitative considerations about boundaries towards risk assessment should be added. Environmental impacts due to accidents and undesired events are not part of the LCA but part of the environmental risk assessment that may be reported under the additional environmental information. However, due to the process technological peculiarities, it has been established that the site selection criteria adopted, including criteria of the risk and safety assessment of the CO_2 storage sites, shall be declared, as corollary information. As concerns the verification procedure of these integrations, any literature reference or methodology used to acquire and describe additional environmental information shall be openly accessible and made available to the verifier.

4. Conclusions

The scope of this paper was to investigate a set of key issues that are fundamental in the development of robust methodological rules for the application of LCA to CCS. For this purpose, a methodological framework coherent with a type III environmental declaration such as EPD was chosen. The proposed rules were discussed with reference to the existing state-of-the-art for this complex integrated assessment.

It was firstly highlighted that the service must be considered as an end-of-life process, allowing its integration into every feasible CO_2 generation source. Consequently, it was precised that the definition of functional unit shall be coherent with objective of the overall system. The quantification of the results on a CO_2 basis will provide indication about the specific output of CCS, allowing users to draw a direct connection between the environmental impacts and the emission reductions. Besides, the selection of the system boundaries was analyzed, with the aim of including the whole technological spectrum that may be involved in such differentiated processes. The importance of considering CO_2 leakage has been strengthened. Moreover, allocation choices have been discussed, stressing the adherence with Polluter-Pays (PP) method and addressing the impacts of electricity generation to its specific set of rules. Finally, a set of suitable and significant environmental indicators were selected in order to give specific useful information to users when reporting the environmental performance of the system.

No value-based judgements are included, since it is up to the users to make their evaluation of the environmental performance based on the information that are made available. The dissemination of the LCA-based information compiled through harmonized specific rules may allow organizations to communicate the environmental performance of any CCS systems to a diverse group of audiences, being both related to business-to-business (B2B), business-to-public authorities (B2P) and business-to-consumers (B2C).

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