Using life cycle assessment to inform technology development: a case study of the life cycle impacts of acetone production from captured CO2

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Using life cycle assessment to inform technology development: a case study of the life cycle impacts of acetone production from captured CO_2

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Introduction: This research investigates how life cycle assessment (LCA) can support technology development by assessing the decarbonization potential of PYROCO$_2$, a fermentation process that converts captured carbon dioxide and hydrogen into acetone. The aim with this research is to analyze how well an LCA study provides environmental insights to the technology development process. For this, an LCA study for the PYROCO$_2$ consortium is presented and the analysis of it is presented in this article. The conducted LCA study identified three types of goals, defined to accommodate different actors' interests in the PYROCO$_2$ project.

Methods: The assessment followed standard steps: goal and scope definition, inventory analysis, impact assessment and interpretation. To inform technology developers, the LCA study identified environmental hotspots, explored scenario-based impacts and compared the results against conventional acetone production. The LCA study results were further analyzed to identify how the goals of the LCA study were addressed through methodological choices and how this supports the technology development process.

Results: Results show that CO_2 production and electricity consumption are key environmental hotspots, with impacts sensitive to CO_2 source and electricity mix. Compared to conventional acetone production, PYROCO$_2$ demonstrates potential to reduce climate change and resource depletion impacts, though trade-offs occur in ecotoxicity and human toxicity. Uncertainty remains due to the low technology readiness level (TRL 4-5).

Discussion: Moreover, while the LCA study informed technology development, its ability to fully address its goals was constrained by a mismatch between when the assessment would suit best and the technology's current readiness level. Multiple LCA studies across development stages would be needed to fully support technology advancement. Overall, the study highlights that the value of LCA in technology development lies not only in its results but in how the study is designed, with goal and scope definition playing a central role in its relevance and usefulness. It further shows that LCA can support the development of emerging carbon capture technologies by identifying decarbonization potential and trade-offs, provided that the study design is aligned with the needs of technology developers.

KEYWORDS

carbon dioxide capture and utilization (CCU), CO_2 utilization, early-stage technology, emerging technology, goal and scope definition, prospective life cycle assessment (pLCA)

1 Introduction

Climate change mitigation is an urgent global priority, driving efforts to develop technologies that reduce carbon dioxide emissions (IPCC, 2023). To assess whether these technologies effectively contribute to reduction of carbon dioxide emissions, life cycle assessment (LCA) plays a crucial role (Khoo and Tan, 2024). One group of emerging technologies for carbon reduction is carbon capture and utilization (CCU) technologies. This paper focuses on a specific CCU technology currently under development, the PYROCO$_2$ process, which involves a two-step fermentation method to produce acetone from hydrogen and captured carbon dioxide. An LCA study is required to assess the decarbonization potential of the technology as well as possible environmental impacts of the process.

Given that the PYROCO$_2$ process is still under development, the LCA study is conducted within the context of the technology development project and its project members. Technology development is a long and complex process, characterized by a high level of uncertainty in the early stages, which makes conducting an LCA a challenging task if it is to deliver meaningful insights to a range of project members. Nevertheless, incorporating LCA early in the development process can provide valuable insights into the environmental impacts of the technology, helping to guide decision-making during development (Hetherington et al., 2013).

In the context of technology development, recent research has primarily focused on methods for performing prospective or ex-ante LCA (e.g., Arvidsson et al., 2017; Cucurachi et al., 2018; Buyle et al., 2019; Moni et al., 2019; Thomassen et al., 2019; Thonemann et al., 2020; van der Giesen et al., 2020). This distinct type of LCA method differs from conventional LCA by modeling the assessed emerging technology as its future developed industrial system. However, prospective LCA is not the only method suggested for evaluating emerging technologies. A few studies have explored different types of LCA, for different goals and uses of LCA studies, based on different stages of technology readiness level (TRL) or development stage (Hetherington et al., 2013; Gavankar et al., 2014; Thomassen et al., 2019), as well as dimensions of technical and market maturity (Bergerson et al., 2020). The TRLs are defined to be a scale from 1—basic principles observed, to 9—actual system proven in operational environment (European Commission, 2017). However, none of the these studies identify the knowledge needs of different project members during the development stages.

The LCA study presented in this work is a future-oriented study that diverges from common interpretations of prospective LCA. Rather than modeling the emerging technology at TRL 9 and situating it within a projected future background system, this study defines its goal and scope based on the knowledge needs of the stakeholders involved in the technology's development. At the current stage of technology development, the projected scale of interest to assess is the demonstrator plant. Moreover, there is little use in modeling a future background system for a near-future system at TRL 7, planned to be built in 2027.

Furthermore, in the context of LCA for CCU systems, a literature review (Nyqvist et al., 2025) identified a recurring methodological gap: many studies either omit a clear goal statement or present it in overly broad terms, such as "to assess environmental impacts." This lack of clarity impairs the understanding of methodological choices, and consequently the trustworthiness of the results, of an LCA study. Accordingly, the LCA presented in this work was conducted with deliberate attention to this aspect.

A number of studies have investigated various fermentation processes to convert carbon dioxide into chemicals (e.g., Griffin and Schultz, 2012; Acharya et al., 2015; Dürre and Eikmanns, 2015; Liew et al., 2016; Teixeira et al., 2018; Köpke and Simpson, 2020; Fackler et al., 2021; Agrawal et al., 2023), presenting them as sustainable decarbonization technologies. To the authors' knowledge, there is only one study incorporating LCA results published on a process to produce acetone through fermentation (Liew et al., 2022). This study claims a carbon-negative fermentation route confirmed by life cycle analysis. An addendum (Liew et al., 2025) provides additional information about the LCA performed, providing more information on why it is a cradle-to-gate study and credit is taken for uptake of steel mill emissions. However, the goal of the LCA presented by Liew et al. (2025) was stated to be to understand the potential environmental benefits by comparing greenhouse gas emissions to those from conventional production routes, but important details of the goal and scope are not reported and it is not stated whether the LCA study was used for anything else than confirmation. By focusing on how the LCA study informs technology development, our study takes a contrasting methodological approach.

Given the lack of clear guidance on how LCA can inform early-stage technology development, there is a research need to investigate this and we contribute to the body of knowledge with insights from a development project as case. In contrast to prevailing interpretations of prospective LCA that model fully mature systems within distant future backgrounds and LCA studies with vague goal definitions, this work defines goal and scope based on the knowledge needs of technology developers and models the assessed system at demonstrator scale (TRL 7). In doing so, the study reframes how and why LCA is applied at a specific stage of technology development, demonstrated through the PYROCO$_2$ project as a concrete case. While the LCA results are primarily intended to support decision-making within the project consortium, the methodological approach and insights developed in this study are transferable beyond CCU systems and are of broader relevance to LCA practitioners and researchers working with emerging technologies under active development. Consequently, this paper contributes to a broader understanding of how LCA can be purposefully designed to inform technology development.

2 Methods

This study uses an LCA study in a project case as basis for analyzing how LCA was used to inform technology development. The method is illustrated in Figure 1. To shape the LCA study for the PYROCO$_2$ process for its technology development context, special attention was given to the goal definition and related

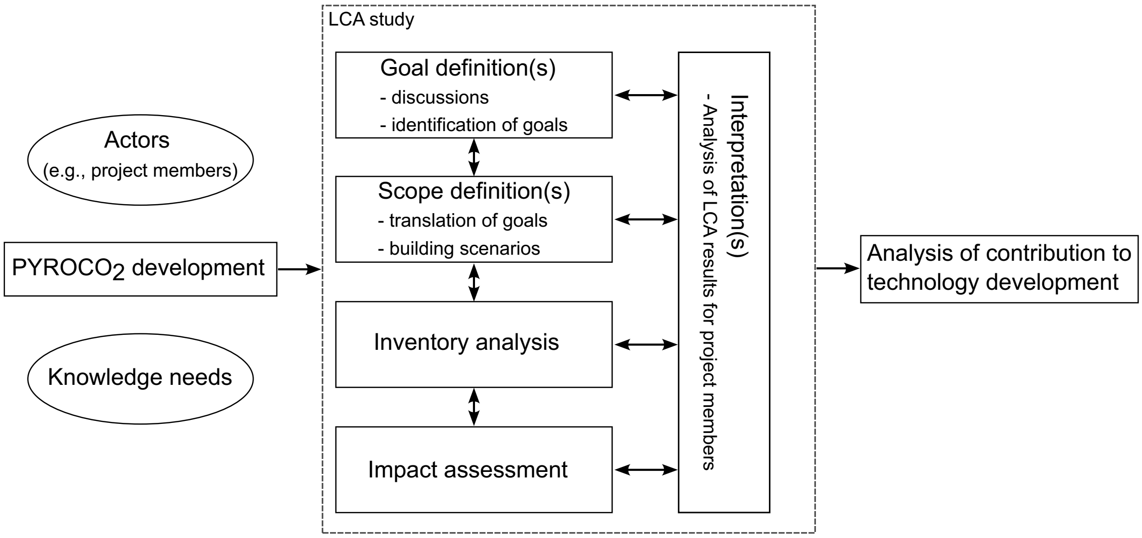

FIGURE 1
A schematic diagram of the method used in this study.

methodological choices. Hence, the goal definition is expanded and explained, and separated from the scope definition. Also, the LCA results were analyzed to identify the contributions of this LCA study in the early stages of technology development of the PYROCO$_2$ process.

2.1 The project case

The LCA study was carried out within the currently ongoing CCU-project PYROCO$_2$, which is a project in the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037009 (PYROCO$_2$, 2024). The goal of the project is to demonstrate the PYROCO$_2$ process, which is a thermophilic microbial bioprocess to produce acetone from industrial carbon dioxide and green hydrogen. The project aims to produce climate-positive acetone that can be further processed into chemicals and materials with a negative carbon footprint. The LCA is one part of the sustainability assessment including techno-economic, economic, environmental and social aspects. One purpose for the LCA is to ensure that the new technology leads to carbon reduction.

The project started at TRL 4-5 (technology validated in lab and in relevant environment) and is planned to progress to TRL 7 (system prototype demonstration in operational environment) during the project's duration time (2021-2026). According to project plans, a preliminary LCA study was delivered halfway in the project (the LCA study presented in this paper) and another LCA is expected at the end of the project. At the time of delivery of the LCA presented in this article, laboratory experiments are confirmed and the design of the demonstrator plant is set, but how the full process will function is still uncertain or unknown.

2.2 The LCA study

As the studied PYROCO$_2$ process is not yet implemented, the LCA study conducted modeled a future system. The study was conducted in cooperation with partners in the PYROCO$_2$ consortium, especially for the definition of goal and scope. This was done through discussions with project partners for understanding general interests and especially within the work package focused on the assessment of the project (environmental, social and economic) for alignment of the modeled system between assessments. These discussions helped identify project partners' expectations and informed the design of a study useful to both direct consortium members and external actors connected to the project.

The LCA study presented in this article followed the principles of the standard framework defined by ISO 14040 and 14044, comprising goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006). The goal of the LCA study was set in coordination with partners in the project of the case study and in relation to the desired deliverable in the project. The goal was discussed at several meetings and actors from different working groups were asked about what aspects of the environmental impacts they were interested in and how they could use results of an LCA study.

The scope of the LCA study was then determined according to the defined goals and after additional discussions for aligning within the work package of sustainability assessments. These discussions primarily focused on which system boundaries of the LCA study would best align with the other sustainability assessments and the interests of the project consortium. The full contents of the scope in the scope definition phase were based on what is described by Baumann and Tillman (2004): system description, system boundaries, functional unit, choice of impact categories, allocation, data requirements and assumptions and limitations.

Data for the inventory phase were provided by consortium partners and included laboratory results, process simulations, assumptions, and estimates reflecting the state by January 2023. Additional data were sourced from relevant literature and environmental databases. The modeling, impact assessment and interpretation were performed by using the Activity Browser (Steubing et al., 2020), Python and Brightway2 (Mutel, 2017). The results were presented in an LCA report for internal usage in the PYROCO$_2$ project, and also at a project meeting with the consortium of the project.

2.3 Contribution to technology development

To evaluate the informational contribution of the LCA study to technology development, an analysis was conducted to evaluate the extent to which the LCA study's stated goals were fulfilled. This evaluation was performed in the broader context of the technology development process and included an examination of the methodological aspects affected by each goal and limitations encountered in addressing each goal within the conducted LCA study. Each goal was then mapped onto a scale from 1 to 9, corresponding to the TRLs as defined by the European Commission (2017). This mapping was designed to identify the stage in the technology development process, represented by the TRLs, where each type of LCA goal would be the most relevant and impactful. The placement was approximated based on two key considerations: (1) potential users of the LCA results and the point in the development timeline at which these insights would be most beneficial to them, and (2) the degree of technological maturity required to adequately address each goal.

3 Results

The LCA study presented in this paper was performed within the frame of the PYROCO$_2$ project for a deliverable halfway through the project, in 2024. The goal, scope, inventory and life cycle impact assessment results are presented here. In Section 3.5, the results from analyzing the goals in relation to informing technology development are presented.

3.1 Goal definition

The LCA study presented has a broader purpose to provide information and learnings about the environmental perspective on the PYROCO$_2$ process, for the PYROCO$_2$ consortium. A specific interest is the decarbonization potential of this new technology. The LCA can also be used for general learnings about what the system looks like and what the inputs and outputs are, both for internal and external actors.

One goal for the LCA is to find the processes that contribute the most to the environmental impact, i.e., to find the environmental hotspots. The use of this information is mainly for technology developers for future improvements in the process design.

A second goal for the LCA is to understand how impacts change depending on uncertain aspects of the future process (heating or cooling need for the fermentation processes), chosen inputs (carbon dioxide source) and the location of the future deployed system. The demonstrator plant is planned to be built in Norway. Additional locations are explored because possible industrial partners investigated are in France but also other countries in Europe.

A third goal for the LCA is to inform prospective investors about the system and how the process compares to other acetone production processes. Partners within the consortium need environmental data to attract industrial partners interested in deploying the technology. They are particularly interested in comparing the acetone produced from the PYROCO$_2$ process to other (conventional) alternatives. The goal is not to make an accurate comparison, but to put the possible impacts in perspective through showing it next to the benchmark values.

In summary, the goal definition produced three questions to be addressed by the LCA study:

- What are the potential environmental hotspots in the PYROCO$_2$ process?
- What are the potential changes in environmental impact of the PYROCO$_2$ system if the heating needs of the fermentations change or different carbon dioxide sources or electricity mixes would be used?
- Will the PYROCO$_2$ acetone have a lower environmental impact than the acetone currently present on the market?

3.2 Scope and modeling requirements

In this chapter, the assessed system is described and the necessary methodological choices made are explained. The scope of the LCA modeling is determined by the goal(s) for the LCA study.

3.2.1 System description

The system under study, what is here called the PYROCO$_2$ process, produces acetone from hydrogen and captured carbon dioxide through fermentation. The modeled system is based on a system, of the demonstrator plant producing 4,000 tons of acetone per year. The main focus of this LCA study is the PYROCO$_2$ process itself, which is highlighted with the foreground boundary in Figure 2. A simplified representation of the system is illustrated in Figure 3. The PYROCO$_2$ process consists of two different fermentation processes, one producing acetic acid from carbon dioxide and hydrogen, and a following process producing acetone from this acetic acid. An electrolysis process is utilized to produce hydrogen for the first fermentation and oxygen is used in the second fermentation. More processes are included in the more detailed flowchart in Figure 4.

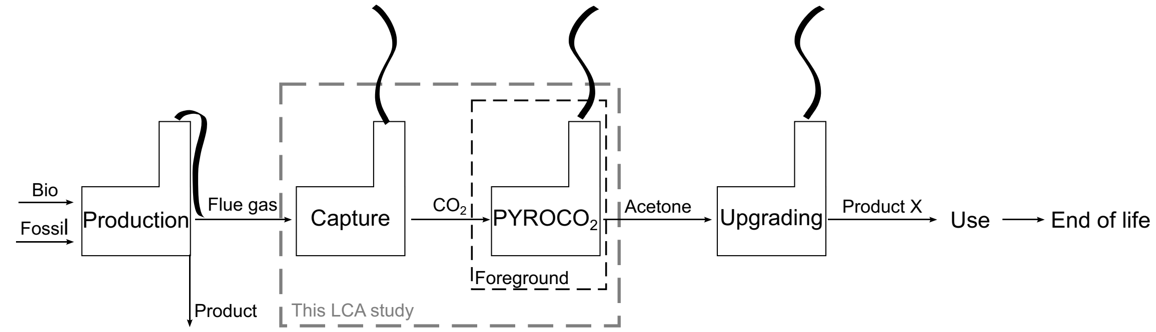

FIGURE 2
A simplified representation of the life cycle of acetone as a CCU product, focused on the flow of carbon from origin to end of life. The dashed lines represent the system boundaries of this preliminary LCA study. "Bio" and "fossil" stands for biogenic and fossil sources of carbon, such as biomass and limestone.

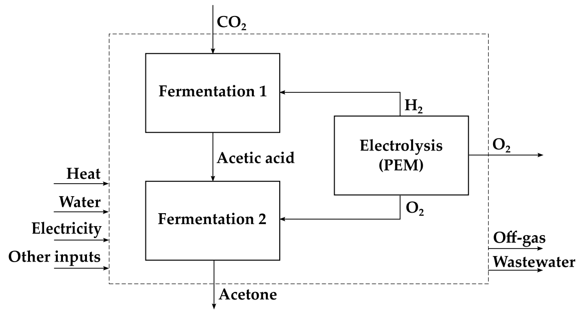

FIGURE 3
A simple flowchart of the studied $PYROCO_2$ process, the foreground system.

The main inputs and outputs of the studied foreground system are presented in Figure 3. The hydrogen is provided by an electrolysis process on site and the carbon dioxide is delivered as a product. Heat, water, electricity and other inputs (such as macronutrients, vitamins and trace elements for the media feed) are shown as inputs to the whole system. Apart from the acetone product and excess oxygen from the electrolysis, off-gas from the fermentations and wastewater from the distillation are expected outputs of the system.

3.2.1.1 Base case

The base case to be analyzed is a system where the first fermentation process is heated and the second one is cooled. The carbon dioxide provided to the process is produced conventionally, thus not captured from flue gas of an industrial point source at this stage of the project. In the base case, the site where the demonstrator is located is set in Norway and the Norwegian electricity mix is used.

3.2.1.2 Comparisons to base case

For the second goal of the LCA, the base case is compared against several scenarios to explore how variations in system parameters influence the results. These parameters concern heating and cooling, source of carbon dioxide and electricity mixes of different countries.

3.2.1.3 Scenarios: heating needs of the fermentation processes

Fermentations heated is a scenario where both fermentations are heated while *Fermentations cooled* is a scenario where both are cooled, to keep them at the desired temperature. These scenarios are constructed because it is uncertain whether the fermentations will produce heat so there is a need for cooling, or they will need to be heated to be kept at desired temperatures. Furthermore, there is also a scenario *Fermentations heated by waste heat*, where the heat need for the fermentations is assumed to be met by industrial waste heat and thus does not have any impact. The waste heat is in this scenario available at the industrial park where the plant is built. There is an uncertainty regarding the availability of the waste heat at the location of the plant, either internally or from another part of an industrial cluster. This scenario also informs decisions regarding the future location of the plant in order to also meet the required demand for waste heat, if necessary.

3.2.1.4 Scenarios: CO_2 captured, biogenic and CO_2 captured, fossil

Other alternatives of CO_2 are, in this LCA study, captured with monoethanolamine (MEA) from flue gas of either biogenic or fossil origin. These scenarios are developed due to uncertainties regarding which industries will supply the carbon dioxide and where both these industries and the overall process will be located in the future.

3.2.1.5 Scenarios: electricity mix of France and electricity mix of Germany

Scenarios are constructed for locations that are possible in the future, in this LCA study France and Germany. These two countries are of particular interest to the project, as they represent significant centers of industrial activity in Europe. Many aspects differ depending on the location (e.g., sources of carbon dioxide, cooling water availability or streams from other industrial processes), but for simplicity, only the electricity system was varied to assess how the electricity mix of another location could influence the results.

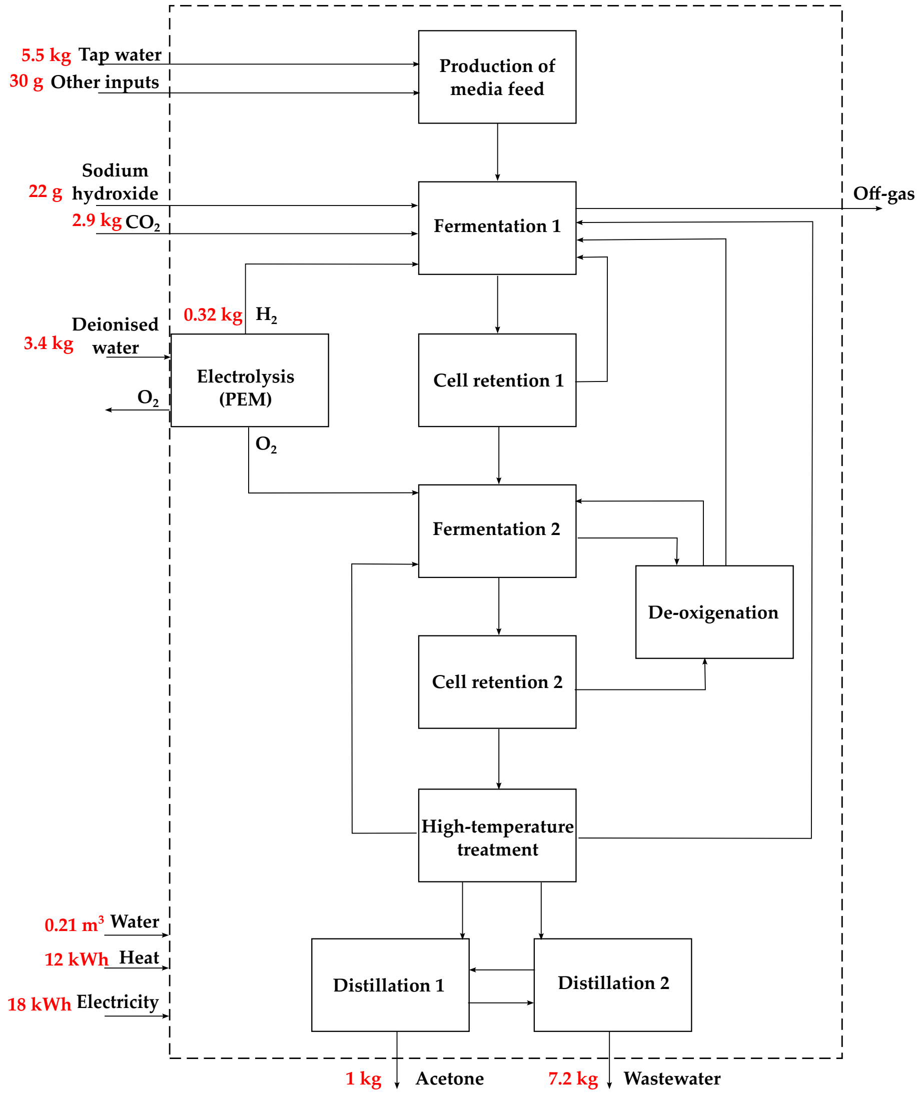

FIGURE 4
A detailed flowchart of the studied PYROCO$_2$ foreground system, with sizes of essential flows in red.

3.2.1.6 Comparison with alternative conventional products

For the third goal of the LCA study, the base case of the modeled system was compared to other acetone production alternatives. Given the uncertainty regarding which type of acetone, if any, would be replaced, several datasets were chosen from the ecoinvent database for a range of reference values. These represented some different production routes, such as acetone from isopropanol, from phenol production and from acetic acid production.

3.2.2 System boundaries

The boundaries of the technical system in relation to the industrial carbon capture system can be seen in Figure 2 and the foreground system boundaries in Figure 3. The production of CO_2 is included as a background process and not included within the foreground system boundaries of the project, since it is not within the PYROCO$_2$ project to capture or produce. However, one of the study's goals is to assess how the impacts vary depending on the selected CO_2 source and thus the background system is changed in a few scenarios. The downstream upgrading of acetone to other products is not included within the boundaries of the study since the focus is on the acetone production. The decisions the project consortium make are concerned with the system which only incorporates the production of acetone and not the use. Since the use of acetone is outside of the control of the consortium, it is not included in this LCA study.

3.2.2.1 Geographical system boundaries

The geographical boundary is focused on the production site in Norway for the base case but other sites are theoretically explored in the different scenarios. The planned demonstrator plant in the PYROCO$_2$ project will be built in Norway. Both the hydrogen and the carbon dioxide are assumed to be produced on site. Other materials are assumed to be bought from a European or even global market. When exploring future sites of implementation, the electricity system is changed to that of France and Germany.

3.2.2.2 Boundaries relative to capital goods

It is not the goal of this LCA to learn about the construction of the plant, as the learnings about the processes themselves are of interest for the technology developers. Another LCA study with a different purpose could look into more detail on the effects of constructing a CCU system. Hence, capital goods, infrastructure and construction are not included in the boundaries of the LCA conducted. For this assessment, the construction of the plant is estimated by the impacts of the construction of an ethanol fermentation plant (from the ecoinvent database). It is deemed sufficient to have some proxy for the impacts of construction of the demonstrator plant.

3.2.2.3 Time horizon

The LCA study models a future demonstrator plant but does not model any future background system. The future plant is assessed as if it was built in present time, based on environmental data that has been collected from other processes. The planned demonstrator is expected to be built for start of operations in 2027, and industrial sized plants would be set further in the future. For informing technology developers at this early stage of technology development, present data can be used.

Other time aspects are lifetimes of the plant and the products. When needed, e.g., for distribution of environmental impact of the construction of the plant itself, 20 years is used as the lifetime of the plant. This is an approximation of the lifetime of an industrial plant. Furthermore, the lifetime of the CCU products created would be of importance for a “to-grave” study but this is restricted to “to-gate” and thus the product use is excluded. What happens to the products during use and end of life is also outside of the project scope. It is still uncertain which products will be produced from the acetone and what the uses of these will be.

3.2.3 Functional unit

The choice of functional unit reflects the function of the assessed system and the goals of the LCA. The functions of the CCU system as a whole are several: to produce a product (e.g., cement), capture and treat a waste flow (e.g., flue gas) and produce a second product from the carbon dioxide captured (e.g., acetone). However, in this LCA study the analysis focuses on the function to produce acetone (see Figure 2). The function to capture and treat flue gas belongs to a background process necessary to produce captured carbon dioxide, but it is not the purpose of this LCA to analyze this function. The main focus is on the acetone production because the goals of this LCA are to provide information for technology developers of the acetone production, potential changes in the environmental impacts of this process and preliminary comparisons to market acetones for possible investors. Therefore, the functional unit chosen in this LCA study is 1 kg of acetone produced by the PYROCO$_2$ process in the demonstration plant.

3.2.4 Choice of impact categories

The chosen impact categories in this LCA study are climate change, depletion of non-renewable energy resources, ecotoxicity and human toxicity. In the life cycle impact assessment, the method chosen was CML v4.8 2016 (Leiden University, Leiden, The Netherlands). Climate change was chosen because it is a focal point, since the project aims to mitigate greenhouse gas emissions, particularly CO_2. It is crucial to explore whether the process has the potential to yield reductions in climate change impact, both compared to alternative processes and in absolute carbon reduction (i.e., net negative emissions).

The rest of the impact categories were included to give a more comprehensive understanding of the environmental impacts of the PYROCO$_2$ process. Since one reason for implementing CCU is replacing fossil carbon sources with waste flue gas, depletion of non-renewable energy resources was chosen as one of the impact categories. Furthermore, ecotoxicity and human toxicity were chosen because impacts on nature and human health were of interest for a more comprehensive assessment of environmental impacts, since that was not covered by climate change and depletion of resources. There are different types of impacts that could disclose these impacts, but in this case terrestrial ecotoxicity and human toxicity were chosen. These categories were chosen because they were representative for several of these impacts in this study, since the results conveyed the same message as other impact categories connected to ecotoxicity and human health.

3.2.5 Allocation

There are system boundaries in relation to other technical systems that require allocation. One is the boundary between the producer of another product (e.g. cement) that provides the flue gas for capture, and the CCU system or carbon capture unit (see Figure 2 for the boundary between *Production* and *Capture*). The multiple outputs from the *Production* system in Figure 2 are the product produced and the flue gas that is captured. Hence, there is a need for allocation of environmental impacts between these two outputs. In this study, the flue gas is assumed to arrive to the carbon capture process as a waste flow with no burden, as the full burden is allocated to the product produced. Consequently, the carbon dioxide does not come with any burden from the production of the product (e.g., cement) but with the burden of capture and purification of flue gas. Thus, the CO_2 carries the burden of its production like any other materials in the background system.

Another multi-output process in the CCU system where allocation is needed, is the electrolysis where both H_2 and O_2 are produced and used in the processes but also some excess O_2 is produced (see Figure 3). The purpose of the electrolysis is to provide these gases to the PYROCO$_2$ plant and thus all the environmental impacts of the electrolysis process are allocated to the PYROCO$_2$ process.

3.2.6 Data requirements

For the goal of investigating potential magnitudes of change in environmental impacts, the quality and accuracy of data is not critical. Moreover, precise data is currently unavailable, as the assessed system is still in the design phase. Consequently, the data used is derived from simulations and calculations informed by laboratory data and assumptions provided by the project's technology developers.

3.2.7 Assumptions and limitations

As the assessed system is at an early development stage, several details in the LCA model are built on assumptions. The assessment is limited by the knowledge about the process and the data available, but for the goal of helping technology developers find the probable hotspots and learning about the future system, this is sufficient.

For cooling and heating, sizes of flows are approximated. The cooling of processes is roughly estimated based on heat transfer and the specific heat capacity of water assumed to come from a nearby lake of 5 °C temperature. This would be different in other locations but is not varied for the different location scenarios in this assessment. Also for heating with steam, flows are roughly estimated based on the specific enthalpy of vaporization of water and energy conservation principles.

There are also excluded processes in the assessment due to the lack of data or knowledge. Due to unavailability of process demand and environmental data for macronutrients, vitamins and trace elements in the media feed, the impact of the media feed is conservative, including only some of the ingredients that data could be found for. Furthermore, there is not any knowledge about the content or treatment of wastewater and off-gas, thus assumptions are required. The treatment of wastewater is modeled as average wastewater treatment in a wastewater treatment plant (data from ecoinvent). Off-gas treatment is not foreseen as required within the frame of the demonstrator plant. Due to lack of data, the emissions released through the off-gas are also excluded.

3.3 Life cycle inventory

An inventory of processes within the PYROCO$_2$ process, through studying process schemes, resulted in the detailed flowchart shown in Figure 4. The sizes of flows (all arrows in the figure) were collected based on simulations and calculations, creating an inventory used for the life cycle impact assessment calculations in the Activity Browser (Steubing et al., 2020).

For background processes, data was retrieved from ecoinvent 3.11 (cutoff) or literature (see Table 1). When available, national averages were chosen (e.g., for electricity), otherwise European or even global market data were used for some materials. Where background data was not found within the project or in the ecoinvent database, literature data was used. For the scenarios with carbon capture processes, data on carbon capture with MEA was used, from Duval-Dachary et al. (2023). Literature data was also used for the carbon footprint of yeast used in the media feed, retrieved from COFALEC (2012).

3.4 Life cycle impact assessment and interpretation

The results of the life cycle impact assessment with respect to the goals of the assessment are presented here. Results for additional impact categories can be found in Supplementary material.

3.4.1 Goal 1: identification of hotspots

The main environmental hotspots were found to be the CO$_2$ production (MEA use and electricity use) and the electrolysis (electricity use). The impact of carbon dioxide production was lower with the literature data for captured carbon dioxide than for ecoinvent data for carbon dioxide production, but it was still a hotspot. Within the PYROCO$_2$ process itself, the high temperature treatment had a relatively large impact due to the electricity use for heating.

3.4.1.1 Climate change

Carbon dioxide production stands for 60% of the climate change impact in the base case, 33% in the fossil capture case and 12% in the biogenic capture case. The remaining climate change impact comes mainly from the electricity use by the electrolysis and high temperature treatment.

3.4.1.2 Resource depletion

Electricity is the dominating process when it comes to resource depletion. In the base case where the Norwegian electricity mix is used, impacts trace back to imports of electricity from other countries. Also MEA has an impact on resource depletion, around 25% in the base case where it is used in carbon dioxide production but only 6% in the cases using literature data for carbon capture.

3.4.1.3 Ecotoxicity

For terrestrial ecotoxicity, carbon dioxide production and electricity are again the dominating sources of impact. This impact stems from infrastructure construction such as the chemical plant, transmission network and hydropower plant construction. For carbon dioxide, the contribution is 55% for carbon dioxide production in the base case but only 10% in the capture cases.

3.4.1.4 Human toxicity

In the impact category human toxicity, the carbon dioxide production is dominating with 70% of the impact in the base case, from MEA use and the construction of the chemical plant. In the cases with literature data for carbon capture, this contribution is 23%, from MEA use and electricity. The remaining impact is mainly from electricity use in the electrolysis and high temperature treatment.

3.4.2 Goal 2: scenario comparison

Apart from the base case, scenarios explored in the life cycle impact assessment consider the heating and cooling of

TABLE 1 Inventory data per functional unit and sources for background processes.

Product	Value	Source
Tap water	5.5 kg	ecoinvent 3.11: market for tap water (Europe without Switzerland)
Yeast	11 g	COFALEC, 2012
Other inputs to production of media feed (macronutrients, trace elements)	19.6 g	ecoinvent 3.11: market for ... (RER or GLO)
Sodium hydroxide	22 g	ecoinvent 3.11: market for sodium hydroxide, without water, in 50% solution state (GLO)
CO_2	2.9 kg	ecoinvent 3.11: carbon dioxide production, liquid (modified to electricity mix of country); Duval-Dachary et al., 2023
Deionised water	3.4 kg	ecoinvent 3.11: water production, deionised (modified to Norway)
Water	0.21 m^3	Biosphere flow: water, river
Heat (by steam)	12 kWh	Electricity need ecoinvent 3.11: market for electricity, medium voltage (Norway, France, Germany)
Electricity	18 kWh	ecoinvent 3.11: market for electricity, medium voltage (Norway, France, Germany)
Wastewater (treatment)	7.2 kg	ecoinvent 3.11: market for wastewater, average (Europe without Switzerland)

fermentations, different sources of carbon dioxide and different electricity mixes (see Section 3.2.1). The results from the scenario comparison (see Figure 5) show that the heating and cooling of the fermentation processes does not make a big difference on the environmental impacts. Compared to the base case, changing the source of carbon dioxide can decrease the impact and other electricity mixes can increase the impact. The reduction due to captured carbon occurs because the impact of captured carbon dioxide is smaller than conventional CO_2, but these differences are uncertain as they both depend on database and literature data. The difference between carbon of biogenic or fossil origin is only visible for the climate change impact, where biogenic carbon has a lower impact due to the non-captured emissions during carbon capture. Furthermore, it is visible that when the electricity mix changes from Norwegian to French or German, the impacts in all categories presented increase. Therefore the location and background system of a future PYROCO_2 plant plays a big role for the environmental impacts of it.

3.4.3 Goal 3: comparison to conventional acetone alternatives

Depending on which market acetone the PYROCO_2 acetone (base case) is compared to, the impacts in different impact categories are both higher and lower (see Figure 6). However, to compare the PYROCO_2 process to database data for the conventional processes is not a fair comparison. The PYROCO_2 process is under development while the conventional alternatives have been implemented at industrial scale, and the data comes from different sources. However, the comparison does show the impacts of the planned process in relation to established processes. Considering how much the impacts change depending on location, the impacts could be much higher than the acetone alternatives in all categories, with other electricity mixes than the Norwegian, but the impacts could also be lower with captured carbon dioxide (cf. Figure 5).

3.5 Analysis of the conducted LCA study

In line with the purpose and goals with the LCA, the LCA study focused on identifying environmental hotspots within the PYROCO_2 process design using simulated data, while also considering changes in different scenarios and providing comparisons for investors. These goals affected the modeling in different ways and each have their limitations regarding what can be answered. Furthermore, they could fit the technology development process at different times. These points in time are visualized in Figure 7 and additional characteristics that distinguish the three goals of the methodology are summarized in Table 2.

The approximated most suitable timings of the three types of goals addressed were placed in relation to the TRL sequence, see Figure 7. The first goal, goal 1, is mainly directed toward technology developers interested in the process design and is suitable for a technology at low TRL. Goal 2 is more directed toward industrial partners considering future implementations and is thus more suitable when the technology is about to be implemented. Goal 3 is aimed at marketing toward possible investors, which is most suitable to do when the studied technology is at the same TRL as the alternatives it is compared to. Hence, the different goals could fit in LCA studies performed at different stages in technology development. However, the three goals were addressed in the current LCA study and these different types of goals served different purposes.

A selection of aspects (goal, purpose, audience, LCA method characteristic, suitable TRL) were compared between the three goals of the LCA study, see Table 2. The table shows that the different goals and purposes of each goal, aimed toward different subsets of the project members, correspond to different major method characteristics in the LCA study. This example illustrates how the goals of an LCA study influenced the method choices. Moreover, the TRLs when the analysis would fit are further in the future than the stage the development was in at the point of delivery of this LCA study, and therefore there were different levels of uncertainty in the analyses performed. As the assessed technology was at TRL 4-5, goal 1 fits well with this context. Furthermore, the

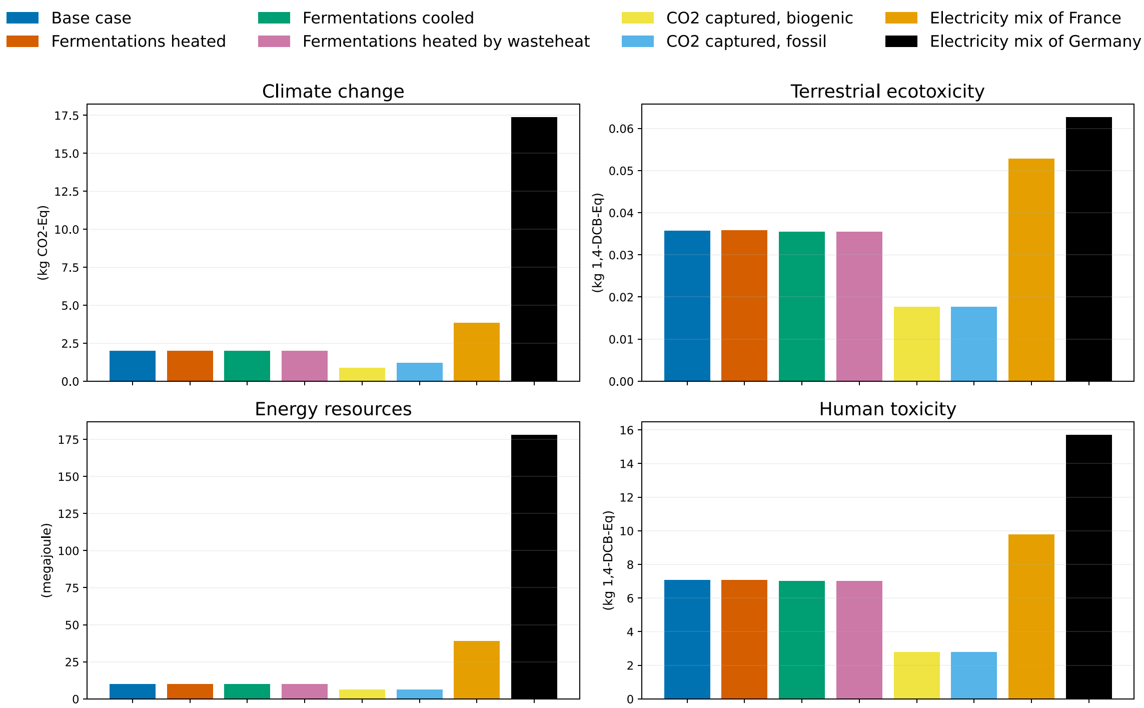

FIGURE 5
Scenario results for the four chosen impact categories.

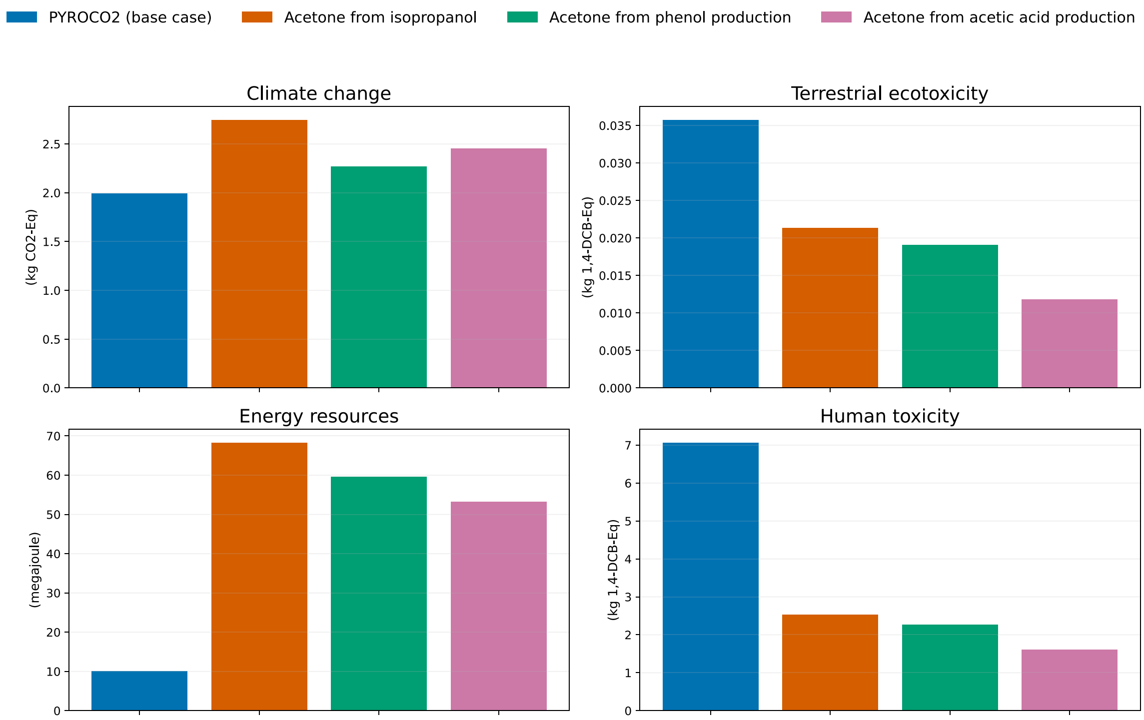

FIGURE 6
Comparison of PYROCO$_2$ acetone (base case) to alternative acetone products, for the four chosen impact categories.

assessed system was modeled at TRL 7 and the LCA study could therefore inform (based on simulations and assumptions) on goal 2. However, TRL 9 was not projected in this study and therefore goal 3 can only be speculated on.

3.5.1 Goal 1

The focus on the foreground system and simulated data for future process design in this LCA study allowed the identification

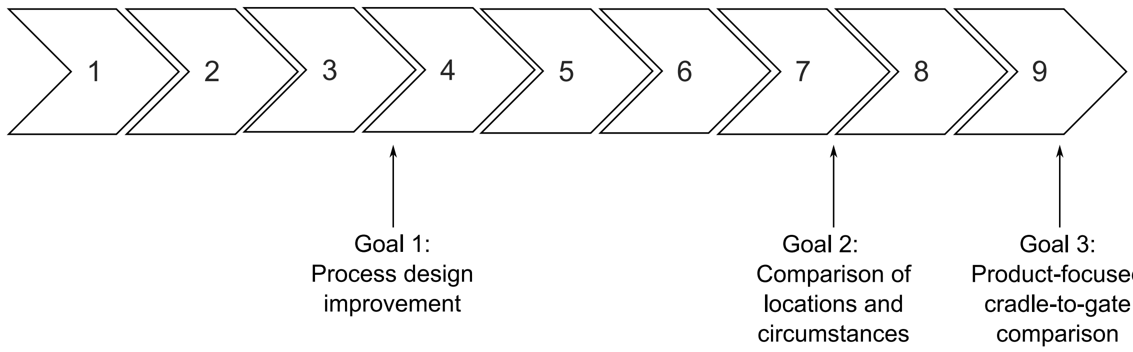

FIGURE 7
The types of goals identified in this study in relation to TRLs where the analysis would fit.

TABLE 2 Aspects of the LCA study compared for the three goals of the LCA.

Aspect	Goal 1	Goal 2	Goal 3
Goal	Identify hotspots	Explore scenarios	Compare to current acetone on the market
Purpose within the project	Improve process	Consider possible locations	Inform prospective investors
Audience	Technology developers	Industrial partners	Market managers
LCA method characteristic	Detailed modeling of the foreground system	Varying of chosen parameters	Comparing to reference values from database
TRL (when the analysis would fit)	4	7	9

of environmental hotspots in the processes within the control of the technology developers in PYROCO$_2$ and can therefore inform on possible improvements in future designs or aspects to be aware of when choosing future suppliers for feedstocks. However, the hotspot identification was limited by the knowledge about the future process and thus can only indicate approximately which processes will be the hotspots in a future system. Only including the PYROCO$_2$ process itself in the foreground system also limited the analysis as the upstream and downstream processes were not investigated. The processes preceding the production of CO_2 could be included in another type of LCA study, from the perspective of the emitter, for example a cement plant. The processes succeeding the PYROCO$_2$ process could be included in another LCA study looking into what happens with the acetone produced, how it is used and where it ends up. These LCA studies would give other perspectives on the same system, within the same research project.

3.5.2 Goal 2

The exploration of scenario-based changes in environmental impact within this LCA study focused on parameters that would likely vary at different industrial sites and could inform industrial partners about how the environmental impacts could change under different circumstances. The scenario construction was, however, constrained by limited modeling choices for the background system, such as using database-data for electricity mixes of different countries. The scenarios were limited to a few cases (a few alternatives for heating, CO_2 source and electricity mix) and other LCA studies could be done to look more into additional aspects of different locations, such as specific carbon sources and carbon capture technologies available, electrolysers at site or the water and heat utilities available. The presented LCA study can only answer how the impacts change when a few parameters vary, not which of all the possible locations will be the best.

3.5.3 Goal 3

The inclusion of comparisons to conventional alternatives in this LCA study, aimed at providing environmental data for market managers to communicate to potential investors. This comparison was limited by relying on current database data but still informative to the market managers as it shows that the process seems to be, at TRL 7, in the same range as current alternatives on the market. Database data was used since it is out of scope for the project to investigate the conventional alternative production routes. In the future, the current conventional alternatives would most likely change, e.g., to more renewable production routes. To compare a future PYROCO$_2$ acetone to future renewable acetones would be another type of LCA study with a different purpose and goal. This would require thorough investigation of new and old processes and their expected future developments. The presented LCA study can only give approximate comparisons to the available database data, not answer if the PYROCO$_2$ acetone will be better than the other alternatives on the market, now or in the future.

In summary, the three different goals have their limitations and were addressed in different ways in the presented LCA study, for the different actors in the PYROCO$_2$ project. Although they could be addressed in three separate studies at different points in time, the three goals were included in this study to accommodate the different actors and their knowledge needs in the PYROCO$_2$ consortium at the current stage of development.

4 Discussion

In this section, the LCA results are discussed with focus on the uncertainties related to the LCA study. Furthermore, the goals of the assessment are examined, exploring how they influenced the LCA process and highlighting the differences in goal types. Lastly, the key methodological choices made and not made in the LCA study are discussed.

4.1 Discussion of LCA results

In line with previous research on CCU using bioprocess technologies (e.g., Griffin and Schultz, 2012; Acharya et al., 2015; Dürre and Eikmanns, 2015; Liew et al., 2016; Teixeira et al., 2018; Köpke and Simpson, 2020; Fackler et al., 2021; Agrawal et al., 2023), the current LCA results indicate that, under certain conditions, this technology may offer a viable pathway to reduce climate change impacts and decrease fossil fuel dependency. However, these previous studies only speculate on potential carbon savings but do not present any LCA studies. The specific case of production of acetone through fermentation has earlier been explored and tested in one study of another process, claiming it has a negative carbon footprint confirmed by an LCA study (Liew et al., 2022). However, our LCA study can not confirm that the technology would result in reduced emissions. Furthermore, negative emissions can only be achieved when capturing and permanently storing carbon emissions of biogenic or atmospheric origin (IPCC, 2018). In the presented LCA study, the carbon used is treated as a feedstock and not as a negative emission, and no credits were given for uptake or storage of the carbon in the acetone produced to comply with the IPCC definition. In the LCA study by Liew et al. (2022), credit was taken for uptake of emissions and thus the results are not comparable to the results of our study. Moreover, it is not possible to compare other methodological details as these were not reported in the article by Liew et al. (2022), or in the addendum (Liew et al., 2025).

The LCA results are uncertain but give indications of the environmental impacts of a future demonstration plant. The results indicate that the environmental impact is primarily influenced by the choice of CO_2 and electricity used, while other factors like heating or cooling demand of the fermentations have minimal effect. This means that small changes in the design of the fermentation processes should not drastically affect the overall environmental impacts. However, these results are based on estimations and it is also uncertain what will be emitted through the off-gases and wastewater leaving the plant, or how these waste streams will be treated. Hence, there is a possibility that the design and future decisions could affect these aspects and influence the environmental impacts of the system.

Despite the uncertainty due to the early technology readiness level (TRL 4-5) of the assessed technology, the main take-aways can still inform future development. Since the assessment is based on an ideal, probable future design of the system, the future real demonstration plant will most likely not be exactly as the one assessed here. However, this LCA study informed about the aspects to consider to reduce the environmental impacts of the system when it is implemented in the future. Hence, this LCA study fulfills only its purpose to provide information and learnings about the environmental perspective on the PYROCO$_2$ process, for the PYROCO$_2$ consortium. The purpose of informing the consortium was addressed by the internal report delivered and the presentation and discussion of flowcharts of the system and graphs of environmental impacts. Furthermore, the consortium was informed about possible environmental impacts for the three specific goals investigated. However, these questions can not be answered with certainty.

4.2 Discussion of goals with the LCA study

We recognize that the investigation of the three goals defined in the presented LCA study are not enough to fully answer the questions posed in technology development. The LCA results only informs the project consortium about possible environmental impacts under certain circumstances. Furthermore, the goals also address different actors to different extents (see Table 2), and would be more applicable at different stages of technology development (see Figure 7). Hence, more LCA studies are needed on the PYROCO$_2$ technology, to address the questions in this LCA study further and in more detail but also to address other questions not yet posed.

There are many possible other types of LCAs that could be done on the same system for other purposes. For instance, the hotspots identified in the current LCA study could be further investigated. A future LCA study on this system could investigate more specific CO_2 sources and the capture technologies needed, to guide a decision regarding reducing the environmental impact of this hotspot. A different type of study could expand the modeled system beyond the factory gate to investigate the impacts of the full life cycle of the products. A future study could explore the production routes to different chemicals, fuels and materials that could be produced from the acetone produced in the PYROCO$_2$ process. Another type of LCA study could forecast future systems and environmental impacts further in the future. In a future study, this could be done for different TRLs and for different time scales, e.g., when the implementation of an industrial-scale plant of the PYROCO$_2$ process can be predicted.

The three goals with the current LCA study can be detected as types of LCA studies identified in previous works. We recognize some of the roles identified by Sandin et al. (2014) in this completed LCA study. Through the delivered report to the European Union, the LCA has one role to fulfill a requirement (to have an LCA study conducted). Through the hotspot analysis and scenario assessment (goals 1 & 2), the LCA can have the role to guide technical R&D. However, goal 3 to compare to market alternatives is not recognized in any of the roles identified by Sandin et al. (2014). Nevertheless, we do find that this goal relates to the use of LCA for comparison to incumbent technologies identified by Bergerson et al. (2020), concerning emerging technologies introduced into mature markets. As the PYROCO$_2$ process is an emerging technology introduced into a mature market, this use fits well.

4.3 Discussion of methods

The methods chosen in the LCA study performed shaped an LCA study aimed to be meaningful to the project members of PYROCO$_2$. As can be seen in Table 2, different LCA method characteristics correspond to addressing knowledge needs of different actors involved in the project. Hence, the chosen scope definitions are not universal recommendations to all LCA practitioners and the results are not transferable to other applications such as other projects or policy-makers. However, the methods utilized for defining the goals and scopes of the LCA are recommended for other LCA practitioners. These include discussing the LCA study with project members and defining a scope for the specific purposes identified as most important for project members at their current stage of development.

Although this LCA study assessed a technology currently at TRL 4-5, but simulated and modeled at TRL 7, data was not forecasted into the future. Neither was an industrial plant at TRL 9 set in a future background system assessed, as often recommended for prospective or ex-ante LCA (e.g., Arvidsson et al., 2017; Buyle et al., 2019; Cucurachi et al., 2018; Thonemann et al., 2020). However, scaling up uncertain data and putting it in a future background system would not be useful for the goals of the presented LCA study. The goal of the PYROCO$_2$ project is to reach the scale of a pilot plant (TRL 7). Hence, simulating data on further assumed developments far into the future (e.g., TRL 9) would not directly support the project at its current state in regards to the questions posed in the current LCA study. However, a future industrial scale could be investigated in another LCA study with a different goal for a different purpose, e.g., to investigate what the future impacts of an industrial plant could be given a certain path of development.

The expanded and explicitly explained defined goals, based on the review by Nyqvist et al. (2025), in the presented LCA study significantly enhanced the goal and scope definition and guided the reporting and analysis of the results. This separation proved useful, facilitating a clear scope definition and presentation of LCA results linked to the goals. The purpose of the assessment and the three specific goals were explicitly reflected in the scope definition as well as the results and analysis of the article. For example, the choice of system boundaries and functional unit focused the LCA study on the acetone production instead of the whole CCU system, to aid the purpose of informing specifically the project consortium developing the PYROCO$_2$ process. Separating the goal from the scope in this completed LCA study allowed for a thorough analysis of the purpose of the LCA and helped characterize the performed LCA study. This approach is recommended for others conducting LCA studies and should be considered in guidelines describing how to perform LCA studies.

5 Conclusions

This study aimed to analyze how well an LCA study provides environmental insights to the technology development process in the PYROCO$_2$ project. The goal and scope were defined to address the knowledge needs of the actors in the project, which shaped an assessment specific to the PYROCO$_2$ project consortium's current needs. Rather than extrapolating to a hypothetical future industrial system, the assessment focused on a near-term design planned for implementation at demonstrator scale, reflecting the decision context of the project. The LCA study presented had several roles in technology development, through its three distinct goals with the assessment. The three goals within the same study demonstrate that the LCA method can be used for various purposes and how the goals affect the LCA study. This also highlights the importance of defining the goal clearly in order to purposefully design an LCA study.

Despite the limited data and knowledge about the future demonstrator plant, the LCA study informed technology development at its current stage. The LCA results showed that the PYROCO$_2$ process could be a carbon-reducing and resource-saving technology, compared to existing conventional alternatives. However, the results also showed that there could be trade-offs with impacts of ecotoxicity and human toxicity. Furthermore, the impacts could also increase depending on the electricity mix used. Given the environmental hotspots identified in the presented LCA study, efforts to reduce the overall environmental impact of the PYROCO$_2$ process should prioritize optimizing the choice of electricity and CO_2 sources. Furthermore, these effects could be explored further in future work, such as investigating different carbon capture or electrolysis technologies in more detail. Future work will also take into account changes in design of the process under development, and if available incorporate data from measurements.

The analysis of the LCA study performed showed what the presented LCA study addressed but the answers are not certain and there are remaining questions related to technology development. The stages of development where the analysis for each of the three goals in this LCA study would fit are further in the future than the project has progressed. Still, as actors within the consortium expressed interest in these types of analyses, some information on these questions was communicated through the LCA study. It is evident that additional LCA studies on the same system are necessary to deepen our understanding and support informed decision-making in technology development.

Further research is needed on how to design LCA studies to better support technology development. In the case of emerging carbon capture technologies, LCA plays an important role in assessing decarbonization potential. To effectively inform and support technology development, LCA studies must be meaningful for technology developers. Future research should therefore focus on improving goal and scope definition, as this study has demonstrated how goals, purposes and intended audiences shape the application of LCA in technology development.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

EN: Writing – review & editing, Investigation, Methodology, Visualization, Writing – original draft, Conceptualization, Formal analysis. MJ: Writing – review & editing, Funding acquisition, Supervision.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2026.1770000/full#supplementary-material

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