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THE ROLE OF CARBON CAPTURE AND UTILISATION IN THE PATH TO NET ZERO:

RECOMMENDATIONS FROM THE CO2MOS PROJECT

Prepared by COZMOS project partners

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EXECUTIVE SUMMARY

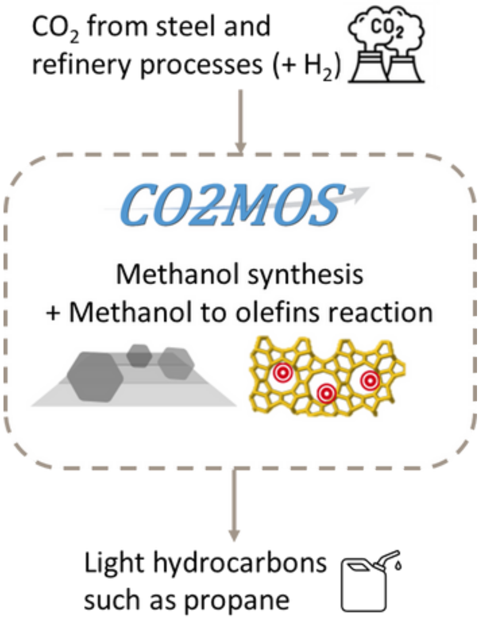
To limit global warming to below 1.5°C, global net anthropogenic CO_2 emissions need to reach net zero around 2050. There are several ways to reduce global CO_2 emissions, such as improving energy efficiency, increasing renewable energy production, electrification, using high energy density molecules as an alternative to fossil ones, and capturing CO_2 from power plants and other emission points[1-2]. For the first time, the Intergovernmental Panel on Climate Change, in its 6th Assessment Report released in 2022[3], recognised Carbon Capture and Utilisation (CCU) as one of the solutions to mitigate climate change. Several forecasts for the chemical industry show CCU will contribute 10-30% of the demand for embedded carbon in 2050[4].

Carbon Capture and Utilisation (CCU) refers to the capture and conversion of CO_2 into products, e.g. fuels, chemicals and building materials. Some of the products that cannot be used directly as a fuel, can be used as intermediates to produce other fuels such as diesel, gasoline and aviation fuels that are compatible with existing infrastructure. The substitution of fossil-based products by CO_2-based ones reduces CO_2 emissions, even if the technology is not emission-negative by itself and if the CO_2 is emitted after the combustion[5].

COZMOS is a Horizon 2020-funded project that aims to provide breakthrough technology for converting CO_2 to fuels. The project has developed an innovative catalyst that overcomes the thermodynamic limitations inherent in using CO_2 for these value-added products. COZMOS, a 4-year programme, was launched in 2019 and is due to finish in October 2023, involving industrial partners from the steel, refining, chemical and engineering sectors, research and technology organisations and universities.

The COZMOS process can produce CO_2-based propane. The propane market is expected to continue growing. Thus, if propane could be derived from CO_2, this could reduce fossil fuel use. Propane is a fuel currently found in lighters, aerosol deodorants, propane gas fireplaces, propane cooking stoves, grills, barbeques and outdoor kitchens, and camping and caravanning gas. The COZMOS project has tested the catalyst at pilot plant scale in a refinery setting, conducted a Life Cycle Assessment (LCA) and techno-economic assessment of the technology, and assessed the public's acceptance of CCU technologies.

This paper will highlight recommendations arising from the COZMOS project for CCU to play a meaningful role in the transition to net zero. It will cover the main benefits of implementing CCU, the current CCU policy landscape and recommendations from the COZMOS project for policymakers, university/researchers and LCA practitioners, separately. The next section summarises the key recommendations.



RECOMMENDATIONS FOR POLICYMAKERS

1. Address decarbonisation and defossilisation of all sectors that require carbon as a feedstock. Decarbonisation implies an elimination of carbon from an economic activity or industrial process, it describes the transformation of industries, particularly the energy sector, to cut CO_2 emissions and eventually reach "net zero" and an emission-free society. Defossilisation involves becoming independent of fossil raw materials.
2. Consider the full carbon cycle and carbon ownership.
3. Introduce a feed-in transition for CO_2-based fuels.
4. Provide funding for universities and industry to collaborate and work on the technology bottlenecks and address the funding disconnect in funding for low and high technology readiness level projects.
5. Improve communication in order to increase the public awareness and acceptance of the technology.
6. Encourage the assessment of each CCU pathway and technology considering the full life cycle impacts.

RECOMMENDATIONS FOR UNIVERSITIES/RESEARCH INSTITUTIONS

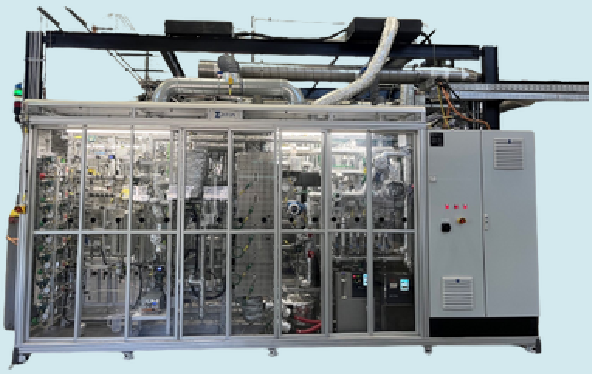
1. Identify which technologies and products would be most useful to society, in collaboration with industry.
2. Improve the current production of hydrogen and the energy efficiency of water electrolysis.
3. Focus on increasing the technology readiness level of these technologies so they become commercially available.

RECOMMENDATIONS FOR LCA PRACTITIONERS

1. Positively recognise the benefits of reusing CO_2 and the substitution of fossil carbon.
2. Account for benefits between CO_2-producer and CO_2-user.
3. Consider the carbon footprint of the CO_2 supply.

COZMOS PILOT PLANT

COZMOS catalyst



COZMOS pilot plant hosted at Tüpraş, in Izmit, Turkey.

BACKGROUND INFORMATION

INTRODUCTION TO CCU

Carbon Capture and Utilisation (CCU) involves capturing CO_2 from industrial processes or directly from the atmosphere and then utilising it for various applications, such as making synthetic fuels, chemicals, and building materials. This process reduces greenhouse gas emissions and creates value from CO_2, which would otherwise be emitted.

A wide range of chemicals and materials can be derived from CO_2, for example, solvents, plastics, fibres, and synthetic rubber. It can also be used in the process of making concrete, asphalt, and other building materials.

The CCU process offers an opportunity to create value from CO_2, which can have economic benefits for industries that use it as a raw material. CCU is an emerging field with enormous potential to contribute to the transition to a low-carbon economy, and it is receiving increasing attention from policymakers, scientists and businesses worldwide.

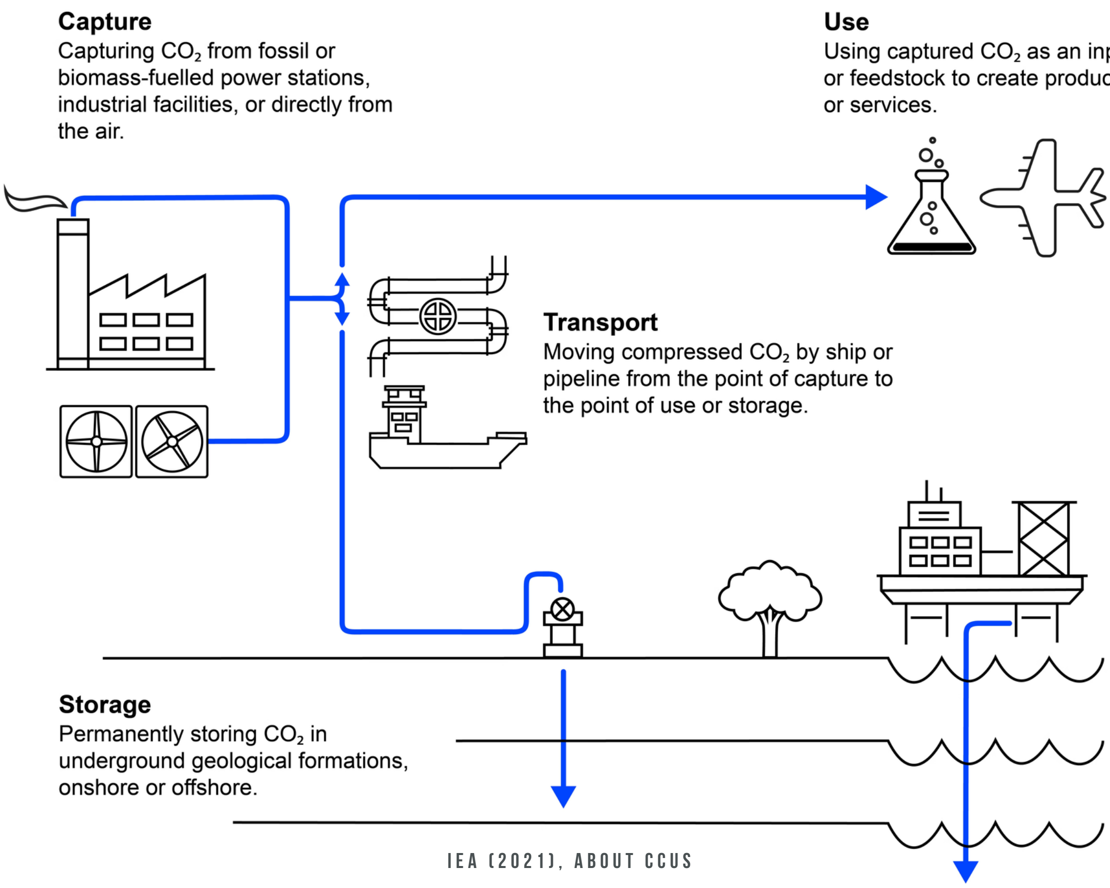
CCU vs CCS

CCU and Carbon Capture and Storage (CCS) are two technologies aimed at mitigating climate change by reducing greenhouse gas emissions. Often, CCS is used interchangeably with the term CCU[6]*. Grouping both terms does not reflect their different approaches.*

CCS focuses on capturing carbon dioxide and storing it in underground geological formations, preventing its release into the atmosphere. CCS is widely recognised as supporting decarbonisation, allowing continued use of fossil-fuelled power plants whilst reducing CO_2 *emissions*[7–8]*. On the other hand, CCU aims to capture carbon dioxide and convert it into usable products, such as building materials or synthetic fuels, thereby providing an opportunity to create value from* CO_2 *emissions. CCU also reduces the use of fossil carbon (e.g., coal, natural gas) for these products (also known as "defossilisation").*

While CCS and CCU can potentially reduce carbon emissions, the two approaches have different benefits and limitations. The long-term storage of CO_2 *underground is an end-of-pipe solution. Additionally, the deployment of CCS is influenced by a range of policy and regulatory factors, which vary across different regions and countries. In some regions, the lack of a clear policy framework or regulatory incentives for CCS deployment can limit its adoption. In contrast, CCU has the potential to create value by using* CO_2 *as a feedstock, but the technology is still in its early stages*[9]*.*

CCU is a complement to CCS for large-scale emission reductions, both will play a role in the transition to a low-carbon economy[10]*. Ultimately, both CCS and CCU are important tools in the fight against climate change, and their deployment will depend on each country or region's specific needs and circumstances.*



IEA (2021), ABOUT CCUS

BENEFITS OF IMPLEMENTING CCU

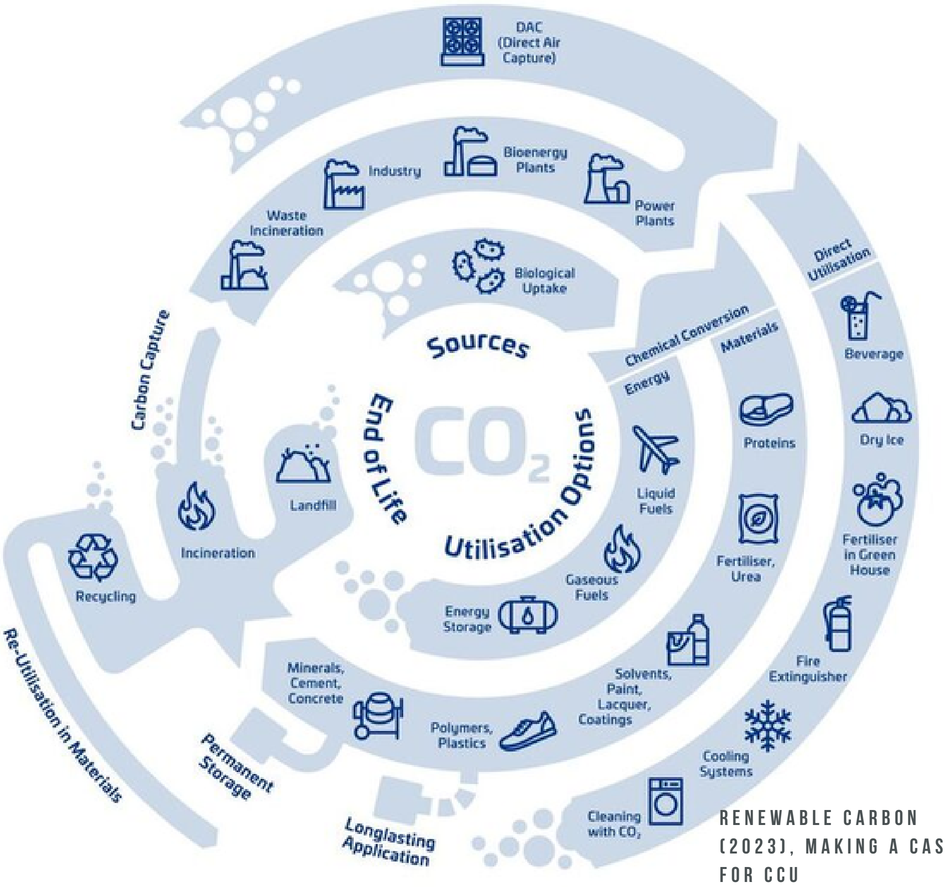
A SOLUTION FOR HARD-TO-ABATE SECTORS

Significant efforts have been made to reduce global CO_2 emissions across all sectors. These include improving process efficiencies, electrification and using non-fossil feedstocks where possible. However, the emission reduction potential of process efficiency improvements is insufficient to reach Net Zero. Similarly, electrification is not possible or feasible in hard-to-abate sectors (e.g. steel, petrochemicals, aluminium, cement and fertilisers). Heavy industries account for over 20% of global CO_2 emissions today[11]. CCU could be a cost-effective approach to decarbonise cement, iron and steel and defossilise chemicals manufacturing.

Many applications will still require high energy density molecules. These include shipping, aviation, feedstock for chemistry and storage of renewable energy. Fuels from biomass or waste streams can be used as drop-in alternatives in existing systems. However, contrary to CO_2, there is a limited amount and availability of biomass and waste feedstocks. Within the transport sector, CO_2 represents one of the few feedstocks for sustainable fuels for long-distance transport, particularly aviation.

Green hydrogen is another high energy density alternative. Global hydrogen use is forecast to increase exponentially in the near future. In the Sustainable Development Scenario, the International Energy Agency predicts a sevenfold increase by 2070[12]. The majority of the low-carbon hydrogen production is from water electrolysis, but it requires significant amounts of renewable energy. In 2070, 40% of low-carbon hydrogen production is predicted to come from fossil sources, with carbon capture[12]. CCU can support the rapid deployment of low-carbon hydrogen production. This production can be quickly scaled up to support the growing needs from transport, industry and buildings. However, hydrogen is challenging to transport and store, and its introduction into existing infrastructure is limited, up to 20%vol can be blended into the gas pipeline network without modifications. CCU also supports the upscaling of renewable energy, as it enables the storage of surplus energy in energy carriers, such as Liquified Petroleum Gas (LPG) which are easier to store and transport than hydrogen.

Due to these limitations, there will be significant residual CO_2 emissions after different decarbonisation strategies have been implemented[13], and some sectors will continue to emit CO_2. Even in a low-carbon European economy, one-fifth of today's CO_2 could still be produced, around 346 Mt of potential feedstock CO_2[14]. **CCU represents an alternative for the production of high energy density molecules. However, it should not use CO_2 from sources where low-carbon alternatives are possible, only residual emissions from hard-to-abate sectors.**



RENEWABLE CARBON (2023), MAKING A CASE FOR CCU

CCU IS ALIGNED WITH A CIRCULAR ECONOMY

While CO_2 emissions must be reduced to reach climate mitigation targets, a holistic system approach is needed to make manufacturing more sustainable. **Other sustainability issues need to be considered, such as global supply chains, circularity of materials, reusability and recyclability.** A circular economy is complementary to reducing emissions, as it could avoid the negative consequences of focusing exclusively on CO_2 emissions and having a "carbon tunnel vision" [16].

Continuing business as usual and emitting carbon into the atmosphere is no longer an option. However, the current strategy proposed in many sectors involves the capturing and permanent storage of CO_2. This approach can be equated to landfill in a linear economy. Finding sustainable carbon sources will be key for circular and sustainable manufacturing. The capture and utilisation of CO_2 as a feedstock from an emission point source supports this idea. This approach both reduces CO_2 emissions and promotes a circular economy. Implementing CCU can support in closing the material loop. Reusing the CO_2 molecule a single time could result in up to 50% emission reduction, as it would prevent a fossil molecule from being extracted from the ground.

It is important to emphasise that CCU can only provide these benefits when powered with renewable energy. Most CCU processes need large amounts of renewable energy, directly or indirectly, in the form of green hydrogen. Using renewable energy for CCU is a sensible application in the chemicals and materials sectors, aviation, and shipping. As for these applications, there are no alternatives to using carbon in the molecules or viable carbon-free alternatives.

CONTINUED USE OF EXISTING INFRASTRUCTURE

CCU technology can be retrofitted to existing emission points such as power and industrial plants. It would enable the continued use of oil and gas pipelines, as well as liquified natural gas (LNG) terminals and tankers. CCU could provide the basic platform chemicals to the chemical industry[15]. Power and industrial plants could otherwise emit 600 billion tonnes of CO_2 over the next five decades[6]. When the CO_2 is captured and utilised, the CO_2-based products can be easily introduced into the existing infrastructure, without the need to fund a new infrastructure system. Additionally, it would reduce dependency on imports for these products, strengthening energy security.

CCU CAN SUPPORT DECARBONISATION, BUT THERE IS NO SINGLE SOLUTION TO THE PROBLEM

A range of complementary technologies will be needed to reach climate change targets and cover end-users' needs. CCU represents a robust solution for residual emissions from hard-to-abate sectors.

CURRENT CCU POLICY LANDSCAPE

CCU is an emerging field with large potential to contribute to the transition to a low-carbon economy, and it is receiving increasing attention in recent years. This section will provide a short overview of legislation impacting CCU in Europe, the UK and the USA.

The following policies and initiatives are in place or under discussion impacting CCU in the EU:

- The Emission Trading Scheme (ETS) considers captured CO_2 from processes as "emitted". The only exception is when the captured CO_2 is permanently stored. The current EU ETS scheme does not account for any climate benefits from CCU. However, the latest revision will allow for GHG emission reduction when CCU is applied for mineralisation or products that provide long-term storage, such as construction materials[17].

- The Net-Zero Industry Act[18] attempts to reduce import dependence on critical technologies. It presents CCUS as a key "net-zero technology" and makes provisions for supporting CCUS technologies below a TRL of 8.

- The Renewable Energy Directive (RED II) includes targets for Renewable Fuels of Non-Biological Origin (RFNBO) and considers Recycled Carbon Fuels (RCF) for emission reductions in the transport sector. RFNBOs are fuels such as green hydrogen, methanol or e-fuels produced with renewable energy, providing at least a 70% reduction in GHG emissions. RCFs are fuels produced from either a waste stream of non-renewable origin or from waste and exhaust gases of non-renewable origin (such as CCU of industrial point sources).

- The Fuel EU Maritime[19] and ReFuelEU proposal[20-21] also include targets for RFNBOs for shipping and aviation, respectively.
- The Carbon Border Adjustment Mechanism (CBAM) addresses carbon leakage and may incentivise CCU products with long-term storage[22].
- Within the Science-Based Targets initiative (SBTI) and depending on the permanence of storage and allocation of the savings, CCU can be classed as an emission reduction or Beyond Value Chain Mitigation[23].
- In March 2023, the European Union approved the use of e-fuels in cars as an exemption to its previous ban on internal combustion engines from 2035. This change sends a clear signal that synthetic fuels made from captured CO_2 can support the defossilisation of the transport sector.
- More generally, there is support for creating a more circular economy, to which CCU can contribute. The European Green Deal, launched in 2019, considers the production of products that can be repaired, recycled and re-used[24]. The Circular Economy Action Plan proposed in 2020 aims to "make sustainable products the norm in the EU, ensure less waste, focus on the sectors...where the potential for circularity is high"[25]. The EU has also outlined its plans for scaling up the manufacturing of crucial clean technologies to bolster the bloc's competitiveness and reduce its reliance on imports from China.

In a UK context, the UK Government launched a set of calls to investigate CCUS in the UK[26-27]. However, the announcement of the sixth Carbon Budget in April 2021 stated that "setting this budget is about the government's ambition to cut emissions, rather than announcing specific policies that will deliver that reduction in emissions. We will bring forward policies to meet Carbon Budgets"[28]. **It will be key to set specific policies to drive change towards decarbonisation and defossilisation, and reduce dependence on fossil fuels.** More recently, the UK government pledged to invest up to £20bn from its spring budget 2023 to support CCUS, as part of its Net Zero Innovation Portfolio CCUS Innovation Programme[29]. It is expected to deploy two industrial CCUS clusters by the mid-2020s (track 1) and a further two by 2030 (track 2) to achieve its CO_2 capture goal. In late 2021, it selected the HyNet and East Coast Clusters for track 1 development.

In the USA, the Inflation Reduction Act has extended the tax credits for direct air capture[30], which complements funding in the Bipartisan Infrastructure law for CCUS[31], including $2.5 billion for the *Carbon Capture Demonstration Projects Program* and $937 million for *Carbon Capture Large-Scale Pilot Programs*. More recently, President Biden announced a $100 million grant program to jumpstart carbon recycling. It will cover technologies like CCU that transform waste emissions into valuable resources[32].

Recent policies have started to identify CCU as a key decarbonisation technology. However, current policies are lagging and are rather fragmented. The treatment of CCU as a technology is inconsistent across policies. More consistency and ambition are needed to deploy this technology. The strong focus on net zero tends to disregard the future needs for carbon as feedstock and only focuses on zero-carbon energy and carbon storage of residual emissions. **Adequately accounting for the climate benefits of CCU would incentivise this valuable technology and provide a clear regulatory framework for deployment.** This would reduce investment uncertainty and accelerate commercialisation. It is recognised that the cost of CO_2-based products will be higher than fossil-based products, so will need subsidies and incentives to regulate the costs to the end-user. This investment is expected to come initially from governments.

The learnings from the COZMOS project have been distilled into a number of recommendations for policymakers, universities and research institutions and LCA practitioners. The recommendations are shown in the following pages.

RECOMMENDATIONS FROM THE COZMOS PROJECT

RECOMMENDATIONS FOR POLICYMAKERS

In order to reduce emissions and promote a circular economy across all sectors, holistic thinking has to be implemented into policies. Recognising that a mix of technologies will be needed to reach Net Zero is required. The combination of hydrogen and electrification is insufficient to complete the transition, and alternative technologies will be needed. While the focus of policies should be on decarbonising as much as possible, developing CCU technologies in parallel as a solution for residual emissions will help to achieve our climate targets.

1. More specific policies are needed, **focusing on improving circularity** and including CCU as an important tool to support this.

2. Introduce policies that **address decarbonisation and defossilisation of all sectors that require carbon as a feedstock**, such as the chemical and materials sector, which will continue to require carbon as a feedstock. Decarbonisation implies an elimination of carbon from an economic activity or industrial process, it describes the transformation of industries, particularly the energy sector, to cut CO_2 emissions and eventually reach „net zero" and an emission-free society. Defossilisation involves becoming independent of fossil raw materials.

3. Another aspect to be considered in policies is the **full carbon cycle and ownership**. Moving towards a carbon custodianship model would increase the public's awareness of the carbon origin and destinations. It would also help increase consumer responsibility for purchased energy and goods, and indirectly reduce emissions via a behavioural change. A sense of responsibility from individuals and groups is required to ensure equity in society[33].

4. Any policies looking to support CCU would benefit from **introducing a feed-in transition**, where CO_2-based fuels and products are progressively incentivised while carbon-intensive fuels are disincentivised.

5. **Funding is required for universities and industry to collaborate and work on the technology bottlenecks**. And although funding exists to progress projects from low technology readiness levels (TRL), many projects are not reaching TRL 9. Long-term vision is needed to filter and funnel the projects as they progress in TRL; however, this is currently lacking. **There is a disconnect in funding for low TRL and higher TRL projects**, both in technologies and in the size of funding.

6. Currently, public awareness and knowledge of CCU is low, making the public sensitive to framing and bound to the agenda of communicators, whether it's to support or oppose a technology[34]. **Improving public communication and engaging with relevant stakeholders would increase the public awareness** of the technology and the transparency of CCU projects.

7. **Each CCU pathway and technology should be assessed considering the full life cycle impacts**, ideally including the entire supply chain and lifetime of the product. This would ensure that the technology is fit for purpose and would be adequate for tackling residual emissions and promoting a more circular economy.

RECOMMENDATIONS FOR UNIVERSITIES/RESEARCH INSTITUTIONS

1. In order to prioritise which technologies should be developed and progressed, it is key for universities to collaborate with both industry and governments. This collaboration will help **identify which technologies and products would be most useful to society** and work on finding solutions to the different technology and environmental bottlenecks. A knowledge transfer between disciplines and sectors is needed to develop these processes and accelerate their implementation.

2. One of the key bottlenecks for the COZMOS technology is the need for hydrogen in the feed. It is added to the feed to convert the CO_2 to propane. This significantly affects the economic and environmental performance of the process. **Improving the current production of hydrogen or improving the energy efficiency of water electrolysis would benefit the economic and environmental performance of CCU processes.**

3. According to the IEA, 75% of the emissions reductions needed will come from a range of technologies currently in development[35]. Further research can **increase the technology readiness level of these technologies** so they become commercially available. Universities have a key role to play in further developing these technologies.

RECOMMENDATIONS FOR LCA PRACTITIONERS

Life Cycle Assessments (LCAs) are invaluable tools to understand the broader implications of a technology beyond climate change, considering factors such as resource depletion. It helps to identify and mitigate unintended consequences, ensuring a holistic understanding of the impacts and benefits associated with a product or process.

The climate benefits associated with CCU will depend on several factors, like the source of CO_2 and energy for capture, the displaced product, and the retention of CO_2 in the final product. Utilising CO_2 does not necessarily reduce the climate change impacts. A robust life cycle assessment is needed to quantify the climate benefits of CCU. There have been several attempts at developing LCA guidelines for CCU[5-36], within the context of ISO 14044, but there are still gaps to be addressed for a robust LCA of CCU technologies. **A harmonised approach for accounting for the impacts of CCU technology would support in clarifying the benefits and incentivising the technology.**

The following are recommendations for LCA practitioners:

1. **Positively recognise the benefits of reusing CO_2 and the substitution of fossil carbon.**

Reusing carbon is an approach toward closing the anthropogenic carbon cycle and a circular value chain. Most studies consider the CO_2 reductions if the process emissions for the CCU process are lower than those from the extraction of coal, gas or oil and disregard the benefits of substituting a fossil feedstock. In line with a life cycle approach, expanded system boundaries, cradle-to-gate or cradle-to-grave, should be used to account for the benefit of reusing the CO_2, and these should be clearly communicated. There is a net carbon benefit to using CO_2 twice before releasing it into the atmosphere.

2. **Accounting for benefits between CO_2-producer and CO_2-user.**

The direct emissions are reduced when the CO_2 is captured at an emission point source. There will be additional GHG emissions from the capture and utilisation process. The CO_2 becomes a co-product of the original CO_2-emitting process. Additionally, when the captured CO_2 is utilised and converted into a value-added product, the CO_2-based product also becomes a co-product from the original process. This attribution of credits between the CO_2-producer and the CO_2-user is complex. Depending on how the LCA system boundaries are set, there will be different discussions on how to allocate the environmental benefits of the overall process. When considering the CO_2-producer, the carbon footprint associated with the captured CO_2 becomes relevant. According to Müller et al.[14], the emissions associated with the feedstock CO_2 should be the difference between increased emissions and avoided emissions.

3. **Accounting consistently for the carbon footprint of the CO_2 supply will be key.**

The emissions reduction from CCU strongly depends on the choice of CO_2 source, as the CO_2 concentration and energy demand for capturing it will differ. CO_2 sources with a high concentration of CO_2 should be prioritised for CCU to optimise the energy used in the capture process. In previous studies, the carbon footprint of the captured CO_2 varied from strongly negative to strongly positive for the same emission point source[14]. This inconsistency is linked to methodological choices in the LCA studies; however, it is key that the carbon footprint of the CO_2 supply is correctly accounted for. Müller et al.[14] recommend adhering to physical relationships to assess the carbon footprint of the supply of CO_2. They refer to physical relationships as the marginal changes needed for adding CO_2 capture and transportation to existing operations and their associated GHG emissions. They recommend assessing the system-wide impacts using system expansion or product-specific environmental impacts with the substitution approach. Allocation by mass or economic value was discouraged as it would lead to suboptimal decisions.

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