# Harnessing potential of biological CO2 capture for Circular Economy

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# Executive summary

The CooCE (Harnessing Potential of Biological $CO_2$ Capture for Circular Economy) project was established to explore the integration of carbon capture and utilization (CCU) technologies into circular economy frameworks. Funded by the ACT initiative, CooCE focused on developing and piloting biological pathways for $CO_2$ conversion into three high-value products: biomethane, bio-succinic acid (bioSA), and polyhydroxyalkanoates (PHAs/bioplastics).

Project Objectives and Scope

CooCE aimed to bridge the gap between laboratory research and real-world application (TRL 4–6) through:

- Bio-CCU integration with renewable energy for biomethane production
- Bioconversion of sugar-rich waste and biogas into bioSA
- Microbial $CO_2$ fixation into biodegradable plastics (PHA)
- A robust integrated sustainability assessment (environmental, economic, social, and policy dimensions)
- Market replication strategies for broader CCU uptake

**Methodology and Technologies**

Three key technological pathways were developed and tested:

- Biomethane production via biological hydrogenation of $CO_2$ using surplus renewable electricity.
- BioSA synthesis, employing succinogenic bacteria that convert $CO_2$ and sugars into an industrially relevant bioproduct.
- PHA production, leveraging both chemolithotrophic and phototrophic organisms to generate bioplastics from $CO_2$.

**Sustainability and Socio-Economic Impact**

Imperial College London led an extensive sustainability assessment, incorporating:

- Life Cycle Assessment (LCA): Biomethane and bioSA showed promising $CO_2$ emission reductions under renewable power scenarios. PHA had higher emissions due to low yields and solvent use.
- Social Life Cycle Assessment (S-LCA): Thirteen indicators were assessed using stakeholder mapping, surveys, and the Social Hotspot Database. The analysis identified areas needing policy attention and social risk mitigation.
- Economic Assessment: All pathways faced cost challenges compared to fossil alternatives. Biomethane showed the highest readiness, while PHA needed significant process optimization.

- Integrated Sustainability Assessment (ISA): Pathways 1 (biomethane) and 2 (bioSA) were identified as more sustainable across multiple criteria, while Pathway 3 (PHA) showed limited feasibility without major improvements.

**Market Deployment and Replication**

The CooCE Sustain e-platform and a multilingual handbook were developed to support stakeholder engagement and dissemination. Training programmes reached over 100 stakeholders, highlighting the potential of CCU technologies in industrial decarbonization. A spin-off company is under consideration to commercialize the biomethane pathway.

**Key Outcomes and Recommendations**

- Policy: Tailored policies for CCU feedstocks, processes, and bioproducts are needed. Integration into existing energy and waste policies is crucial.
- Technical: Improvements in energy efficiency, product yields, and solvent substitution are vital, especially for PHAs.
- Economic: Government incentives and industry partnerships are essential to de-risk investments and accelerate market uptake.

**Impact**

CooCE has demonstrated that integrating CCU with circular economy principles is technically feasible and socially acceptable, with strong potential for decarbonizing critical sectors. Its success hinges on supportive regulatory frameworks, financial incentives, and continued research and innovation.

# 1. Background

Global warming and climate change are recognized to be largely driven by greenhouse gas (GHG) emissions, particularly carbon dioxide ($CO_2$) from fossil fuel consumption and land-use changes. While reducing overall emissions remains essential, additional strategies that capture and utilize $CO_2$, turning a waste product into a resource, have gained momentum. Carbon capture and utilization (CCU) mitigates environmental impact and reduces reliance on fossil-derived materials by producing valuable chemicals or fuels from $CO_2$. In this context, the CooCE project has been supported by Accelerating CCS Technologies (ACT), an international initiative designed to speed up the development of carbon capture, storage, and utilization solutions. ACT unites national funding agencies to pool resources, encourage cross-border research, and enhance the commercial viability of CCS/CCU technologies, thereby helping projects like CooCE bridge technological gaps and accelerate their pathways to implementation.

One promising CCU avenue involves biogas, which is generated through the anaerobic digestion of organic wastes and typically contains 53–70% $CH_4$ and 30–47% $CO_2$. Although the $CO_2$ in biogas does not increase net GHG emissions, it can hinder fuel applications by lowering the combustion efficiency. Upgrading biogas to high-purity biomethane (>95% $CH_4$) thus improves its versatility and permits direct grid injection or use as transport fuel. Concurrently, $CO_2$ removed during upgrading can serve as a substrate for microbial production of high-value compounds. For instance, hydrogenotrophic microorganisms can consume $CO_2$ and $H_2$ (from surplus renewable electricity) to form $CH_4$, offering a biological Power-to-Gas solution under milder conditions than thermocatalytic methods. Studies demonstrate that advanced reactor configurations (e.g., trickle-bed reactors) and packing materials can alleviate mass transfer constraints, facilitating continuous or intermittent hydrogen supply.

Beyond generating renewable methane, $CO_2$ assimilation by specific microbes can yield valuable biopolymers, most notably polyhydroxyalkanoates (PHAs). The bacterium *Cupriavidus necator* is well known for accumulating PHA (particularly poly(3-hydroxybutyrate), PHB) under chemolithotrophic conditions, although operational hurdles remain. Low gas solubility and explosion risks in $H_2$–$O_2$ mixtures pose engineering challenges for stable, large-scale production. Additionally, direct utilization of raw biogas streams for chemolithotrophic PHB production is still underexplored, particularly regarding the tolerance of *C. necator* to $CH_4$ and other minor gases. Further insights into transcriptional regulation and metabolic shifts from heterotrophy to autotrophy may unlock greater yields and process resilience.

Another route to bio-based plastics involves phototrophic microorganisms, such as *Synechocystis* strains, which use sunlight and $CO_2$ to synthesize PHB without expensive organic carbon feeds. In such cyanobacteria, nitrogen limitation or high light intensities can boost PHB accumulation, though balancing biomass growth and polymer synthesis remains challenging. Identifying high-producing strains, like *Synechocystis sp*. B12, and deciphering their genetic regulation can significantly improve productivity and reduce costs in large-scale photobioreactors (B12, 2023).

Meanwhile, bio-succinic acid (bioSA) production exemplifies another $CO_2$ utilization pathway. *Succinogenic* bacteria (e.g., *Actinobacillus succinogenes*, *Basfia succiniciproducens*) metabolize sugars in conjunction with inorganic carbon, capturing $CO_2$ into a four-carbon dicarboxylic acid widely used in the pharmaceutical, food, and chemical sectors. The addition of carbonates and manipulation of $CO_2$ partial pressure can enhance succinic acid yield, but the balance between productivity and by-product formation requires careful optimization. Further research aims to clarify how elevated $CO_2$ solubility and key enzyme activities affect overall carbon flux and selectivity.

Despite these advancements, technical and economic challenges persist. Gas–liquid mass transfer limitations, process safety in oxyhydrogen systems, and the cost of downstream processing can hinder scale-up. Moreover, many microbes tested in controlled laboratory settings have not been evaluated under real biogas conditions or varying $CO_2$ concentrations. Addressing these gaps is essential for designing robust, efficient CCU systems that simultaneously reduce emissions and generate marketable outputs, ranging from upgraded biomethane to bioplastics and bio-succinic acid. The growing impetus to integrate CCU with renewable energy, industrial symbiosis, and circular economy principles underscores the need for further research on reactor design, strain engineering, and process integration. By overcoming current bottlenecks, CCU technologies can help close the carbon loop and drive the shift toward more sustainable industrial and energy practices.

**General objectives**

The exploitation of CO2 capture, utilisation, and storage technologies (CCUS) in industrial applications faces significant challenges due to high investment costs and fierce international competition. In view of this, the CooCE project aims to accelerate CCUS adoption by inserting it in a circular economy framework, developing (TRL 4) and demonstrating (TRL 5-6) novel biotechnological platforms. The aim of the project is articulated in the following General Objectives related to specific work packages (WPs):

- To exploit synergies between bio-CCUS and excess renewable electricity to produce biomethane equivalent to natural gas (>95% CH4) and to develop and demonstrate the technology at pilot scale. (WP2)
- To improve the bioconversion efficiency of sugar-rich waste streams to bioSA (80% compared to results from first generation feedstocks) using biogas as a CO2 source, with concomitant biogas upgrading to biomethane (CH4>90%) and to demonstrate the technology at pilot scale. (WP3)
- To develop and optimize the process to produce PHA from CO2 using real gas streams achieving a CO2 capture of 2 kg CO2/kg biopolymer and to demonstrate the technology at pilot scale. (WP4)
- To evaluate the technologies by an integrated sustainability assessment using techno-economic, environmental, and social criteria with a full life cycle (LCA) and other methodology. (WP5)
- To accelerate the market uptake of the proposed CCU technologies by replicating to other CO2 intensive industries and sectors. (WP6)

Since the CooCE project officially commenced on October 7, 2021, but the Kick-off Meeting was held on November 29, 2021, all project activities have been considered to start from the latter date. Consequently, a two-month extension was granted to the Italian and United Kingdom partners (06/12/2024), while a six-month extension was allocated to the Danish partners (06/03/2025).

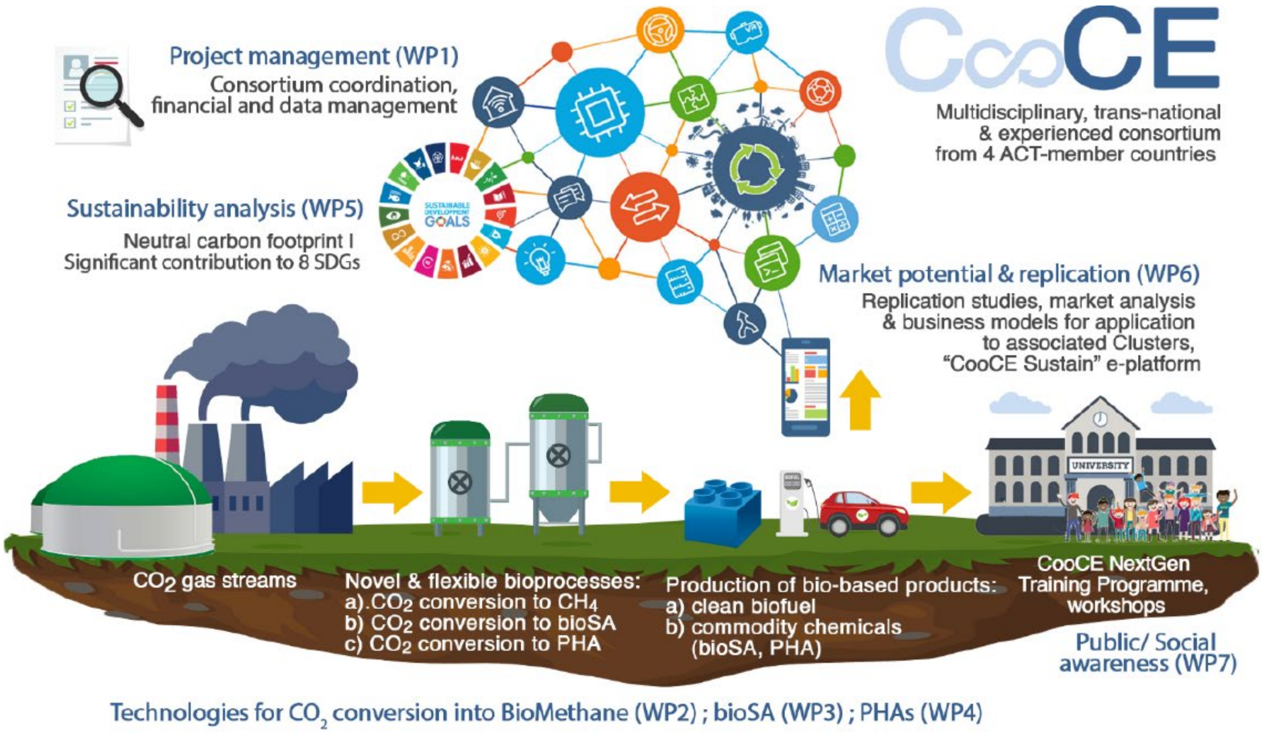



Figure 1. Overall concept of CooCE project.

CooCE was a multi-disciplinary trans-national team bringing together all the relevant skills and organizations needed to address the full extent of the challenge to capture CO2 from biogas and exhaust gases and develop new methods of utilizing the CO2 streams (Figure 2).

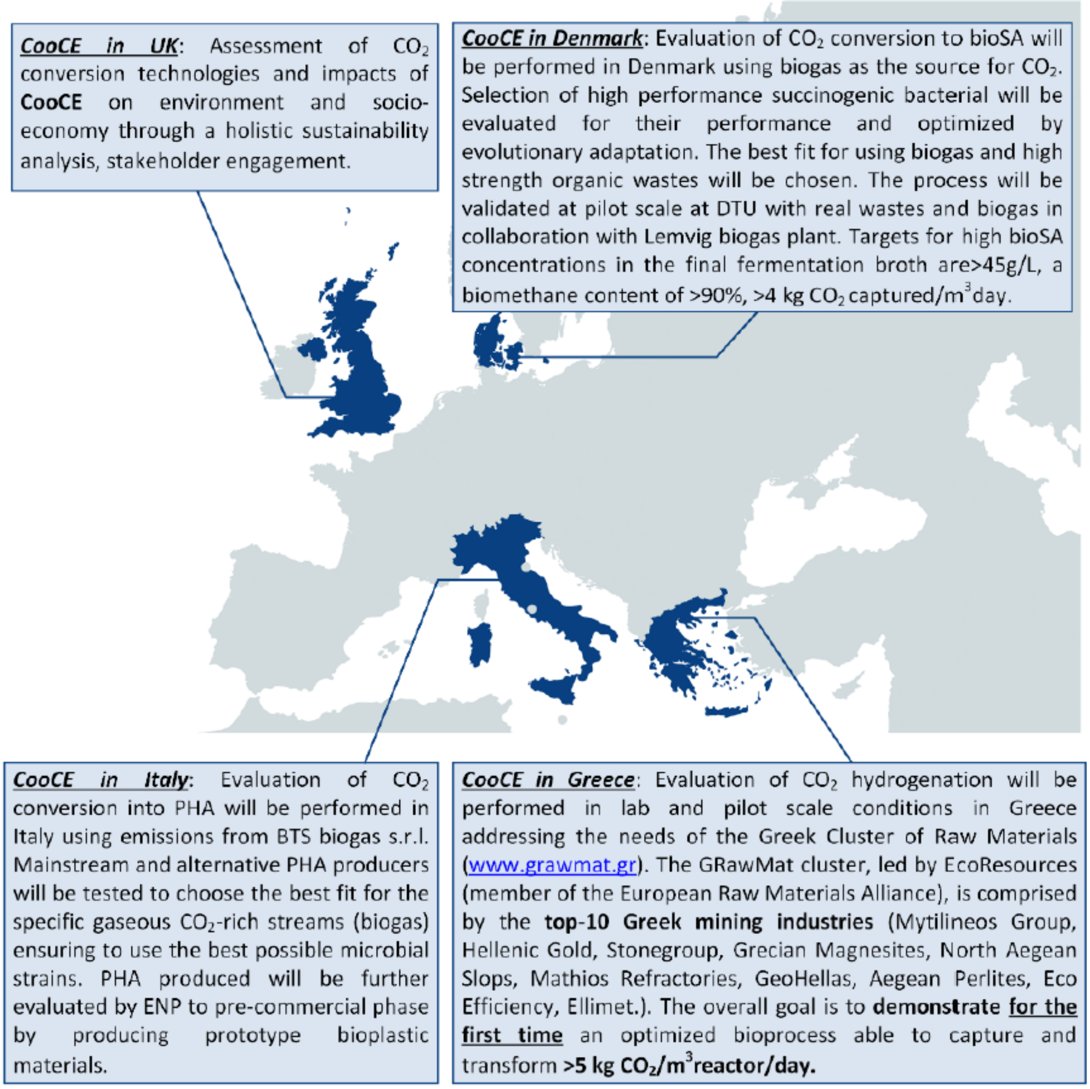



Figure 2. CooCE technologies for CO2 capture and utilisation

In most cases the technological solutions needed to valorise such streams are known. The challenge is transferring this know-how to where it is needed and creating the political and social environment underpinned by economics (business case) that encourages both transfer and adoption of these ideas to take place.

The project was divided into 7 work-packages (WP), each with its own tasks, deliverables and associated milestones in order to facilitate implementation and monitoring of progress. The individual WPs will feed into each other, as well as deliver independent research results at the highest level (Figure 3).

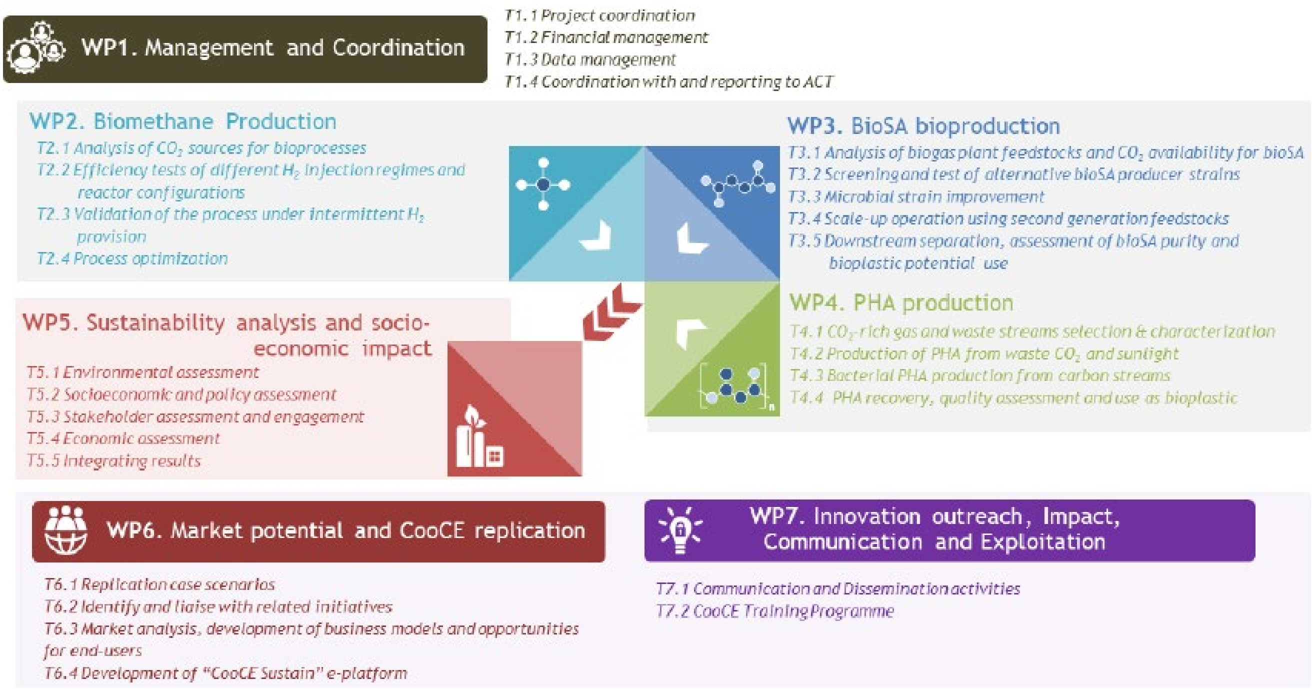



Figure 3. Pert diagram of the components showing their interdependencies.

# 2. Overall methodology

The technologies incorporated into the CooCE platform were focused on the three pathways. They included the biomethane, the bio-succinic acid and the bioplastics pathways and the sustainability assessment. These are described below.

a) Conversion of CO2 into biofuels - Biomethane

Biomethane is considered as one of the most promising alternative fuels for the future according to EU strategies3. Therefore, technologies such as Power-to-Gas among which is the hydrogenation of CO2 to CH4 are emerging. Within this concept, renewable energy electrifies water electrolysers for H2 generation that is subsequently used for CO2 conversion into CH4. The process can both be done by thermocatalytical and biological routes. Biological CO2 hydrogenation has the advantage that it can be performed at mild temperature and ambient pressure, thus with a low energy cost. Moreover, the process is conducted with a variety of exogenous CO2 sources, such as biogas (CO2 content ~35-50%) or exhaust/flue gas (5-17% CO2) offering great flexibility and replicability. It must be underlined that apart from generation of biofuel as end-product, this technology serves as an exemplary method for seasonal on-site energy storage (Figure 4).

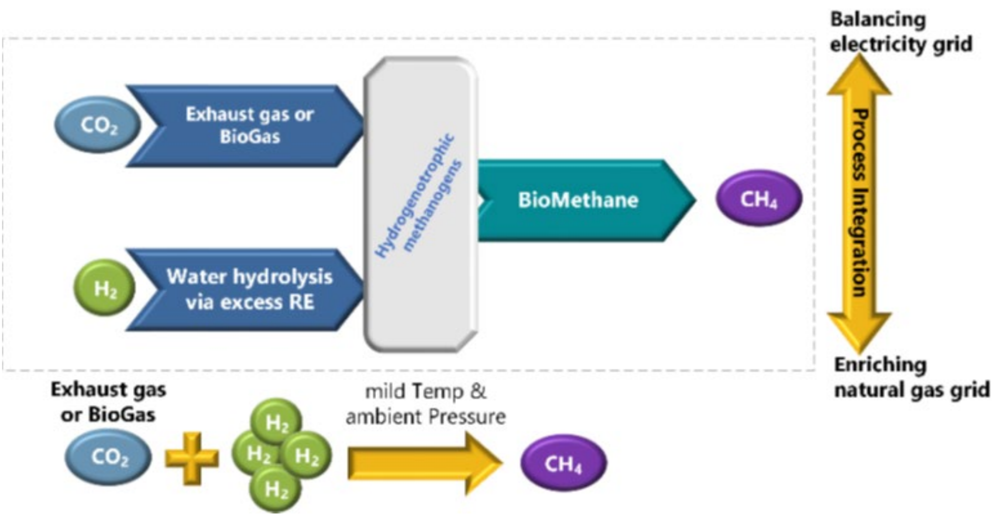



Figure 4. CooCE concept for biomethane production

b) Conversion of CO2 into Bio-Succinic acid (bioSA)

Succinic acid is a C4 diacid precursor of numerous commodities in chemical, food, agricultural and pharmaceutical industries7,8. According to the market report9, the succinic acid market size is projected to grow from USD 131.7 million in 2018 to USD 182.8 million by 2023, at a CAGR of 6.8%. The increasing demand from the industrial, personal care and food & beverage industries strengthens the succinic acid market. The increasing adoption of succinic acid as a substitute of adipic acid in polyurethane production are also boosting factors. The share of bioSA in the SA market is currently low (a few percent) but it is expected to drastically increase along with the Green Transition programmes. Especially bioSA is not only substituting a fossil produced chemical but also captures CO2 in the production process. The green wave through the world has contributed that many companies are shifting from fossil produced SA to the more environmentally sustainable bioSA (Figure 5).

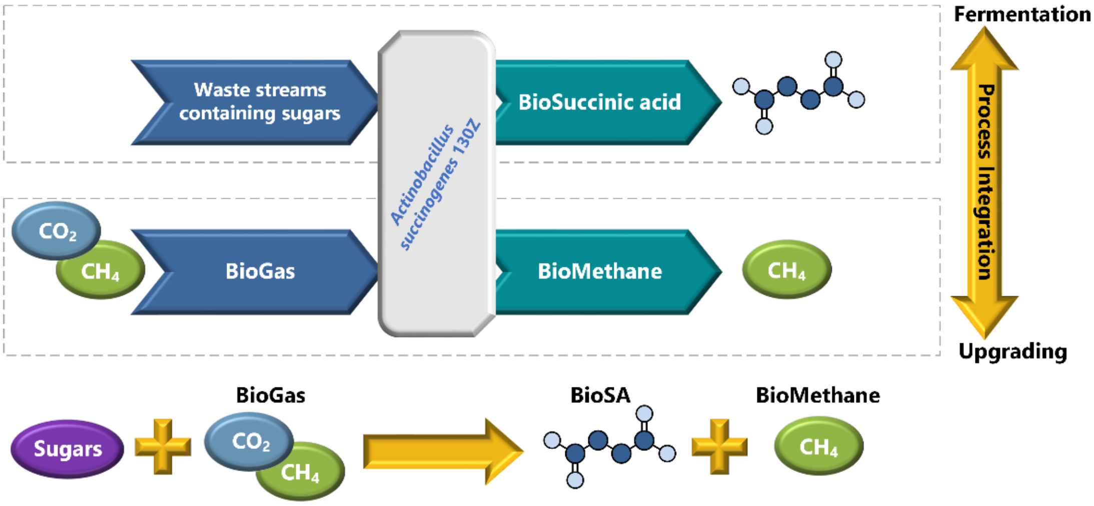



Figure 5. CooCE concept for bioSA production

c) Conversion of CO2 into biopolymers, such as polyhydroxyalkanoates (PHAs)

PHAs are biologically produced polyesters. These molecules accumulate inside bacterial cells for energy storage. CooCE proposes bio-catalytic technologies for treatment of CO2-rich streams and cost-effective production of biopolymers. The used biocatalysts (*C. necator* DSM 545 and cyanobacteria) are microorganisms with an elevated capacity for conversion of CO2 into PHA (a biodegradable polymer) (Figure 6).

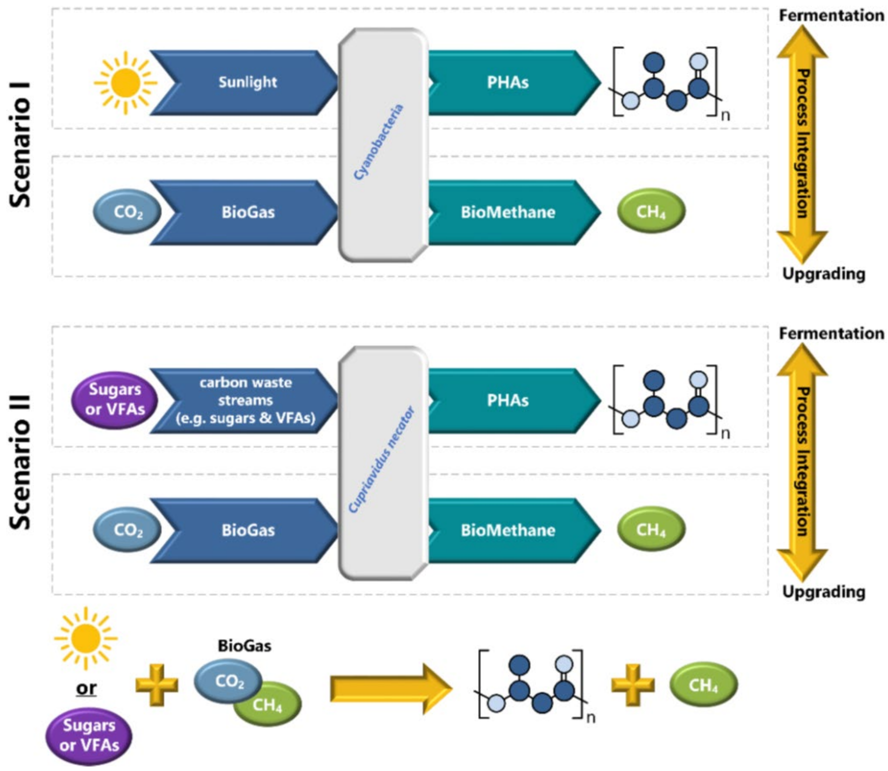



Figure 6. CooCE concept for PHAs production in two scenarios.

The Sustainability assessment followed a mixed methodology combining life cycle assessment, environmental, social, economic and policy sustainability assessments and an integrated sustainability assessment (Figure 7). These methods are fully explained in the sustainability chapter.

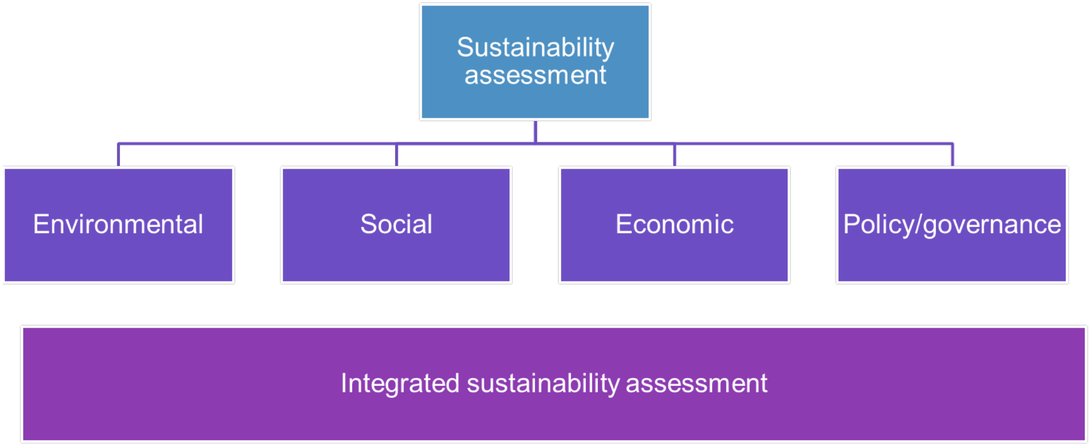



Figure 7. Sustainability assessment

Imperial organised a workshop with all partners which was conducted on May 20th, 2022, in Padova as part of the consortium meeting. The main aim was to inform about the methods to be used for the sustainability assessment and for partners to know how to integrate the data for the analysis. Imperial produced an excel file to gather data from all partners working on the technical assessments. The data was gathered throughout the project to be able to perform the life cycle assessment of the project.

# 3. Sustainability assessment

This WP focused on the overall sustainability of the project and Imperial was the leader. The

ICL organized a workshop with all partners which was conducted on May 20th, 2022, as part of the consortium meeting. The main aim was to inform about the methods to be used for the sustainability assessment in WP5 and for partners to know how to integrate the data for WP5 analysis.

## 3.1 Environmental assessment.

ICL produced a template file for the environmental LCA to gather data from all partners working on the technical WPs (2-4). The data collection supported intermediate analyses and produced further refinements as the experimental techniques progress throughout the project. Partners provided information on the sources for $CO_2$ in WP1, the biogas feedstocks in WP2 and waste streams for PHB in WP4. During the second year, one-to-one meetings with partners took place to explain the use of the environmental LCA file and how partners should be collecting the information (Fig. 8). Considering the diversity and specificity of each WP process, a version of the environmental LCA was prepared and shared with each partner. In the case of Denmark, it was decided to have one single excel file for the two partners, DTU and LBP, as they work collaboratively (Fig. 8).

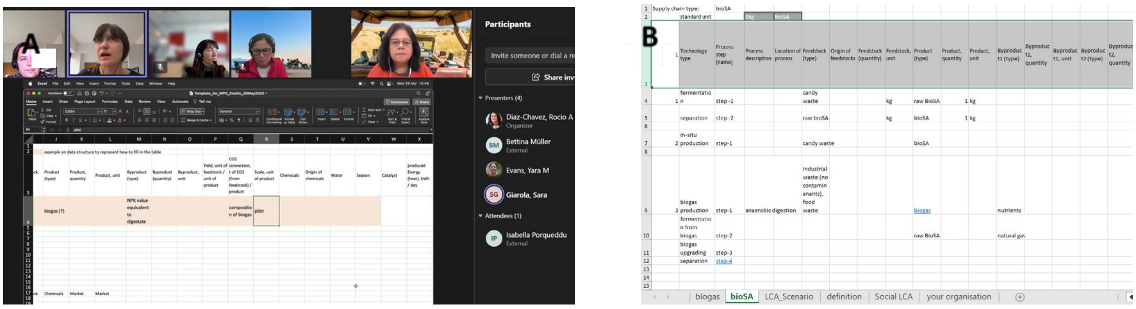



Figure 8. A. Example of meeting with BTS. B. Example of the template file for DTU and LBP partners.

Methodology: The method applies a Life Cycle Assessment (LCA) developed using a “cradle-to-gate” approach following the ISO 14040 and 14044 standards. The LCA evaluates the Global Warming Potential (GWP) of the three technologies and includes the $CO_2$ emissions accounting for the provision of ancillary chemicals, the supply of power, and the plant operations involved in the product manufacturing (Figure 9). The three technologies use biogas (at 55 vol.% of methane) as a feedstock and contribute to create a “biogas-to-platform chemicals” biorefinery. Figure 10 shows the supply chain analysis and figure10 the process assessment.

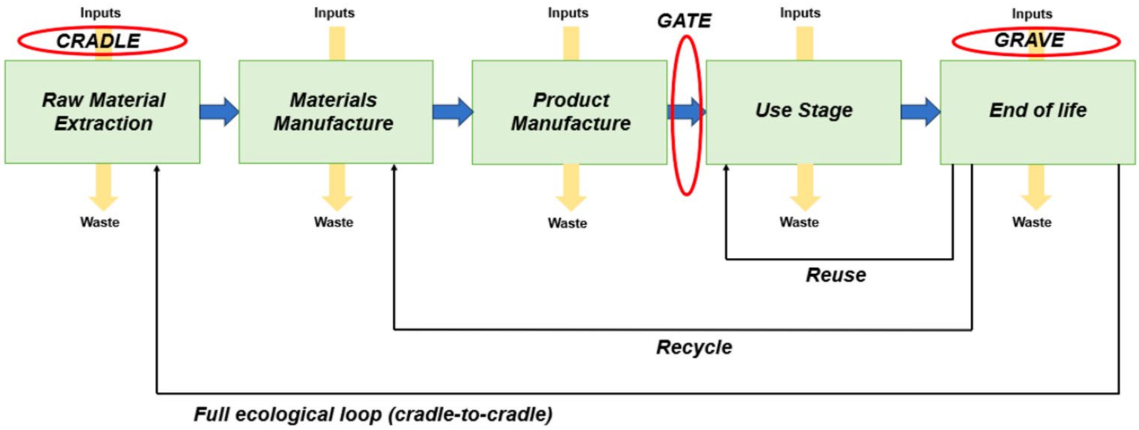



Figure 9. CO2 emissions are evaluated with a cradle-to-gate approach

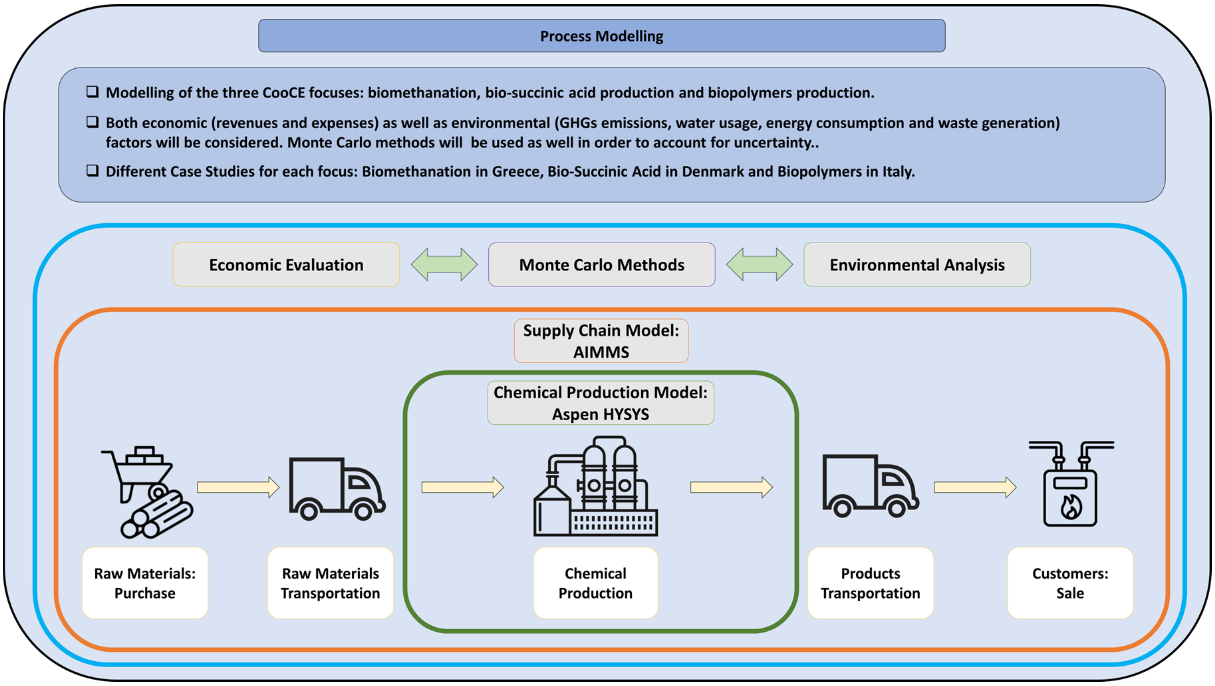



Figure 10. Process modelling

All the technologies, other than the biopolymer option, show improvements in the CO2 emissions compared to the fossil alternatives (i.e. natural gas, fossil-based succinic acid, and fossil low-density polyethylene) in selected scenarios. Key uncertainties come from the energy consumption of the processes, especially when hydrogen is a feedstock (such as for producing biomethane and biosuccinic acid) as the emissions become linked to the carbon intensity of each country’s power system. Other energy needs come from the separation steps: impurity removal and crystallisation for the biosuccinic acid; distillation and solid separation for the biopolymer production. The lower maturity level of the biopolymer route is reflected in the low yields, high energy and fossil-derived solvents requirements. Figure 11. shows the results of the CO2 emissions assessment.

| | | Biomethane | Bio-succinic acid | Bio-polymers |
|---|---|---|---|---|
| Raw material | Photovoltaics | 0.394 | 0.053 | 39.264 |
| Electricity | | 0.19 | 0.087 | 8.548 |
| Natural Gas | | 0 | 0.085 | 0.253 |
| Total (w/o credit) | | 0.584 | 0.225 | 48.065 |
| Total (with credit) | | -2.166 | -0.148 | 46.05 |

| | | Biomethane | Bio-succinic acid | Bio-polymers |
|---|---|---|---|---|
| Raw material | Mixed | 0.394 | 0.053 | 39.264 |
| Electricity | | 1.39 | 0.64 | 62.644 |
| Natural Gas | | 0 | 0.253 | 0.253 |
| Total (w/o credit) | | 1.784 | 0.778 | 102.161 |
| Total (with credit) | | -0.966 | 0.405 | 100.146 |

| | | Biomethane | Bio-succinic acid | Bio-polymers |
|---|---|---|---|---|
| Raw material | Wholesale | 0.394 | 0.053 | 39.264 |
| Electricity | | 1.991 | 0.916 | 89.707 |
| Natural Gas | | 0 | 0.253 | 0.253 |
| Total (w/o credit) | | 2.385 | 1.054 | 129.224 |
| Total (with credit) | | -0.365 | 0.681 | 127.209 |
| Fossil | Energy mix | | | 1.8 |

Figure 11. Environmental Assessment: CO2 emissions

Three important issues need to be considered for the $CO_2$ emissions assessment:

1. The source of electricity and the renewable share is crucial to determine the emissions.
2. The reuse of $CO_2$ within the product synthesis could be assigned a credit compared to the fossils.
3. The temporary $CO_2$ presence in the product cannot be considered as a form of storage.

Electricity and waste generation in the CooCE platform was also assessed for each one of the pathways. The results of the assessment are presented below in Table 1.

Table 1. Environmental assessment: energy and waste

| | Case | Biomethane | Biosuccinic acid | Biopolymer |
|---|---|---|---|---|
| Electricity, kWh / kg of product | Photovoltaics, Grid, Mixed | 4.663 | 4.342 | 256.306 |
| Waste, kg / kg of product | | 17.52 | 46.2 | 81.23 |

Three issues also need to be considered for this assessment:

- Electricity and waste generation are estimated at a process level
- All the technologies show a high energy consumption, with biopolymers reaching the highest levels
- Wastes are of various nature and contain a different mix of liquid and solids depending on the technologies. Further data will be needed to evaluate how these can be recovered or processed

The CooCE platform can be a promising alternative to fossil-derived materials. Some products (biomethane and biosuccinic acid) show higher readiness than others (biopolymers). Biomethane has a higher GWP than the fossil equivalent, when non-renewable electricity is used, but behaves as a carbon sink if biogenic $CO_2$ is assigned a credit and electricity is from renewables. While biosuccinic acid outperforms, biopolymers perform worse than the fossil counterpart. All the technologies analysed call for research on energy penalty reduction, product yield increase, and fossil-derived solvent substitution. The deployment of the CooCE biorefinery should be aligned with renewables targets in the electricity generation, for an effective emission reduction. Result validity is limited to the modelling assumptions and should not be generalised to any source of CO2. The analysis would need revising whether a different biogas composition or an alternative origin of the CO2 should be considered.

**Final comments regarding this assessment**

- -The biomethane process shows the highest readiness level. Improvements at a process level targeting a reduction in the use of energy, the dependency on hydrogen as well as the improvements in yields could lower the minimum selling price, making it a more valuable alternative to natural gas.
- -The biosuccinic acid shows concerns in the uses of electricity and the amount of waste produced. However, the technology's environmental performance is promising. Although the selling price calculated could be underestimated, the technology economics align with the fossil route.
- -The biopolymer production requires bigger efforts in terms of scale-up compared to the other two routes. Advances in the processes would come from process optimisation targeting an increase in yields which would reduce the use of resources and of energy in the process.

The results of the environmental assessment were submitted in report D5.1.

## 3.2 Socio-economic and policy assessment.

ICL worked on the social-economic assessment on previous projects and has a well-established methodology (Diaz-Chavez, 2010). This includes the assessment of criteria with the Social Hotspot Database (SHDB, 2021); the mapping of stakeholders; surveys and interviews; and policy assessment.

Indicators were selected to be used in the social LCA (Fig. 12).

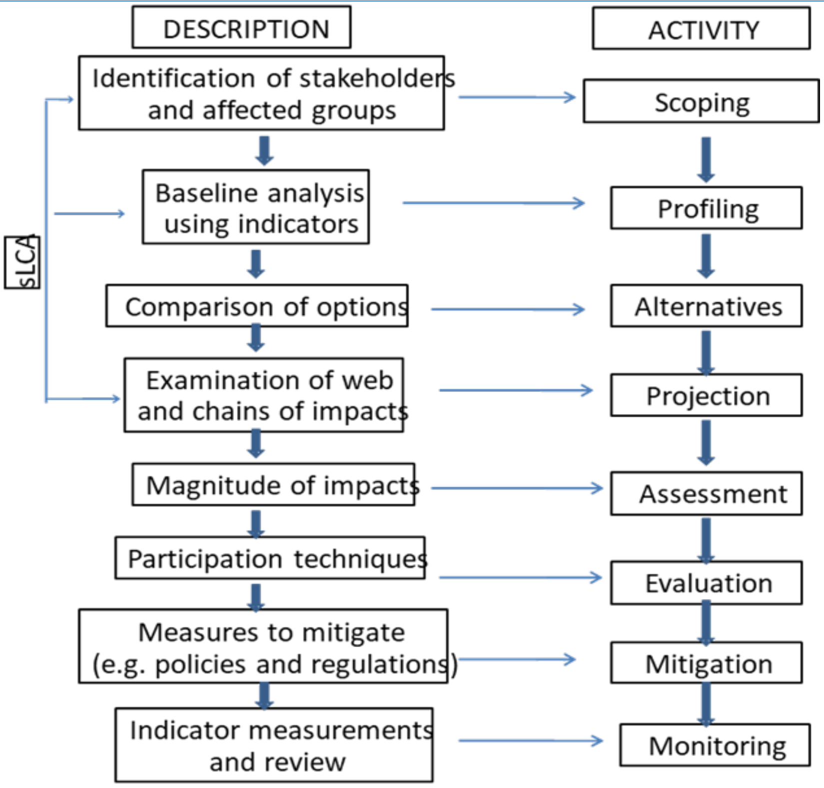



Figure 12. Adapted social impact assessment to sLCA (Diaz-Chavez, 2010).

The overall social assessment therefore included the following points:

- Social Impact Assessment (indicators)
- Social Life Cycle Assessment (indicators)
- Mapping of stakeholders
- Stakeholders' workshop and online survey
- Social Hotspot Database (indicators)
- Policy review (documents)

The assessment also followed the supply chain as in the environment assessment (Fig. 13).

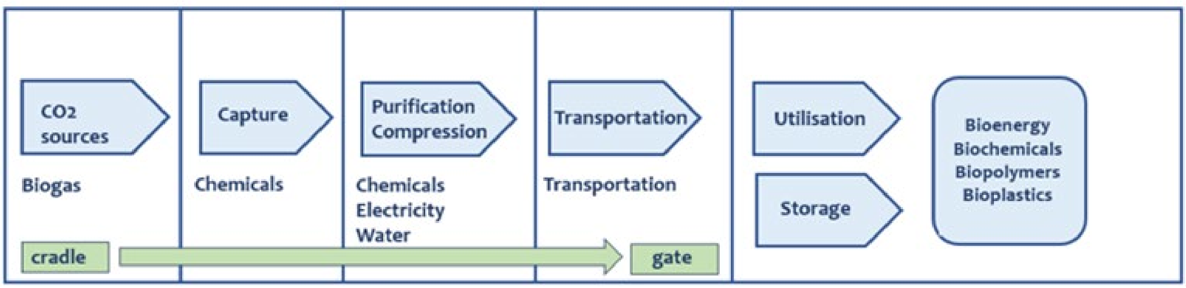



Figure 13. Social assessment within the supply chain

Overall, thirteen social indicators were selected and assessed using statistical data and the HSDB.

Some selected results are presented in table 2 below.

Table 2. Social sustainability assessment of selected indicators.

| Parameter | Criteria | Risk | Benefit | Observations, Issues and Mitigation |
|---|---|---|---|---|
| Gender equity | Inclusion of women | M | H | **Issue**: men are generally more economically active than women in all CooCE countries, although gender employment and pay gaps have been narrowing<br>**Mitigation**: ensure gender equality of opportunity or enhanced opportunity for women to access resources and services for participating in the implementation of CooCE (e.g.jobs, business ownership, supporting services, etc) |
| Labour conditions | Conventions on child labour, forced labour, right to organise | M | H | **Observation**: CooCE countries are signatories of most ILO conventions<br>**Issues**: medium risk of lack of enforcement of labour laws and conventions in four sectors in all countries; high risk of excessive working time and of forced labour in Greece in all CooCE sectors; very high risk for migrant workers in Greece, Italy and the UK across all sectors<br>**Mitigation**: monitor enforcement of legislation for labour protection to prevent excessive working time and exploitation of migrant workers |
| Health and safety | Compliance with health and safety regulations for each stage of the value chain | H | H | **Observation**: all CooCE countries have legislation in place for health and safety at the workplace and are long-standing signatories of the Labour Inspection Convention<br>**Issues**: very high occupational and health risks in all four CooCE countries and sectors; medium overall risk of lack of access to health care<br>**Mitigation**: monitor enforcement of legislation for health and safety at the workplace and at public spaces (i.e. roads) to minimise risk of occupational injuries and hazards and public health hazards |
| Community participation | Involvement/acceptance (feedstocks, technologies, products) | M | H | **Issues**: NIMBY syndrome; poor knowledge about CCUS and biodegradability of products; concerns about impacts on human health and the environment<br>**Mitigation**: ensure engagement of local stakeholders in CooCE implementation; understake awareness-raising campagins on CCUS safety and environmental impacts (e.g. $CO_2$ leakages; use of water and chemicals; biodegradability) |

**Key: M= Medium; H=High**

A policy review was conducted of all regulatory instruments in the EU (e.g., laws, regulations, directives, etc.) relevant to CooCE project and partner countries (Fig. 14). A Research Ethics Application was submitted to the Ethics Committee at Imperial College to cover the activities of primary data gathering and engagement with stakeholders.

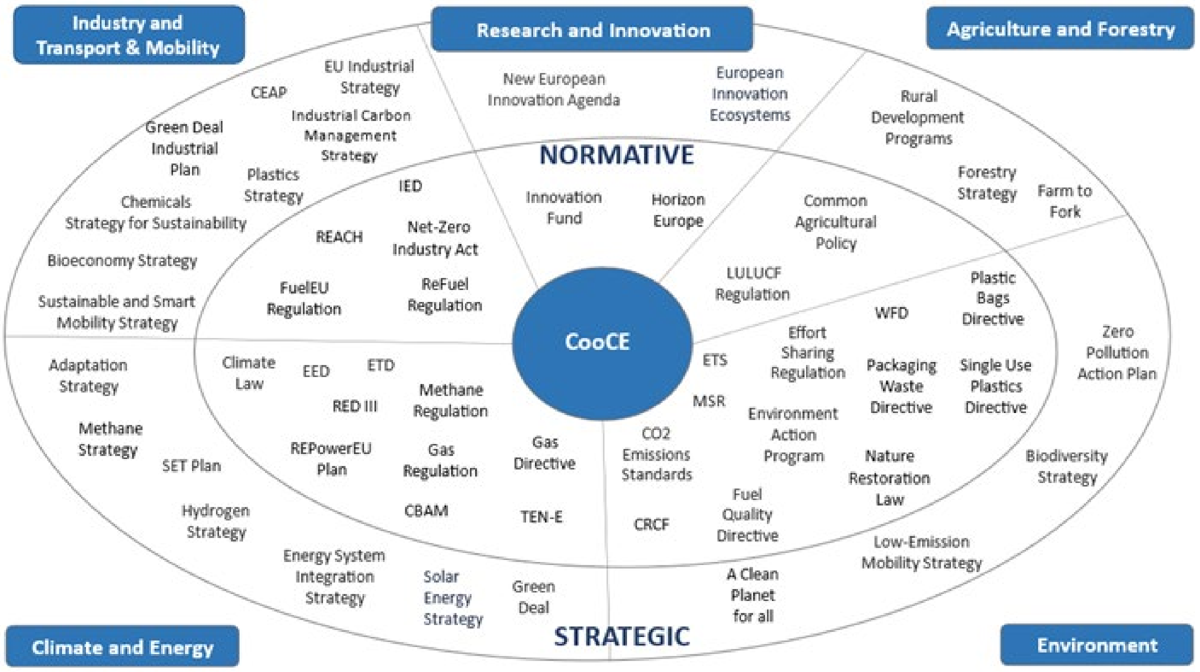



Figure 14. Assessment of EU and UK Policies relevant to CooCE.

The assessment of challenges for different policy instruments was included in the report. An example of some of the findings is provided in the Box below.

Box 1. Example of Challenges in Overarching EU Policy Instruments

**Challenges**: There is a lack of comprehensive and clear regulatory frameworks for CCUS, particularly for the reuse of captured $CO_2$ in products such as chemicals and fuels; financial mechanisms and incentives specifically targeting the use of captured $CO_2$ in products are limited; the carbon price under existing carbon emissions trade mechanisms, such as the UK ETS, is not robust enough to incentivise investment in costly CCUS infrastructure, making capturing and reusing of $CO_2$ less financially rewarding than offsetting emissions; there is a also a shortage of adequate shared infrastructure for transporting and utilising $CO_2$ across multiple industries.

**Recommendations**:

- Create detailed regulations specifically for CCUS projects, outlining the legal, environmental, and operational requirements, such as permitting processes, environmental impact assessments, and safety standards for $CO_2$ deployment across the sectors
- Establish dedicated funding streams for CCUS technologies under the *GGSS* and the *CCUS Innovation Programme*, along with other financial incentives, such as capital grants, tax credits, and enhanced carbon credits for captured carbon products to support industrial-scale deployment of CCUS.

Overall recommendations for policy issues:

- Design policies specific for CCUS (feedstocks, techno-processes, products, bioproducts)
- Improve existing regulatory frameworks relevant to elements of CCUS to account and recognise the contribution of captured carbon bioproducts to energy targets and the CE
- Provide funding and investment mechanisms for developing CCUS biotechnologies

The results of the socio-economic and policy assessment are presented in D5. 3 Report on socio-economic and policy assessment and D5.4 Policy recommendations document.

### 3.2.1 Stakeholder assessment and engagement.

The template file for the environmental LCA also contained a sheet for partners to include stakeholders under different categories (e.g., academic, industry, biogas, farm, etc.) to be able to map them in each CooCE case study (Fig. 15). An additional search is being conducted online and will be utilized to map the stakeholders in general and for each case study. The mapping will be presented in a graphic form such as the example below.

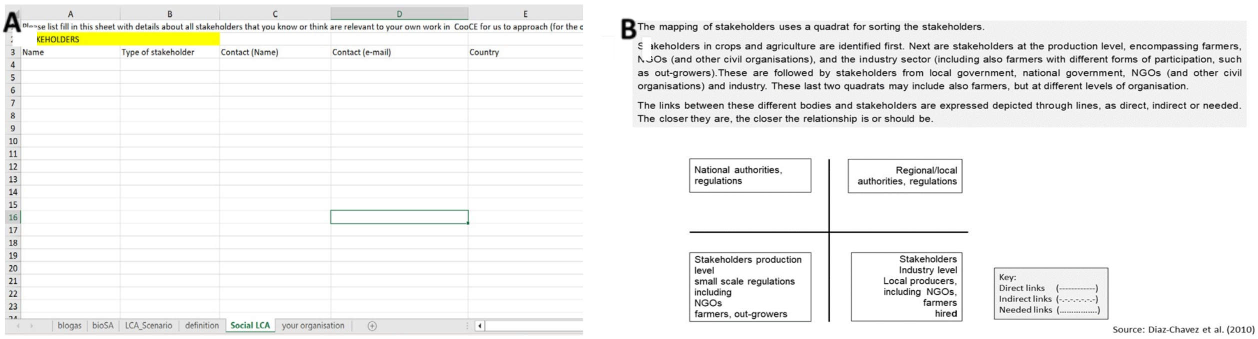



Figure 15. A. Stakeholders data gathering from partners. B. Example of mapping of stakeholders.

The stakeholder assessment was also included in D5.2 on socio-economic assessment along with the results of the survey.

A mapping of stakeholders was conducted to identify major stakeholders and trace the linkages between them. These stakeholders were identified through desk research and linked with help from project partners. The stakeholders and linkages are shown in Figure 13 for each of the CooCE countries. As can be seen in Figure 16, the linkages are traced between different stakeholders as direct, indirect and those perceived as needed, if not yet necessarily extant. This mapping is not exhaustive. Rather, it aims to identify key social actors that would or should collaborate in the implementation of the CooCE concept. It envisages a 'multi-actor approach,' as employed in other EU projects (EU, 2023). In the case of CooCE, this entails bringing together biogas plants and other CO2 emitters, scientists, investors, regulators, policymakers, business owners, associations, and other stakeholders, to collaborate throughout the concept's implementation to develop novel practical solutions to emergent problems through knowledge exchange and innovation dissemination.

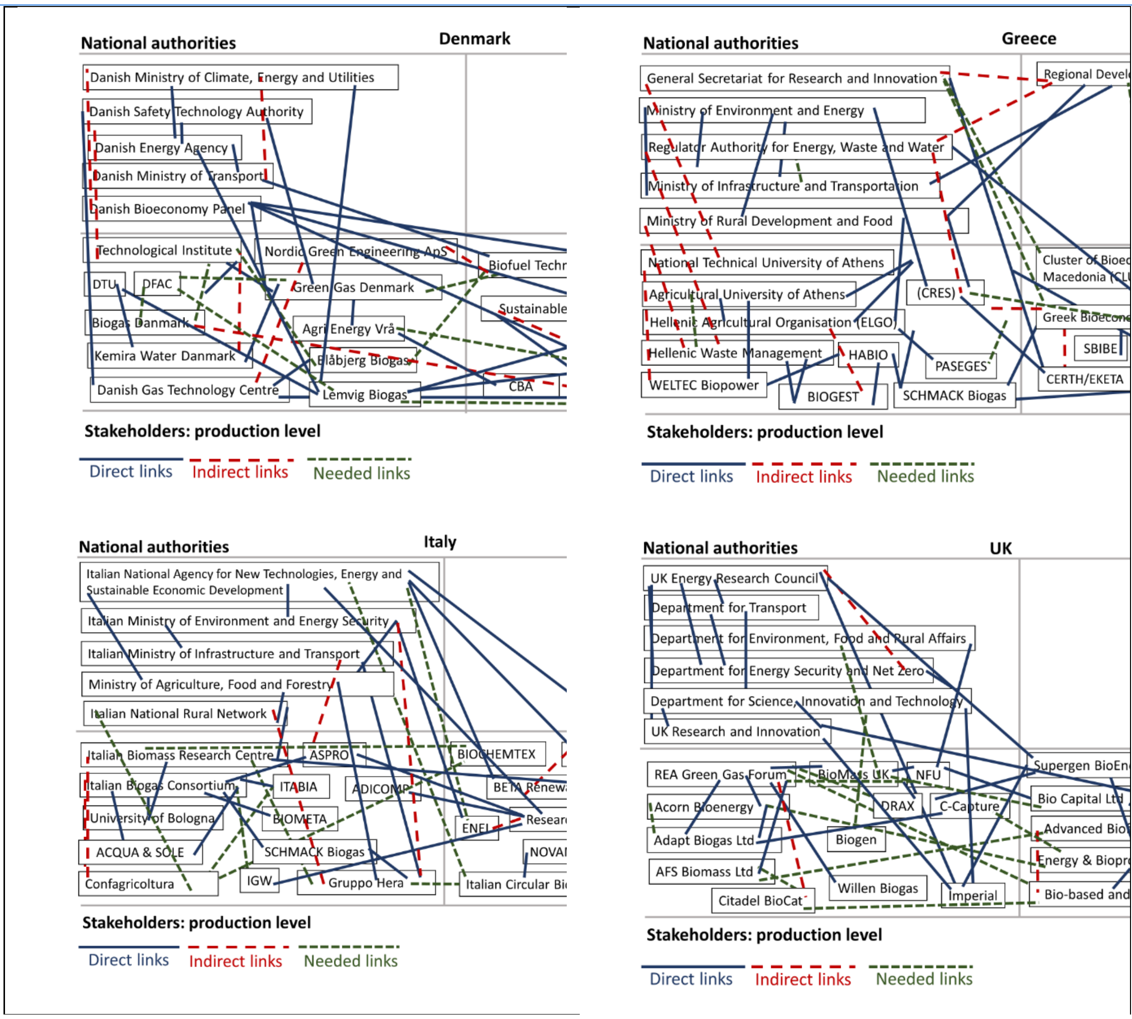
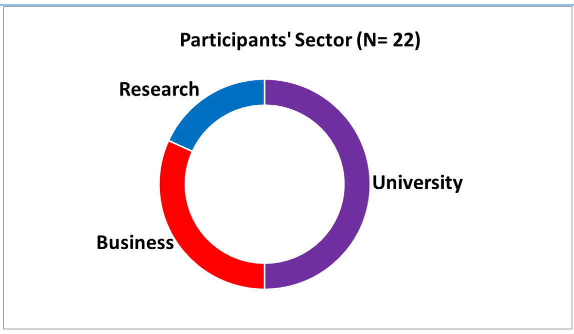
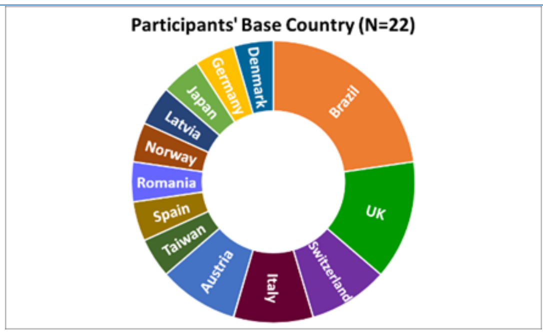



Figure 16. Mapping of stakeholders

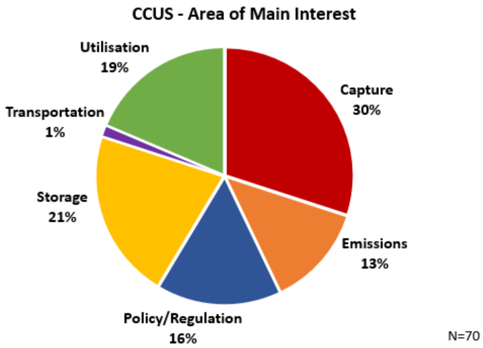
A workshop with stakeholders was held during the European Biomass Conference and Exhibition in Bologna in 2023. A survey was designed and shared with partners as a pilot, to later be shared among the identified stakeholders and during the workshop at the European Biomass Conference (June 9th, 2023, Bologna, Italy). The survey's results were included in the assessment. The workshop allowed to identify important aspects of the CooCE concept. Twenty-two participants from different countries in the EU and other regions attended it, plus a survey with seventy responses (Figure 17).



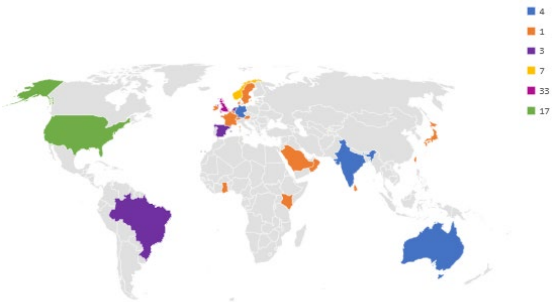

Workshop (2023)




Workshop (2023)




Survey (2023)




Survey (2023)

Figure 17. CooCE stakeholders - Workshop and Survey.

Figure 18 shows the advantages and challenges for the CooCE project identified by the stakeholders. One key challenge identified by several stakeholders was the production of hydrogen needed for the conversions in the pathways. Other important challenges were identified related to policies and regulations.

| Advantages | Challenges |
|---|---|
| ***CooCE Concept*** | ***Concept/CCUS*** |
| Addresses policy agendas for lowering emissions | Competing uses for renewable energy |
| Carbon negative | Complex market for biogas producers |
| $CO_2$ as feedstock | Costly investment |
| Circularity | Energy requirements |
| Decentralised approach | Lack of funding mechanisms |
| Diversified applications | Little known yet |
| Favoured by net zero emissions mandates | Multitude of stakeholders |
| Suitable across industries/sectors | Own $CO_2$ emissions |
| Potentially profitable | Potential shortage of $CO_2$ |
| Revenue pathway for biogas producers | Public perception |
| ***Techno-process*** | Scalability |
| Biodigestion | Slow market expansion in EU |
| Bioreaction | ***Techno-process*** |
| Biomethane upgrade | Bacteria use/storage/platform purification |
| Gases purification | Biogas transportation |
| Integrated System | $H_2$ production |
| System easy to operate | Large-scale growth of microorganisms |
| ***Product*** | Potential $CO_2$ leakage |
| Biogas from $CO_2$ upgrade | Reactor configuration |
| Chemicals platform | ***Product*** |
| Diversified range of outputs | Quality standards for commercial use |
| Fuels from $CO_2$ with $H_2$ | ***Policy/Regulation*** |
| High Purity bio-$CH_4$ | Lack of consistency in EU regulations |
| Bioplastics (rising demand) | Lack of policies for CCUS/its bioproducts |

Figure 18. Advantages and challenges identified by stakeholders during the workshop In Bologna in 2023.

This task entailed the production of a “Best Practice Book.” The handbook was produced as a toolkit with 9 topics presented in factsheets about the key concepts of the CooCE project and the pathways. The handbook was translated into Italian, Greek and Danish, which are the countries of the partners of the project (Figure 19).

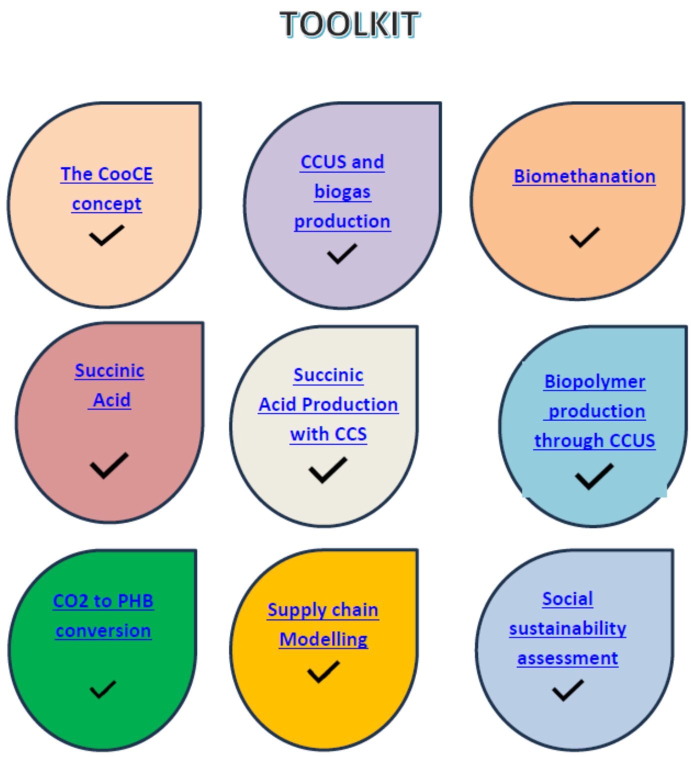



Figure 19. Key topics of the factsheets included in the handbook/toolkit

The Handbook/toolkit can be accessed directly in the portal of the CooCE project.

## 3.3 Economic Assessment

With the information from the environmental LCA and an input-output analysis the assessment considered CAPEX and OPEX.

The report discussed the technologies, their technical specifications, and their economic evaluation. The analysis uses the technical specification and performance of each CCUS technology, developed at a pilot scale by each project partner, namely: biomethane, biosuccinic acid, and biopolymer production. The three technologies use biogas as a feedstock (55 vol.% in methane content) and contribute to create a "biogas-to-platform chemicals" biorefinery. Figure 20 presents the workflow followed for the assessment, same as with the environmental assessment.

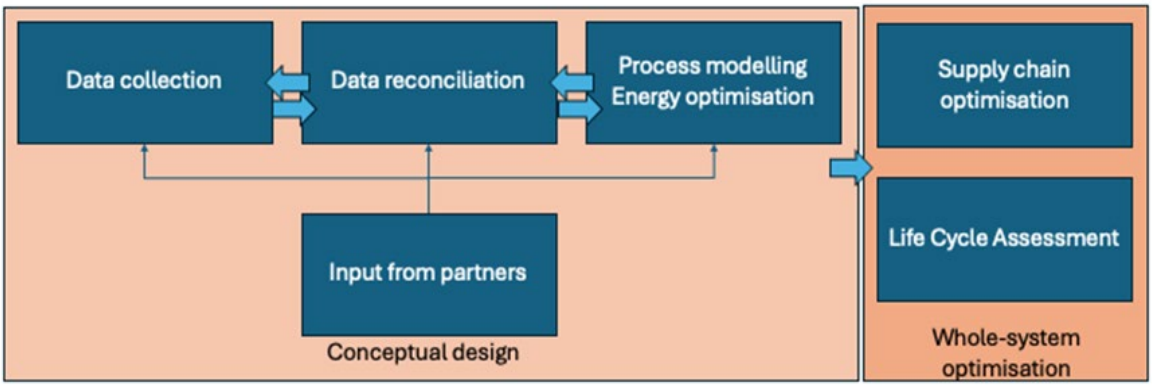



Figure 20. Workflow of the methodology used in the modelling, where the process is modelled from the pilot plant data and energy optimised.

The economic assessment conducted shows that economic feasibility is challenging for each of the three technologies. The resulting minimum selling price is higher than the fossil alternative. Governmental subsidies where the government would share a fraction of the upfront capital costs would reduce the business risk and help overcome technical limitations in conjunction with a consistent research and development (R&D) effort. The biomethane process profitability is linked to the hydrogen and electricity costs. The succinic acid route faces technical difficulties in the separation of the product and the related energy penalty. Finally, key bottlenecks in the biopolymer production are identified in low yields, high energy penalty, and hydrogen inputs, in addition to substantial uses of solvents. Figure 21 shows the key results for CAPEX and OPEX of the analysis.

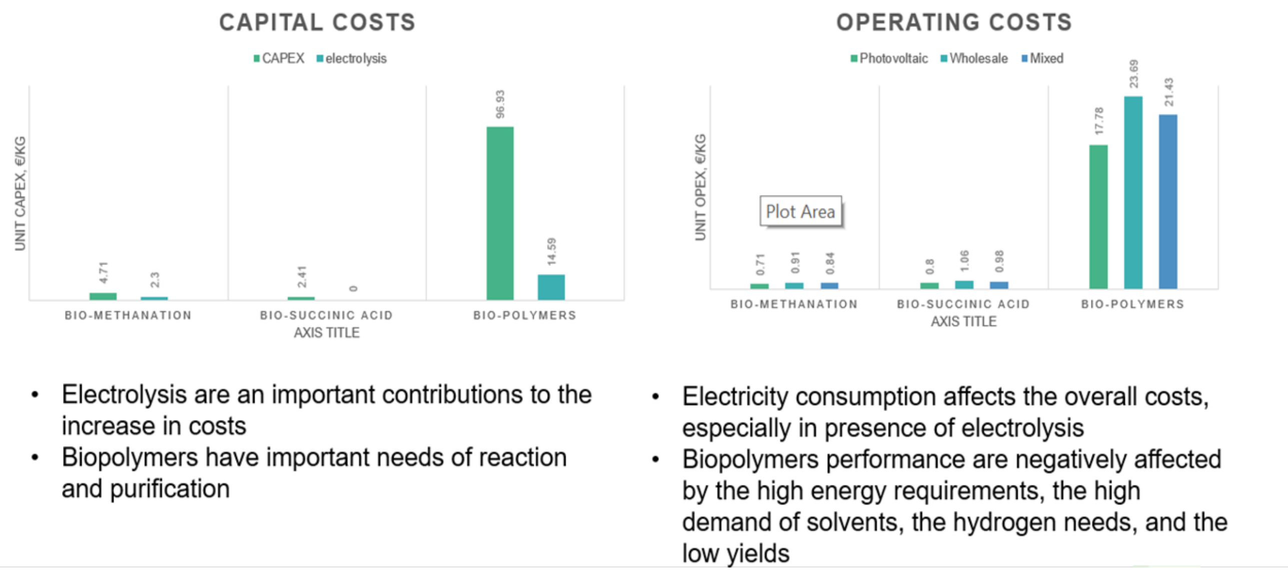



Figure 21. Results of CAPEX and OPEX of the economic assessment of CooCE.

The minimum selling price for each technology was calculated as per figure 22.

| Feedstock | Unit, € / MWh | Reference from literature |
|---|---|---|
| **Biogas methanation** | 82 - 118 | Our work |
| **Fermentation of different feedstocks** | 55 - 110 | European Biomass Association |
| **Fermentation of grass silage** | 62.75 – 136.25 | Other literature |

| Feedstock | Unit, € (2024)/ kg | Reference from literature |
|---|---|---|
| **Biogas** | 40 – 51 | Our study |
| **n.a.** | 4 | Other literature |

| Feedstock | Unit, € (2024)/ kg | Reference from literature |
|---|---|---|
| **Biogas and candy waste** | 1.34 – 1.94 | Fermentation (our study) |
| **Municipal biowaste** | 2.75 | electrochemical membrane bioreactor |
| **Bagasse** | 2.5 – 4.23 | fermentation |
| **Fossil** | 2.3 (up to 9) | maleic anhydride |

Figure 22. Minimum selling price of technologies in CooCE.

The minimum selling price reflects the readiness of the technologies Biomethane and biosuccinic acid were in line with other evidence from the literature Biopolymers have higher selling price showing needs to further process optimisation.

Result validity is limited to the modelling assumptions and should not be generalised to any source of CO2. The analysis would need revising whether a different biogas composition or an alternative origin of the CO2 should be considered.

The Task produced the deliverable D5.5 Report on economic assessment.

## 3.4 Integrated Sustainability Assessment

The Integrated Sustainability Assessment (ISA) evaluates the environmental, technical, economic, social and policy impacts of replacing fossil-based products with bio-based alternatives obtained from application of captured carbon technologies. This integrated approach aims to ensure that efforts are economically viable, environmentally sound, and socially inclusive, guiding the development of commercially successful CooCE value chains.

**Assessment of Pathways for Implementation**

The CooCE concept comprises three pathways based on the capture of CO2 from biogas for production of:

- Biomethane (Pathway 1)
- Biomethane and biosuccinic acid (BioSA) (Pathway 2)
- Polyhydroxyalkanoates/Polyhydroxybutyrates (PHAs/PHBs) bioplastics (Pathway 3)

**Methodological Overview**

The assessment included several tools and methods and the results of each one of the reports produced for environmental, economic, policy and social assessments. The methods included:

- Aim: Identify the most sustainable pathways for implementing CooCE technologies and products
- Integrated Approach: combines findings from environmental, economic, social and policy sustainability assessments, supplemented by a SWOT analysis of the CooCE concept
- Key Tool: Multi-Criteria Evaluation (MCE) using a 'traffic light' scoring system that identifies positive, neutral, or negative impacts based on selected indicators for each pathway; it enables structured comparisons of sustainability performance across pathways
- Scope: 'cradle-to-gate' analysis, covering the lifecycle from raw material acquisition to commercialisation

The final assessment followed a qualitative assessment as traffic light with the following scoring system (Fig. 23).

**Traffic Light Scoring System**

| | Very positive | Positive | Neutral | Negative | Very negative |
|---|---|---|---|---|---|
| Impact | ++ | + | 0 | - | -- |
| Risk Level | Very low | Low | Moderate | High | Very High |

Figure 23. Qualitative scoring system used.

A total of 24 indicators were assessed within five criteria or topics: technological, environmental, social and legal. Figure 24 shows the results.

| Theme | Indicators | Pathway 1: | Pathway 2: | Pathway 3: | Assessment Outcome |
|---|---|---|---|---|---|
| Technological | 1. $CO_2$ Storage | 0 | + | ++ | 3 |
| | 2. Barriers to Commercialisation | 0 | 0 | -- | 1,2 |
| | 3. Electricity Source Reliance | - | - | -- | 1,2 |
| | 4. Hydrogen Reliance | - | 0 | -- | 2 |
| | 1. Process Scalability | ++ | 0 | -- | 1 |
| | 2. Regulatory Frameworks | + | - | -- | 1 |
| | 3. TRL Development | ++ | + | -- | 1 |
| Environmental | 4. $CO_2$ Capture Rate | ++ | + | + | 1 |
| | 5. $CO_2$ Emissions | ++ | + | -- | 1 |
| | 6. Energy Consumption | 0 | 0 | -- | 1,2 |
| | 11. Waste Generation | - | -- | -- | 1 |
| | 12. Water Usage | + | + | -- | 1,2 |
| Economic | 13. Energy Sourcing | 0 | 0 | -- | 1,2 |
| | 14. Location | - | ++ | + | 2 |
| | 15. Market Price | - | + | -- | 2 |
| | 16. Potential for Circularity | + | ++ | + | 2 |
| | 17. Product Demand | + | ++ | + | 2 |
| | 18. Product Volume | + | - | -- | 1 |
| | 19. Revenue Potential | + | ++ | -- | 2 |
| Social | 20. Job Creation | + | ++ | 0 | 2 |
| | 21. Health and Safety | - | -- | - | 1,3 |
| | 22. Gender Equity | + | ++ | 0 | 2 |
| | 23. Labour | + | ++ | 0 | 2 |
| Legal | 24. Policy Instruments | + | - | -- | 1 |

Figure 24. Total indicators assessed in the Integrated Sustainability Assessment.

The Key Results from the ISA can be summarised as follows:

- Pathway 1 and Pathway 2 perform well in terms of sustainability, demonstrating predominantly positive or neutral impacts across the indicators.
- Pathway 3 performs poorly, showing mostly negative impact across the indicators.
- Some indicators (e.g., waste generation, health and safety) show negative impacts across all pathways, requiring targeted mitigation efforts.
- Overall: Pathways 1 and 2 likely to provide substantive positive technical, environmental, economic, social, and policy outcomes.

It is important to note that outcomes do not necessarily imply that an impact or risk is inherently sustainable; rather it suggests that the identified pathway may be preferable to the alternatives

For example:

- Electricity Source Reliance
- Waste Generation
- Health and Safety

Indicators that exhibit negative impacts across all three pathways; these will require mitigation regardless of the pathway chosen

The ISA highlights the potential of Pathways 1 and 2 as sustainable options for CooCE implementation. Nevertheless, while they deliver promising outcomes, further action is needed to address negative impacts and ensure long-term sustainability.

Results of the Integrated Sustainability Assessment were submitted in D5.6.

# 4. Market potential and CooCE replication

This work focused on the dissemination of CooCE project results with UNIPD as the leader but all partners including Imperial contributing with information.

**Development of "CooCE Sustain" e-platform - completed.**

This task details the development, functionality, and content of the innovative digital platform created to enhance stakeholder engagement and knowledge dissemination on carbon capture, utilization, and storage (CCUS) technologies. The beta version introduced an intuitive interface offering access to a CCUS concept database, designed to educate users through data visualizations and multimedia content, emphasizing global trends, sectoral contributions, and future projections in CCUS capacities. The final version expanded the platform significantly by integrating a comprehensive repository of national policies from 18 countries, outlining regulatory frameworks, incentives, and government initiatives to support CCUS adoption. This repository provides users with an organized, country-specific view of existing and planned measures to scale CCUS technologies. The platform's dual focus on technological education and policy insights aims to address technical, economic, and societal challenges, thereby promoting collaboration and accelerating the decarbonization of critical industrial sectors. The complete findings and details of this digital tool are documented in the deliverables titled "D6.3 Report on Beta Version of the 'CooCE Sustain' e-platform" and "D6.4 Report on Final Version of the 'CooCE Sustain' e-platform".

# 5. Communication and Dissemination activities

Non-confidential information and experimental results are currently disseminated internationally and communicated to the target audiences as planned. The CooCE Communication plan has been developed with the collaboration of all partners to ensure the appropriate activities. A survey of local stakeholders for the identification of barriers and opportunities has been initiated. Appropriate dissemination channels for the CooCE project including LinkedIn, Facebook and Twitter have been established in addition to the official project website (https://cooce.eu/). The results and activities have been regularly promoted through the social media platforms (Fig. 15). Such promotions included posting about public events, workshops (online and in presence), conference presentations, research articles and project-related meetings. The aim was to disseminate the major results, developments, and progress of CooCE related activities to achieve a wide outreach. Site visits to the demo pilot scale sites and the final CooCE workshop to showcase the project results and impacts took place in the third year of the project (2024).

## 5.1CooCE- Training Programme.

As part of the CooCE activities, the project developed a training programme aimed at enriching professional curricula within the industrial, corporate and academic sectors. The focus of the programme was to foster the understanding the ‘Strategic Development Goals’ concept, and how novel CCUS approaches can best deploy development and promote bioeconomy.

The CooCE-training programme was built on integrated and advanced methodological tools to provide holistic transfer of knowledge from universities/companies to partners employees and other SMEs/industries with an interest in applying the developed technology.

The training sessions were agreed by partners in meetings organised by Imperial College. Three meetings took place to suggest activities, tools and methods. Additionally, the place and participants and mode of presentation. Figure 1 presents the different activities, tools and methods that were included for the different training sessions. Although the handbook/toolkit was not available for the sessions, it includes all the information useful for the project training tools (Figure 25).


Figure 25. Training tools and approaches used throughout the project.

A training APP was designed by Imperial which was used for the training events explained in deliverable [D7.4](#) . The following QR code (Fig 26) (https://ocwetwe44ejcayif6dmwxh.streamlit.app/)

IMPERIAL APP FOR TRAINING

Figure 26. QR code for training APP.

Four training events were organised as training events as indicated in Table 3.

Table 3. Training events characteristics.

| | Title of event | form | Organised by | Date | Registered |
|---|---|---|---|---|---|
| 1 | Biogenic CO2 use and storage: Enhancing the circularity and climate benefits of biogas | Webinar | Imperial and GBEP with participation of BTS | 15 April 2024 | 40 |
| 2 | "Bio-CO2 from biogas: status, opportunities and challenges of CO2 capture and Carbon Capture Utilization and Storage under the CooCE project". | In person at the 11th GBEP Bioenergy Week "Sustainable Bioenergy for Climate And Development Goals", at FAO, Rome, Italy. | Imperial and GBEP with participation of BTS and University of Padova | 17 June 2024 | 24 |
| 3 | CooCE Online Training Workshop | Webinar | DTU, Imperial, University of Padova | 18 October 2024 | 26 |
| 4 | CooCE Public workshop | In person Botanical Garden of the University of Padova, Via Orto Botanico 15, Padova | University of Padova, Imperial and DTU with partners, | 26 November 2024 | 34 in person 4 online |

To fulfil the objective of the transfer of skills through training, the project created a series of tools and methods not just for dissemination but for training stakeholders interested in the CCUS technology and the novel synergy with circular economy. This was achieved through four specific training sessions where stakeholders had the opportunity not only to learn about CCUs and CO2 capture, but also about the possibilities of producing three key products for climate change mitigation objectives. These were the three pathways to produce biomethane, bio succinic acid and bioplastics (PHB).

Through different innovative methods and tools, modes of presentation and participatory activities, the project managed to provide these trainings to over 100 stakeholders from different sectors such as academia and research, policy and the industry.

The legacy of the project remains on the website with the different material including deliverables, peer reviewed papers, handbook/toolkit and the App will be available for review and use even after the finalisation of the project as a valuable asset for ACT.

## 5.2 Dissemination activities

All dissemination activities have been included in the news section of the project website.

The project had internal meetings online and two in person.

Project meetings:

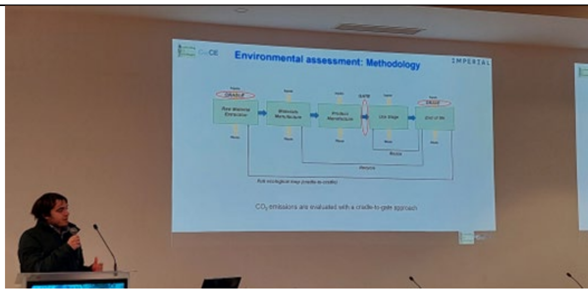
- Kick off meeting 29th November 2021
- First CooCE progress meeting 20th May 2022
- Second CooCE progress meeting 22nd November 2022
- CooCE midterm report and evaluation_06-06-2023
- Third CooCE progress meeting 9th June 2023
- Fourth CooCE progress meeting 7th of December 2023
- Fifth CooCE progress meeting 13th of May 2024
- Final CooCE meeting 26th of November 2024

The CooCE activities include, among others, peer-reviewed publications in international journals, oral, flash poster and poster presentations at national and international conferences, and physical lectures at workshops (Fig. 27).

| | Comment: | SPa = Peer reviewed Paper, PPa = Popular science presentation, Pat= Patent application, Po = Poster, OPa = Oral presentation and paper, PoPa = Poster and Paper, O = Oral Presentatic | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Type of publication | Author(s) or speaker(s) | Title with active link | Reference (Journal/issue, event) | Date | Project partners involved | | |
| 1 | O | Evans Y. and Diaz-Chavez R. | Engaging Social Actors for Acce | 30th European Biomass Conference , online | 09-12 May 2022 | ICL | | |
| 2 | Po | Serna-García, R., Orellana, E., Bucci, | Biologically-mediated CO2 capt | EFB Spring Congress, Barcelona, España (online), Europear | 10-13 May 2022 | UNIPD, BTS | | |
| 3 | WS | Morosinotto T | CCUS Conference and ACT kno | Two-day CCUS conference, Rotterdam | 8-10 June 2022 | UNIPD | | |
| 4 | Oth | P.G. Kougias | Deciphering the microbial "bla | Summer School of MIKROBIOKOSMOS 2022: The role of m | 04-08 July 2022 | ELGO | | |
| 5 | SPa | De Bernardini, N., Basile, A., Zampie | Integrating metagenomic binni | Microbiome, 10(1), 1-18 | 03 August 2022 | ELGO, UNIPD, DTU | | |
| 6 | SPa | F. Vigato; I. Angelidaki; J.M. Woodle | Dissolved CO 2 profile in Bio-Su | Biochemical Engineering Journal, 187. | 22 August 2022 | DTU | | |
| 7 | Po | Serna-García, R., Orellana, E., Bucci, | Biogas upgrading and polyhydr | Spanish national conference, Young Water Professionals C | 16-19 November 2022 | UNIPD, BTS | | |
| 8 | O | Diaz-Chavez R | The role of biomass in the ene | GStic conference in Rio de Janeiro, Brazil | 14 February 2023 | ICL | | |
| 9 | Oth | Diaz-Chavez R | Sustainability Assessment and | University of Parana, Palatina, Brazil | 22 February 2023 | ICL | | |
| 10 | Oth | Diaz-Chavez R | Technical visit Parana company | University of Parana, Palatina, Brazil | 22 February 2023 | ICL | | |
| 11 | O | Serna García, R., Collura, F., Favaro, | Evaluating the potential of tran | 2nd Greenering International Conference | 21-23 March 2023 | UNIPD | | |
| 12 | I | Diaz-Chavez R | Public panel interview at the Royal Geographical Society (with IBG), discussing the links be | | 28 March 2023 | ICL | | |
| 13 | Oth | P.G. Kougias | Experience from other EU fund | Final workshop of H2020-NOMAD: Mobile Bio-Fertiliser So | 27 April 2023 | ELGO | | |
| 14 | O | Serna-García, R., Liberatore, C., Buc | CO2 conversion into biometha | 31st European Biomass Conference | 05-08 June 2023 | UNIPD, BTS | | |
| 15 | O | Collura F., Santin A., Serna-Garcìa R | Biogas Upgrading Paired with B | 31st European Biomass Conference | 05-08 June 2023 | UNIPD, BTS | | |
| 16 | O | Evans Y. and Diaz-Chavez R. | Social participation in and acce | 31st European Biomass Conference | 05-08 June 2023 | ICL | | |
| 17 | O | Gaspari M., Chatzis A., Orellana E., | Metagenomic analysis on hydr | 10th International Conference on Sustainable Solid Waste | 21-24 June 2023 | ELGO, UNIPD | | |
| 18 | Oth | Diaz-Chavez R and Evans Y. | Online survey about CCUS and | 31st European Biomass Conference, Workshop "Harnessin | 5 June - 30 August 2023 | ICL | | |
| 19 | SPa | Lithourgidis A.A., Kotsopoulos T. A. | Bio-succinic acid production, u | Journal of Environmental Chemical Engineering, Volume 1 | 06 September 2023 | DTU | | |
| 20 | SPa | Morlino, M.S., Serna García, R., Savi | Cupriavidus necator as a platfo | Biotechnology Advances 69, 108264. | 03 October 2023 | UNIPD | | |
| 21 | WS | Rocío Díaz Chavez | CooCE HARNESSING THE POTE | 7th ACT Knowledge Sharing Workshop, Paris, France | 04-05 October 2023 | UNIPD, ICL | | |
| 22 | O | M. Gaspari, K. Xyrostilidou, T. Sfetsa | Optimizing Biomethanation Eff | 17th International Conference of the Hellenic Association | 02-03 November 2023 | ELGO | | |
| 23 | Po | Vigato F., Angelidaki I., Woodley J., | Dynamic Effect of CO 2 Concen | 2023 AIChE Annual Meeting - Book of Abstracts (Conferen | 05-10 November 2023 | DTU | | |
| 24 | Po | Santin A., Collura F., Morlino, M.S., | Biogas upgrading and PHA accu | Ecomondo | 07-10 November 2023 | UNIPD, BTS | | |
| 25 | SPa | Serna García R., Morlino M.S., Bucci | Biological carbon capture from | Bioresource Technology, 399, 130556 | 11 March 2024 | UNIPD | | |
| 26 | O | Spatola Rossi, T., Pankaj Gupte, A., S | Valorisation of CO2-rich waste | Carbon Recycling Network Conference | 25-27 March 2024 | UNIPD | | |
| 27 | SPa | Ghiotto G., De Bernardini N., Giange | From microbial heterogeneity t | Chemical Engineering Journal, 485, 149824 | 01 April 2024 | UNIPD, DTU, ELGO | | |
| 28 | Web | Rocio Diaz-Chavez, Bettina Mueller, | Biogenic CO2 use and storage: | GBEP Webinar: Biogenic CO2 use and storage: Enhancing t | 15 April 2024 | ICL, BTS | | |
| 29 | O | Grimalt-Alemany A., Angelidaki I. | Modelling fermentative biogas | 18th IWA World Conference on Anaerobic Digestion, Istan | 02-06 June 2024 | DTU | | |
| 30 | Web | Rocio Diaz-Chavez | NZIP Innovation Showcase: Em | NZIP Innovation Showcase: Emissions Reduction and Rem | 04 June 2024 | ICL | | |
| 31 | O | Rocio Diaz-Chavez, Sara Giarola | Bio-CO2 from biogas: status, o | Rome 11th GBEP Bioenergy Week | 17 June 2024 | ICL, BTS | | |
| 32 | WS | Rocio Diaz-Chavez, Bettina Mueller, | Technologies for CO2 capture a | Rome 11th GBEP Bioenergy Week | 17 June 2024 | ICL, UNIPD, BTS | | |
| 33 | O | Morlino, M.S., Serna-García, R., Spa | Cupriavidus necator as an effic | Young Water Professionals European Conference 2024 | 16-19 June 2024 | UNIPD, BTS | | |
| 34 | O | Morlino, M.S., Serna-García, R., Den | Bioconversion of anaerobic dig | 11th International Conference on Sustainable Solid Waste | 19-22 June 2024 | UNIPD, BTS | | |
| 35 | O | Evans, Y and Diaz-Chavez R | Stakeholders' perspectives in t | 32nd European Biomass Conference | 24-27 June 2024 | ICL | | |
| 36 | Po | Diaz-Chavez R, Evans Y and GIarola | Harnessing the potential of Bio | 32nd European Biomass Conference | 24-27 June 2024 | ICL | | |
| 37 | SPa | Santin, A., Spatola Rossi, T., Morlino | Autotrophic poly-3-hydroxybu | Bioresource Technology, 406, 131068 | 05 July 2024 | UNIPD | | |
| 38 | SPa | Santin, A., Collura, F., Singh, G., Mor | Deciphering the genetic landsc | Biotechnology for Biofuels | 16 July 2024 | UNIPD | | |
| 39 | WS | Dr Yara Evans and Dr Ioannis Zacha | CCUS Conference and ACT kno | ACT and CETP TRI3 CCUS Knowledge Sharing Conference, C | 11 September 2024 | ICL, DTU | | |
| 40 | PPa | Spatola Rossi, T., Morlino, M.S., San | CO2 capture and its bioconvers | Science4all, Padova, 2024 | 28-29 September 2024 | UNIPD, BTS | | |
| 41 | WS | All partners | Third CooCE online training wo | Online | 18 October 2024 | DTU, ICL, UNIPD, ELGO, LEM | | |
| 42 | Po | Morlino, M.S., Spatola Rossi, T., Fra | Advancing biogas upgrading fo | Ecomondo | 05 November 2024 | UNIPD, BTS | | |
| 43 | O | Spatola Rossi, T., Francescato L., Tre | Genetic engineering of Cupriav | 7th Applied Synthetic Biology in Europe Conference | 06-08 November 2024 | UNIPD | | |
| 44 | O | Diaz-Chavez R and Evans Y. 2024 | Socio-economic assessment of | 8th AIEE Energy Symposium on Current and Future Challer | 28-30 November 2024 | ICL | | |
| 45 | O | Sara Giarola, Pablo Basterrechea-R | Enhancing the CO2 potential a | 8th AIEE Energy Symposium on Current and Future Challer | 28-30 November 2024 | ICL | | |
| 46 | WS | Laura Treu, Rocio Diaz-Chavez | Final CooCE -CO2toCH4 conjun | Final CooCE meeting | 26 November 2024 | All partners | | |
| **Post project dissemination activities - up to July 2025** | | | | | | | | |
| 47 | Spa | Spatola Rossi T., Francescato L., Gu | Harnessing the potential of Cu | Bioresource Technology, Volume 419, 132060 | 15 January 2025 | UNIPD | | |
| 48 | O | Evans Y and Diaz-Chavez R | Social sustainability assessmen | 33rd European Biomass Conference | 9-12 June 2025, Valencia | ICL | | |
| 49 | Po | Dr Rocio A Diaz-Chavez; Dr Yara Eva | Integrated Sustainability assess | 33rd European Biomass Conference | 9-12 June 2025, Valencia | ICL | | |
| 50 | Spa | Zacharopoulos, Ioannis; Grimalt-Ale | Complete Scheme for Biosucci | Biochemical Engineering Journal, 218, 109687 | February, 2025 | DTU | https://dc | published |
| 51 | O | Grimalt-Alemany, Antonio; Zacharo | Modelling succinic acid fermen | 16th AIChE - Metabolic Engineering Conference, Copenhag | 12-15 June 2025, Copenhag | DTU | | |

Figure 27. Dissemination activities during the CooCE project and post-project.

The project had a final consortium meeting and public workshop. The meeting was conducted in Padova November 25th-27th, 2024. The agenda is included in the Annex in this report. The meeting included a visit to a biogas plant with the partner BTS and visits to the Laboratories of the partner University of Padova as well as the Botanical Garden where the workshop took place. The workshop presented results from two projects: ACT - CooCE (UNIPD) and LIFE2020 - CO2toCH4 (PPC Renewables. Photos of final meeting in Padova November 25-28th, 2024 (Figure 28).

| | |
|---|---|
|  |  |
| Visit to Biogas plant | Partners and project coordinators with CEO of biogas plant. |
|  |  |
| Group of two projects at Biogas plant near Padova | Imperial team at Biogas plant |
| | |
|  |   |
| Dr Evans presenting at workshop | MSc P Basterrechea presenting on LCA |


Dr S Giarola using the tool developed by Imperial for training


Dr R Diaz-Chavez moderating traning

Participants using the tool for training


Imperial team at workshop


Two projects photo group at final event

CooCE partners visiting labs and demo plant of CO2 use for PHB production (Dumbo)

Figure 28. Photos of last workshop and meeting in Padova 2024.

# 6. Impact

The sustainability assessment of the CooCE platform was innovative as it allowed the optimisation of the supply chains analysis and processes with data directly provided by the partners during the project. The CooCE platform can be a promising alternative to fossil-derived materials. Some products (biomethane and biosuccinic acid) show higher readiness than others (biopolymers). The deployment of the CooCE biorefinery should be aligned with renewables targets in the electricity generation, for an effective emission reduction. Result validity is limited to the modelling assumptions and should not be generalised to any source of CO2.

The successful implementation of CCUS technologies demand a coordinated and comprehensive response as was expressed also by stakeholders. The methodology for sustainability allowed to strengthen collaboration among partners in different sectors and demonstrated that aligning efforts and sharing expertise and fostering greater commitment from businesses and governments a transition toward low-carbon circular economies may be possible. The project also demonstrated that state support will be essential, both in terms of financial incentives and capacity-building, alongside the establishment of stable and coherent regulatory frameworks that provide clarity and confidence for industrial-scale deployment of CCUS. The project stimulated the participation of women in STEM and was more women oriented in comparison with other projects, having women leading tasks and team groups. Finally, the CooCE concept and its techno-processes offer a compelling route for decarbonising industrial and energy sectors, enhancing long-term competitiveness and economic resilience while enabling countries to achieve their carbon reduction targets, advance toward Net Zero, and address the challenges of climate change.

## 6.1 Plans for further technology development

The techno-economic assessment indicated that for all three pathways, economic feasibility remains challenging. In most cases, the resulting minimum selling price of the products is higher than that of the fossil alternative. Biomethanation is the most feasible pathway, though it also presents some challenges. ELGO-DIMITRA aims to commercialize the novel $CO_2$ capture and utilization method developed in WP2 for biomethane production, demonstrated at the pilot scale. Plans are in place to establish a dedicated spin-off company to facilitate technology transfer from research to market, targeting the biogas sector and other $CO_2$-intensive industries. The spin-off will focus on scaling up the technology, improving process efficiency, and pursuing new market opportunities through strategic collaborations and industry partnerships to promote sustainable, circular economy solutions. The WP3 technology for simultaneous succinic acid production and biogas upgrading shows significant promise for scale-up. In biosuccinic acid production the price depends on factors such as product grade, the use of cheap raw materials, and revenue from side products. Additionally, oil price cross-elasticities could impact the results, especially considering the high share of fossil-derived solvents in the processes, particularly in the biopolymer route. Technical improvements are needed, particularly in optimizing the in-situ product recovery system to reduce electricity consumption and refining downstream processes to enhance succinic acid crystal purity. These advancements will help lower the selling price and expand potential applications. Collaboration with industry partners is highly desirable for future funding schemes to accelerate commercialization. WP4 focused on the conversion of $CO_2$ into polyhydroxyalkanoates (PHA), showcasing strong commercial potential due to successful pilot-scale trials and increasing market demand for eco-friendly plastic products. However, biopolymer production currently faces high costs, particularly in synthesis and purification. Further research is needed to improve yields and explore alternative solvents. These advancements will help enhance the economic viability and market competitiveness of PHA production, creating opportunities for broader industry adoption and commercialization.

# 7. Key recommendations

To ensure the successful deployment, scalability, and long-term sustainability of carbon capture, utilization and storage (CCUS) technologies within a circular economy framework, the CooCE project proposes a series of targeted recommendations. These are based on comprehensive environmental, economic, social, and policy assessments carried out over the course of the project. The following recommendations aim to guide policymakers, industry stakeholders, and researchers in supporting the market readiness and societal acceptance of bio-based CCUS pathways.

**1. Policy and Regulation**

- Develop dedicated CCUS policies that recognize biogenic $CO_2$ utilization, define feedstock eligibility, and support bio-based product certification.
- Integrate CCUS within circular economy and renewable energy frameworks, ensuring that captured carbon products are accounted toward climate and sustainability targets.
- Streamline regulatory approval for CCUS-derived products to facilitate commercialization and market entry.
- Provide stable and long-term policy signals to attract investment and encourage industrial adoption of CCU technologies.

**2. Technical Development**

- Prioritize process optimization to improve yields and reduce energy intensity, particularly for bio-succinic acid and PHA production.
- Enhance scalability of biopolymer production through improved fermentation processes, solvent substitution, and downstream purification.
- Promote integration of renewable electricity (e.g., via electrolysis for $H_2$ production) to minimize carbon footprint and enhance CCU sustainability.
- Advance bioreactor designs to address gas–liquid transfer limitations and ensure safe operation with hydrogen and oxygen.

**3. Economic and Financial Support**

- Introduce financial incentives and subsidies (e.g., CAPEX support, green premiums) to reduce market risks and bridge the cost gap with fossil alternatives.
- Support pilot-to-commercial scale-up efforts, including spin-offs and public-private partnerships, especially for high-readiness pathways like biomethane and bioSA.
- Explore value co-creation through valorisation of side-streams and co-products (e.g., fertilizers, biogas digestate).

**4. Sustainability and Assessment**

- Continue integrated sustainability assessments (environmental, social, economic, policy) across the full value chain to ensure holistic performance monitoring.
- Align CCU project development with national renewable energy targets to maximize emissions reductions.
- Update assessments with real-world data as processes scale and diversify $CO_2$ sources beyond biogas.

**5. Stakeholder Engagement and Training**

- Expand training and capacity-building programs on CCU and bioeconomy to industry professionals, policy-makers, and local communities.
- Use stakeholder feedback to refine technologies and address social acceptability, equity, and employment concerns.
- Leverage digital platforms (e.g., CooCE Sustain) for open access to data, tools, and policy insights to facilitate broader replication.

## 7.1 Conclusions

The CooCE project demonstrated that biologically based carbon capture and utilization technologies hold significant potential for decarbonising industry while supporting the transition to a circular and sustainable economy. Through a multidisciplinary approach encompassing technical development, sustainability assessment, and stakeholder engagement, the project identified viable pathways for producing biomethane, bio-succinic acid, and bioplastics from $CO_2$. While challenges remain, particularly regarding cost competitiveness, scale-up, and regulatory alignment, the findings provide a strong foundation for future innovation and market deployment. Continued collaboration across research, industry, and policy will be essential to realize the full potential of CCUS technologies and to accelerate progress toward climate neutrality and resource-efficient economies.

# 8. References

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