Accelerating CCS Technologies

CooCE

Harnessing the potential of biological CO2 capture for the Circular Economy

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Report:
CooCE Handbook methodologies and tools

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Abbreviations

ACRONYM	DEFINITION
BioSA	Biosuccinic Acid
CCUS	Carbon Capture, Use and Storage
CH_4	Methane/Biomethane
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
IC	Imperial College London
EOR	Enhanced Oil Recovery
EU	European Union
EUBCE	European Biomass Conference and Exhibition
EU ETS	EU Emissions Trading Scheme
HRSG	Heat recovery steam generator
H_2	Hydrogen
LNG	Liquefied Natural Gas
Net Zero	Commitment to reaching net zero carbon emissions by 2050
PHA	Polyhydroxyalkanoates (polymers)
R&D	Research and Development
SWOT	Strengths, Weaknesses, Opportunities, Threats
TRL	Technological Readiness Level
T&S	Transport and Storage
WP	Work Package

1. The toolkit

This report aim is to present the **Handbook** of CooCE in the format of a **Toolkit** . It aims to present in a rapid form the key methods, tools and processes used for the different pathways of the CooCE platform. The toolkit is meant to enable industrial actors and other stakeholders to scope the feasibility and procedures for the production of the main products under the CooCE concept.

The toolkit also presents key results of the CooCE project as part of its exploitation goals. The handbook or toolkit addresses nine main topics for rapid access by users for scoping their own activities related to circular economy and the possibilities of using carbon dioxide captured from different sources, in this case biogas plants. Each topic contains a series of live links that enable the user to access various documents within COOCE's webpage and other relevant literature.

The topics presented are:

1. The CooCE concept
2. CCUS and biogas production
3. Biomethanation
4. Succinic acid
5. Succinic acid with biogas upgrade
6. Biopolymer production through CCUS
7. Circular CO2 to PHB conversion
8. Supply chain modeilng
9. Social sustainabilit assessment

The Handbook/toolkit is not intended to replace full methods descriptions but is meant instead to provide ready and easy access to variety of methods, information and resources.

Each section presents references and links. The handbook is also available in Greek, Italian and Danish. By clicking in each section the user can go directly to that section and clicking toolkit will return the page of all sections.

TOOLKIT

- [The CooCE concept] ✓
- [CCUS and biogas production] ✓
- [Biomethanation] ✓
- [Succinic Acid] ✓
- [Succinic Acid Production with CCS] ✓
- [Biopolymer production through CCUS] ✓
- [CO2 to PHB conversion] ✓
- [Supply chain Modelling] ✓
- [Social sustainability assessment] ✓

The COOCE Concept

[Toolkit](#)

The CooCE concept aims to contribute to the shift towards a resource-efficient, low-carbon and climate-resilient economy. It will do so by offering industries a way to decarbonise their operations through a portfolio of diverse and flexible CCUS technologies that can also help reduce dependence on fossil resources. CCUS technologies transform CO_2 into valuable commercial products or materials (e.g. construction materials, fuels, chemicals, and plastics) or into feedstocks for further industrial processing. In the CooCE concept, CO_2 is converted into (final or intermediate) bioproducts using different CCUS technologies (Figure 1), described as follows.

High purity biomethane, (CH_4>95%) is obtained from CO_2 hydrogenation. This technology enables on-site hybrid energy storage: it valorises the renewable energy excess into hydrogen and generates biomethane. Biomethane is usable either as a liquid (equivalent to LNG and that can provide a useful alternative to shipping) or as a compressed gas (equivalent to CNG) that can be used in most vehicles and can be injected into the natural gas grid.

Biosuccinic acid (BioSA) is obtained from a fermentation of biogas alongside a carbohydrate-rich feedstock (typically coming from waste streams). This technology would obviate the need to use biomass feedstocks and avoid land for cultivation. BioSA readily replaces the fossil-based chemical succinic acid. Succinic acid is used for making numerous commodities in chemical, food, agricultural and pharmaceutical industries. Its demand comes from the personal care, beverage, polyurethane, and bioplastics industries.

Biopolymers (PHAs) are obtained through bio-catalytic technologies (based on *Cupriavidus necato*r and *Synechocystis*) which use carbon-rich waste streams such as biogas. These biopolymers are accumulated as storage materials within the cells of microorganisms, serving both as carbon and energy reserve. PHAs have similar characteristics to common plastics. In addition, they are biocompatible and biodegradable. They are produced at industrial scale for many products, such as bioplastics for packaging, prebiotic and nutritional compounds for medical applications, and bio-creams for cosmetics.

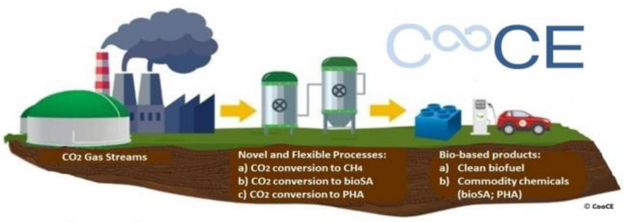

Figure 1 The CooCE Concept

References/Links

CooCE. 20224. Harnessing potential of biological CO2 capture for Circular Economy. https://cooce.eu/

CCUS and biogas production

[Toolkit]

The International Panel on Climate Change (IPCC) (2014) stated that the world must reach net-zero greenhouse gas emissions by mid-century and net negative emissions shortly thereafter to mitigate the severe consequences of climate warming. Therefore, activities such as CO2 recycling help abate anthropogenic emissions, the CO2 emitted is captured and converted into valuable chemicals, fuels, or materials. As CO2 is used as a feedstock in several industries, companies are interested in biogenic CO2, a climate-friendly source of CO2

Biogenic CO2 is carbon dioxide (CO2) resulting from the decomposition, digestion or combustion of biomass or biomass-derived products. Is part of the “natural short carbon cycle”. This atmospheric CO2 is assimilated by biomass through photosynthesis, then returned, as biogenic CO2, to the atmosphere or to the soil, depending on the conversion type and final use of biomass. According to the European Biomass Association (EUBA, 2022), there is no CO2 accumulation in the atmosphere during the natural short carbon cycle, instead, burning fossil carbon dioxide stored underground and previously not accessible releases additional CO2 into the atmosphere.

Sources of biogenic CO2 include: solid, liquid and gaseous biomass fuel combustion, bioethanol fermentation, wine and beer production and biogas upgrading process in the biogas industry, as in the case of CooCE.

Figure 1. Examples of sources of CO2 in the CooCE project

There have been different mitigation measures to mitigate GHG emissions, such as the reduction on use of fossil fuels (including coal and natural gas), improve transport fuels with biofuels, move out from use of fossil fuels for transport, reduce emissions from industrial sector and reduce deforestation and emissions from agriculture among others.

Some of the most recent ones include alternative forms of reducing the eCO2 in the atmosphere using technologies such as carbon capture and storage (CCS), carbon capture and utilisation (CCU), carbon capture use and storage (CCUS) as the one used in the CooCE project. Some definitions from the European Biomass Association (EUBA, 2022) are presented below:

- **Carbon Capture and Utilisation**” or **CCU:** solutions with capture of CO2 for its use as a feedstock to produce fuels, chemicals and materials. Using biogenic CO2, low-carbon or renewable energy sources, they can displace their fossil-based counterparts and thus reduce net carbon dioxide emissions to the atmosphere. These solutions are “**bio-CCU**” and involve sustainable circular carbon economy principles, as it includes CO2 reduction, reuse, recycling and removal.
- **Bio-Carbon Capture and Storage**” or **bio-CCS**, is when biogenic CO2 is captured and permanently stored underground in forms of **geological storage** such as depleted gas fields or deep saline aquifers; it allows CO2 to be permanently removed from the atmosphere.
- **Bio-CCUS**” refers to Biogenic CO2 stored for a long time in a new product, either construction material or plastics. This uses biogenic CO2 to manufacture new materials.

When ccomparing CCU with fossil CO2 and CCU with biogenic CO2 as in the following diagram (EUBA, 2022), it can be seen that there are several advantages of CCU with biogenic CO2.

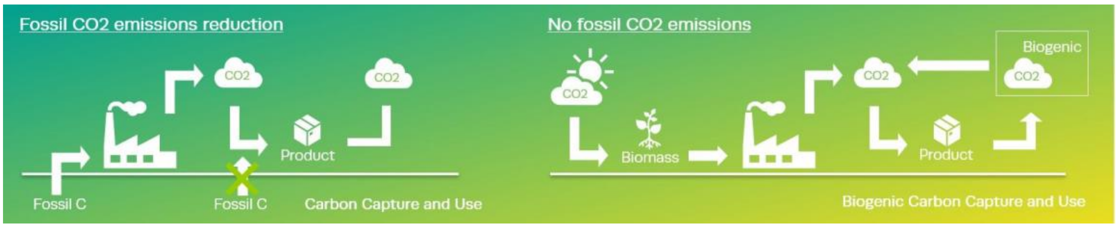

Figure 2. Comparison of CO2 emissions from fossil and non-fossil (EUBA, 2022)

ADVANTAGES

1. the source of CO2 (fossil vs biogenic)
2. the product or service the CO2-based product is displacing and the related emissions avoidance enabled by the use of biogenic CO2
3. the product’s carbon storage length (temporary vs permanent)
4. energy efficiency and carbon footprint for the conversion of CO2 into other molecules
5. the scale of the opportunity for CO2 use

The possibilities of capturing CO2 and been use for other supply chains and products are explained in the CooCE concept. Imperial College contributed to different international *fora* explaining these concepts. Additional concepts and database on CCUS can be found in the CooCE website as well as National Policies on CCUS.

References and links

CooCE. 20224. Harnessing potential of biological CO2 capture for Circular Economy. https://cooce.eu/

Diaz-Chavez R and Muller B. 2024. “Biogenic CO2 use and storage: Enhancing the circularity and climate benefits of biogas”. GBEP webinar. https://www.youtube.com/watch?v=p6bSd3PlSww&t=4s

EUBA, 2022. EBA Statistical Report 2022. https://www.europeanbiogas.eu/__trashed-3/

International Panel on Climate Change (IPCC) (2014). https://www.ipcc.ch/report/ar5/syr/

Biomethanation

[Toolkit]

OPTIMAL CONDITIONS FOR CONTINUOUS EX-SITU BIOMETHANATION

Methane (CH_4) is a colourless, odourless gas and the primary component of natural gas. Because it is widely available and contains a lot of energy, methane is used in many industries. Key applications include energy generation, where it is burned in power plants to produce electricity, heating in homes, businesses, and industrial settings, and as a transportation fuel in the form of compressed or liquefied natural gas (CNG or LNG). Methane can also be generated biologically by converting carbon dioxide (CO_2) and hydrogen (H_2) into it, a process known as "***biomethanation***". This conversion is facilitated by specialized anaerobic microorganisms, known as hydrogenotrophic methanogens. The process is termed *ex-situ* when the CO_2 is sourced from external sources (for example exhaust gases, biogas, syngas etc.) and is supplied with H_2 to the liquid phase of the reactor.

As part of the CooCE project, ELGO-DIMITRA led Work Package 2, which focused on studying the biomethanation process and establishing the ideal conditions. This study was conducted using small-scale (laboratory-scale) anaerobic reactors in a trickle bed configuration (Fig. 1). Reactors of this design are filled with materials that allow microorganisms to settle on them. Two materials were tested: activated carbon pellets and K1 polyethylene Raschig Rings. The reactors were evaluated based on how well they produced CH_4 when the amount of gas supply gradually increased, and when the gas supply was stopped for 2 to 5 weeks. In the first case, K1 Raschig Rings worked better, achieving a CH_4 purity of 95% at all tested levels of gas supply (ranging from $0.083L/L_{Reactor}/h$ to $1L/L_{Reactor}/h$). In the second case, both materials performed well even after long periods without feedstock, quickly returning to 95% CH_4 purity when the supply was resumed.

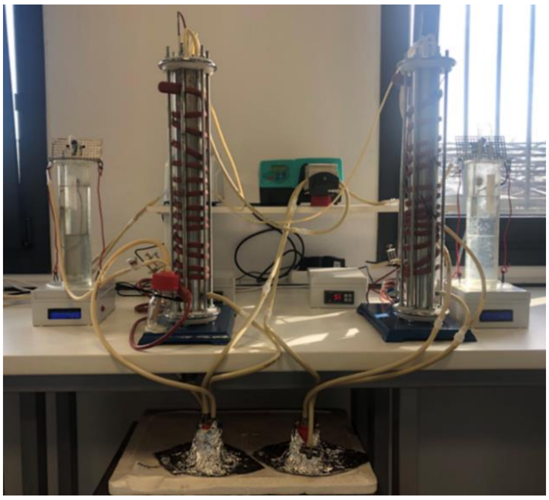

Figure 3. Lab-Scale bioreactors set-up

Additionally, the biomethanation process was tested on a larger scale using a prototype reactor with a 100L working volume (Fig. 2). Based on the small-scale results, K1 Raschig Rings were chosen for the pilot reactor. However, the study showed that scaling up from small experiments to larger ones isn't always easy. When trying to gradually increase the gas supply like in the lab tests, the reactor's performance became unstable. Despite these challenges, with careful monitoring and adjustments, the reactor was able to meet and exceed the CooCE targets, achieving a CH_4 purity above 95% and capturing over 5 kg of CO_2 per m^3 of reactor per day, fulfilling the project's goals.

Figure 4. Pilot-scale bioreactor set-up

Reference and links

https://cooce.eu/hellenic-agricultural-organization-dimitra-elgo/
https://cooce.eu/oral-presentation-in-international-conference-by-gaspari-et-al-2023/
https://cooce.eu/seminar-at-summer-school-by-dr-kougias-in-2022/

Succinic acid

Toolkit

The Technical University of Denmark (DTU) worked on succinic acid which is a dicarboxylic acid with the chemical formula $(CH_2)_2(CO_2H)_2$. Its name derives from the Latin word succinum which means amber, as it was historically produced by amber distillation. Nowadays, though succinic acid is mainly derived industrially by petrochemically based substrates and the main process for its production is the hydrogenation of maleic anhydrite. However, in order to reach the net zero emission goal by 2050 set by the European Union, there is an urgent need for the shift to cleaner and less carbon intensive production methods. This is becoming even more important if it is taken into account that the demand for succinic acid is rising, projected to be 200-million-dollar industry 2026 [1].

The rise in the demand for succinic acid is driven by its role as platform chemical and the vast and diverse variety of applications it has. It can be used as a percussor to produce a wide array of industrial chemicals and as a building block for bioplastics, mainly polybutylene succinate. Due to its properties as surfactant, succinic acid is used as a detergent ingredient and it is also has been used in the food industry, as acidity regulator. Finally, due to its anti-inflammatory properties, it has been found applications in the pharmaceutical industry [2,3].

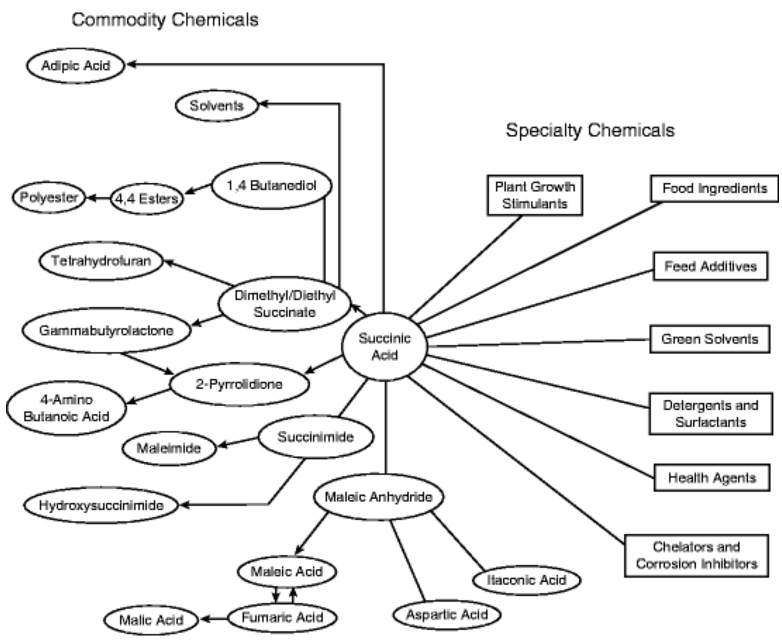

Figure 5: Applications of succinic acid (Zeikus et. al. (1999))

The alternative to the petrochemical based production of succinic acid is the use of biological processes such as microbial fermentation. Their use poses a plethora of advantages: These processes are less energy and carbon intensive compared to process using petrochemically derived substrates, waste streams can be utilized as substrates and the process can be included in a biorefinery system, the microbial production of succinic acid requires the consumption of CO_2, making the process an excellent carbon sequestration method.
Succinic acid is part of the tricarboxylic acid (TCA) cycle. Most of the microorganisms that are able to produce it achieve this through the reverse TCA cycle and therefore, instead of producing CO_2 they consume it. More specifically, for every mole of succinic acid produced 1 mol of CO_2 is required and consequently captured by the process. Moreover, the most abundant CO_2 is the higher succinic acid yield can be achieved, as high concentrations of CO_2 favor the metabolic shift towards the succinic acid pathway, producing less of other organic acid by-products such as acetic and formic acid [4,5].

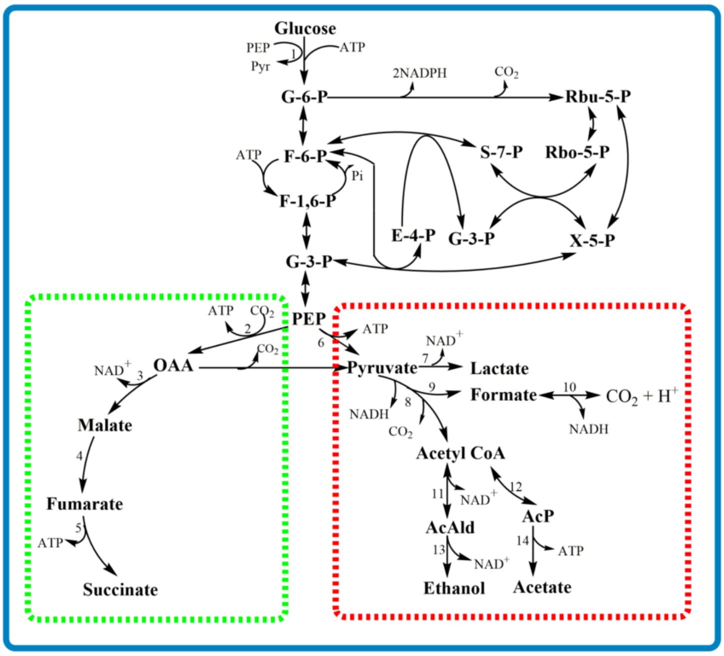

Figure 6: Metabolic pathway of Actinobacillus succinogenes, one of the main succinic acid producing microorganisms (Dessie et. al (2021))

The carbon fixation ability of a succinic acid processes have been demonstrated to be higher, than other carbon assimilating biological processes, such as algae cultivation [6] and its combination with the utilisation of waste streams as fermentation substrate can be a solution for the much needed shift to a more sustainable platform chemical production

Reference and links

1. Intelligence, M. *Succinic Acid Market - Growth, Trends and Forecasts (2019- 2024)*. https://www.mordorintelligence.com/industry-reports/succinic-acid-market (2019).
2. Zeikus, J. G., Jain, M. K. & Elankovan, P. Biotechnology of succinic acid production and markets for derived industrial products. *Appl Microbiol Biotechnol* **51**, 545–552 (1999).
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5. Dessie, W., Wang, Z., Luo, X., Wang, M. & Qin, Z. Insights on the Advancements of In Silico Metabolic Studies of Succinic Acid Producing Microorganisms: A Review with Emphasis on Actinobacillus succinogenes. *Fermentation* **7**, (2021).
6. Zhang, Q. *et al.* Carbon capture and utilization of fermentation CO2: Integrated ethanol fermentation and succinic acid production as an efficient platform. *Appl Energy* **206**, 364–371 (2017).

Succinic Acid Production with CCS

Toolkit

Succinic acid can be produced biologically as it is one of the main metabolites of the tricarboxylic acid (TCA) cycle, the main metabolic pathway microbes are using to produce energy by consuming an organic carbon source. Certain bacteria, such as *Actinobacillus succinogenes* are natural overproducers of succinic acid, as they produce and secretes extracellularly large amounts of it. The production of succinic acid occurs through the reverse TCA cycle and in addition to the organic carbon, CO_2 is needed in order to shift the metabolic pathway towards succinic acid favouring its production instead of the production of other organic acids, such as acetic or formic acid. Moreover, the production of succinic acid and the consumption of CO_2 is happening in 1:1 mole ratio, meaning that this process is well suited to be used as a carbon capture technology [1].

Another biological process with big economic potential a positive environmental impact is anaerobic digestion, where a mixed culture is consuming organic substrate, producing biogas (CH_4 and CO_2) a mixture resembling natural gas. The biogas has a consistency of around 55% CH_4 and 45 % CO_2. However, for it to be able to be able to be used as a fuel and be able to be injected in the natural gas grid, it needs to have a CH_4 content of over 90%. Therefore, biogas needs to be upgraded by removing the CO_2 it contains.

Looking at both processes, there is a clear connection between them, and they can be combined synergistically, creating a platform that produces both valuable chemicals and clean biofuels. The biogas coming from an anaerobic digestion unit, can be used to as the inorganic carbon source for succinic acid fermentation, resulting in the production of both very high quality biomethane and succinic acid.

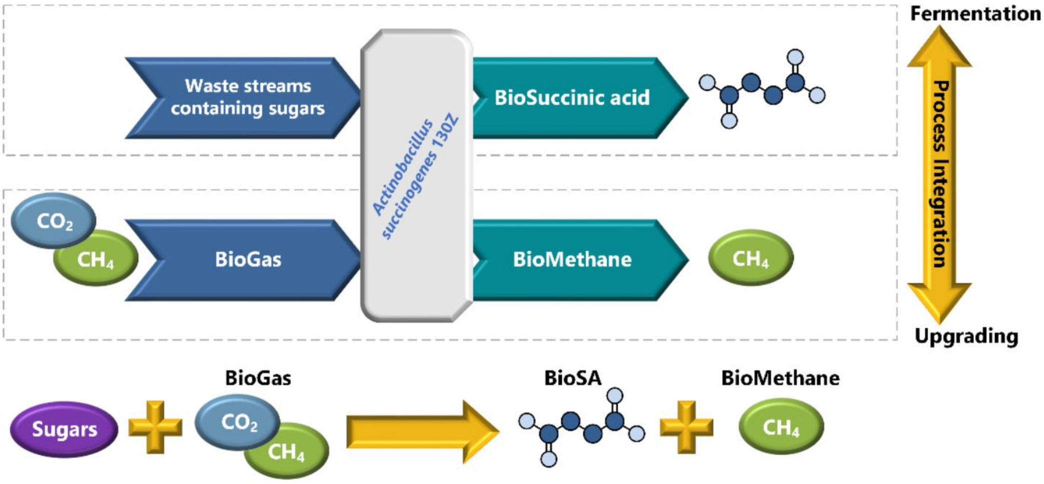

Figure 7: Schematic of the succinic production process developed in DTU

For the process developed at the Technical University of Demark (DTU) on WP3 the waste stream of candy production is used. The wate stream is comprised of three different sugars, namely glucose, sucrose and maltose. This is an excellent substrate for microbial fermentation for a plethora of reasons. It mainly comprises of sugars, which bacteria are able to naturally grow, without the need for any genetic modification, despite being a waste stream it does not contain toxic substances that can have an inhibitory effect on the growth of the bacterial culture, as it is a waste stream it comes with a very low cost, lowering the total cost of the process, while increasing its sustainability and its profitability[2].

The high amount of succinic acid that *A. succinogenes* is able to produce can be a disadvantage, as high concentrations can have an inhibitory effect on its growth and subsequently on the yield and the productivity of the process. For this reason, an in situ electrochemical recovery module has been incorporated to the process. By applying electrical potential on the system, succinic acid is separated using an anion exchange membrane[3].

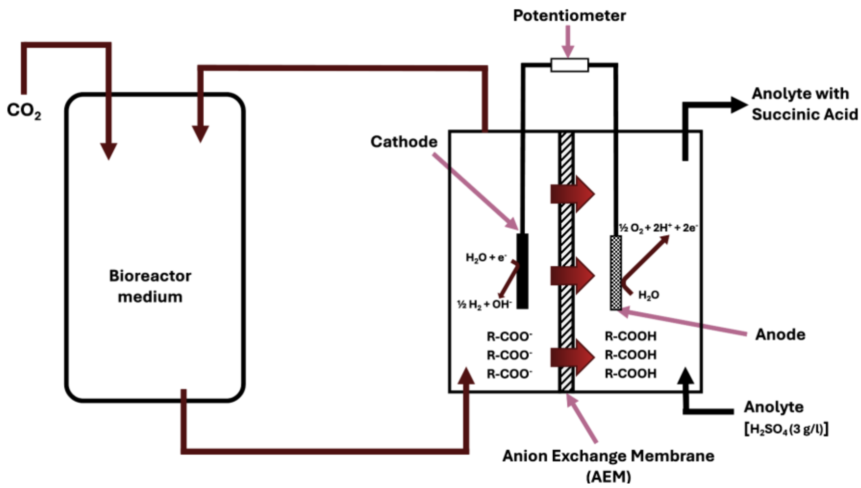

Figure 2: Schematic of the in-situ product recovery process

The incorporation of this module in the process, can lead in multiple advantages: By removing the inhibiting succinic acid and other organic acid by-products, the yield of the process is higher. Succinic acid is separated in-situ leading to diminished cost in the downstream processing part of the process, which is a known economic bottleneck for most bioprocesses[4].

This process that, incorporates both biogas upgrade and in-situ product recovery is a very promising solution for integrating the production of succinic acid in a platform chemical and energy biorefinery, integrating an aspect of carbon capture, boosting its environmental sustainability and economic feasibility.

References and links

1. McKinlay, J. B. & Vieille, C. 13C-metabolic flux analysis of Actinobacillus succinogenes fermentative metabolism at different NaHCO3 and H2 concentrations. *Metab Eng* **10**, 55–68 (2008).
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3. Pateraki, C., Andersen, S. J., Ladakis, D., Koutinas, A. & Rabaey, K. Direct electrochemical extraction increases microbial succinic acid production from spent sulphite liquor. *Green Chemistry* **21**, 2401–2411 (2019).
4. Kumar, R., Basak, B. & Jeon, B.-H. Sustainable production and purification of succinic acid: A review of membrane-integrated green approach. *J Clean Prod* **277**, 123954 (2020).

Biopolymer production through CCUS

Toolkit

Massive plastic usage greatly contributes to pollution and global warming, since production relies mainly on fossil-based carbon and energy sources. Plastics contribute directly to the emission of greenhouse gases (GHGs) in every step of their life cycle, from extraction, refining and manufacturing to disposal. Moreover, they are usually unrenewable and non-biodegradable, so they can persist in the ecosystems for hundreds of years, entering the food chain and ultimately becoming also a human health concern. Biopolymers can be produced by plants (e.g. starch and polylactic acid, PLA), animals (chitosan and chitin), and microorganisms (polyhydroxyalkanoates, PHA) or obtained by processing renewable resources (e.g. biomass, agricultural residues and industrial wastes). The adoption of biopolymers can be environmentally advantageous, even more so if the production process relies on capturing the CO_2 as carbon source.

Among the CooCE project objectives, the production of biopolymers from CO_2 represents an innovative aspect, helping to close the carbon loop, in a circular system where carbon emissions are recycled into valuable products. Biopolymers are naturally produced by living organisms, making them available for production through fermentation: by knowing the appropriate culturing conditions, the metabolism of selected organisms can be leveraged to maximise the production of the target biopolymer.

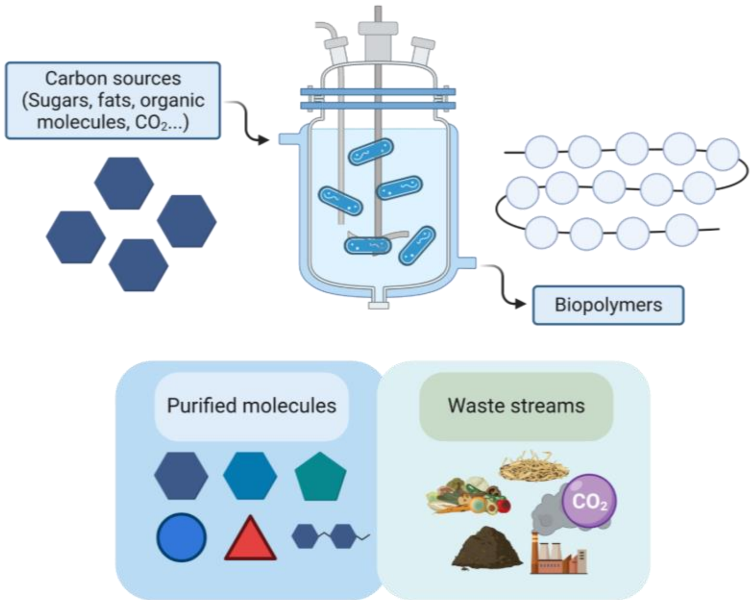

Figure 1. Schematic representation of a bioprocess where microorganisms convert the given carbon source into a biopolymer. Carbon sources are exemplified in the bottom panel.

In a circular economy context, the carbon contained in waste streams can be used as a source for biopolymer production: this is an excellent strategy for lowering costs, while also providing a pathway to dispose of waste streams. In this view, CO_2 is an ideal low-cost carbon source to exploit, as it is abundant in the flue gases of many industrial processes in sectors ranging from steel, iron and cement making to biofuel production and waste incineration. The existence of microorganisms capable of simultaneously fixating CO_2 and producing biopolymers opens the way to the development of alternative CO_2 capture, utilisation and storage (CCUS) routes which rely on these metabolic capabilities.

Traditional plastics still dominate many industry sectors. They are cheap, durable, with several characteristics which make them still difficult to replace for companies. However, their use is associated with issues that are no longer negligible and an environmentally and economically sustainable alternative is urgently needed. The increasing demand of biopolymers in the market is mostly coming from the packaging sector and the production of single-use items, where biopolymers represent a viable alternative to fossil-based plastics. However, PHB, which has the best characteristics in terms of biodegradability, still represents a limited share due to the high costs, which greatly depend on the carbon source. Hence, the development of a cost-efficient CO_2 to PHB conversion represents an opportunity which would respond to increasing market demand and mitigate climate change.

References and links:

- https://cooce.eu/wp4/
- https://www.grandviewresearch.com/industry-analysis/biopolymers-market-report

CO2 to PHB conversion

Toolkit

The University of Padua is involved in the CooCE project with a work package focused on the bioconversion of CO_2 and industrial waste streams into polyhydroxybutyrate (PHB), within a circular economy view. The conversion of CO_2 into PHB is achieved using the bacterium *Cupriavidus necator* and cyanobacterium *Synechocystis* sp. B12. PHB is a highly biodegradable polymer, with properties similar to the more common fossil-based alternative, polypropylene. The microorganisms employed in the bioconversion produce PHB in the form of intracellular granules and are able to use CO_2 as the sole carbon source. *C. necator* is able to store high amounts of biopolymer (up to 70% of the cell dry weight) and fixate CO_2 in presence of hydrogen and oxygen. However, wastewaters rich in sugars and volatile fatty acids can be used for bacterial growth, allowing for the development of a flexible process. The cyanobacterium *Synechocystis* sp. B12 is a photosynthetic organism, so it needs mainly sunlight, water and CO_2 to thrive and doesn't require expensive feedstocks that often represent a huge cost for this kind of biological processes, impacting their overall scalability.

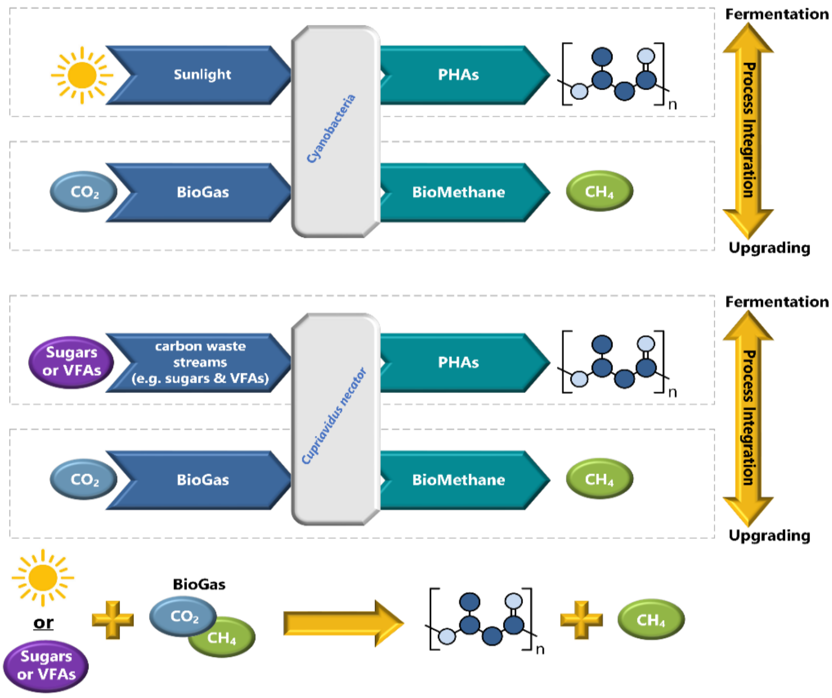

Figure 1. Flow diagram of the bioprocesses for CO_2 to PHB, devised within Work Package 4 of CooCE

Hence, UniPD is developing two bioprocesses for CO_2 to PHB conversion, with the ambitious aim to couple them with biogas production: indeed, raw biogas has a significant amount of CO_2 that can be captured and fixated into PHB, yielding high-grade biomethane (>95% CH_4) that can be injected in the gas grid as an equivalent of natural gas. To this aim, UniPD teamed up with BTS Biogas Srl for provision of real biogas samples to carry out tests and process simulations. Additionally, BTS supports UniPD in process development, participating in the design of the systems necessary for biocatalysis. a pilot reactor, which has been named “Dumbo,” was studied, designed, and built to optimize the solubilization of gases in liquids under safe conditions (especially hydrogen) and promote the desired metabolism of the selected microorganisms (C. necator) present in the culture broth.

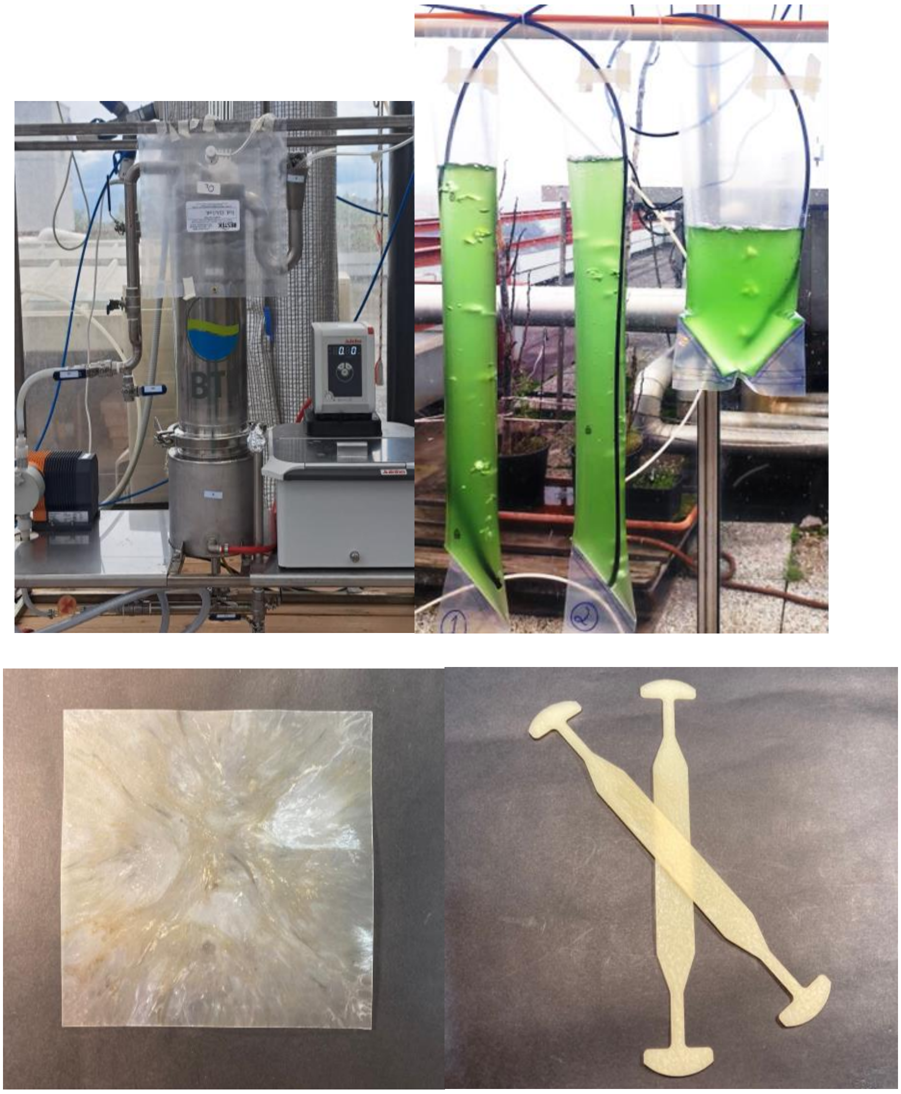

Figure 2. Bioreactors and photobioreactors used for PHB production with C. necator *(top left) and* Synechocystis *sp. B12 (top right). Samples of PHB produced at UniPD have been tested as laminates (bottom left) and packaging applications are being developed (bottom right).*

Currently, UniPD is optimising the two bioconversion systems at pilot scale with synthetic gas mixtures and proving feasibility of the integration with biogas upgrading, with encouraging results regarding the applicability of biogas as a CO_2 source.

The crucial aspect for CO2 to PHA bioconversion is hydrogen availability, and the process must be conducted, at least in the initial phases, in presence of excess hydrogen. The autotrophic metabolism of C. necator also involves oxygen, therefore the gas mixtures inside the reactor are within the explosive range for hydrogen. For these reasons, the design of the reactor ensures that the gas mixture does not come in contact with potential ignition sources. while liquids are atomized by passing through a special nozzle maximizing gas-liquid mass transfer.

The bioprocess of PHA production coupled to biogas upgrading is planned to occur in productive cycles: raw biogas enters the system and H_2 and O_2 are provided to allow CO_2 fixation into bioplastic granules. Methane is not used by the bacterial culture; hence it is purified as bacterial cells accumulate PHA. At the end of the process, when complete CO_2, H_2 and O_2 consumption is achieved, PHA-rich culture broth and upgraded biomethane are harvested from the reactor and a new cycle can start (Figure 3).

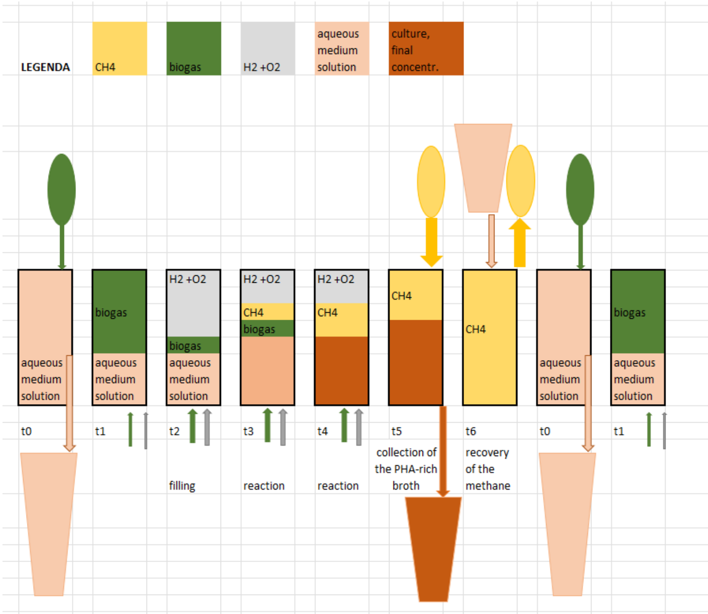

Figure 3. Bioprocess

Gasses were fed according to the following stoichiometry for autotrophic PHB production:

$$33\, H_2 + 12\, O_2 + 4\, CO_2 \rightarrow C_4H_6O_2 + 30\, H_2O$$

References and links

https://cooce.eu/bts-biogas-s-r-l/
https://cooce.eu/oral-presentation-in-international-conference-by-morlino-et-al-2024-mary-dk/
https://www.sciencedirect.com/science/article/pii/S0960852424007727?via%3Dihub
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https://bts-biogas.com/en/

Supply chain modelling

Toolkit

IMPERIAL contributed in the CooCE project with WP5 sustainability assessment. The sustainability assessment included the environmental, social, techno-economic and policy assessment.

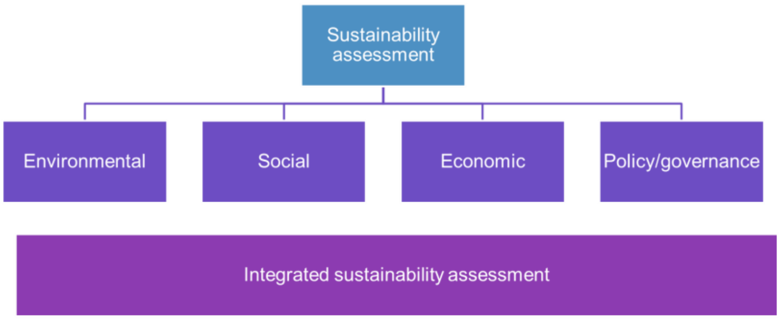


Figure 1. Sustainability Assessment conducted by Imperial.

The environmental and techno-economic assessments are based on supply chains modelling and life cycle assessment to optimise the supply chains considering different factors. The supply chain modelling approach included two sections:

- **The Chemical Process Section:** In this part of the modelling, an actual simulation of an industrial scale plant for the specific chemical process being studied was developed. This allowed to obtain a variety of useful information about the process, such as mass balances, energy balances, economic evaluations, etc.
- **The Supply Chain Modelling Section**: The actual modelling concerning the different supply chain stages to be expected over the life cycle of the process. This includes raw material acquisition, selling of products, transportation stages, etc. The results obtained from the Chemical Process Section were used here as well, as the chemical production is an integral part of the supply chain.

This overall approach is applied for the different technologies studied on the CooCE project: biomethanation, bio-succinic acid production and biopolymer production, although the structure of the modelling will be adapted to the peculiarities of each case. Figure 2 shows the process followed for the environmental and techno-economic assessment.

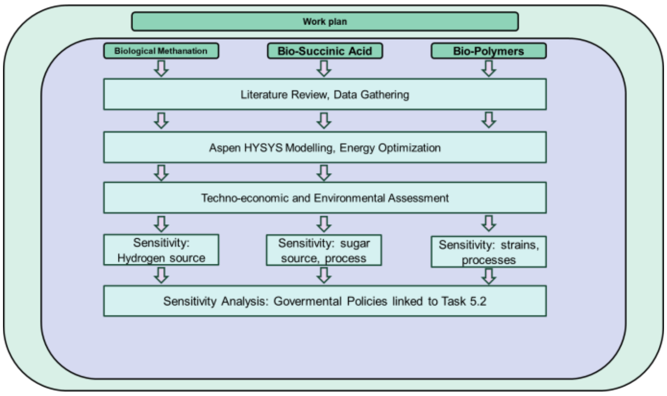


Figure 2. Process followed in WP5 for supply chains assessment

A) **Chemical Process Section**
The Chemical Process Section consists of a mathematical model that will simulate the inner workings of an industrial scale plant of the studied process. This will provide the following:

- **Technological Viability:** The implementation of the model will help define the technological limitations of the initial draft of the plant, resulting in a more refined final scheme for the process.
- **Mass Balances:** Total quantities of raw materials consumed and generated products, as well as utilities used in the plant, such as steam or cooling water.
- **Energy Balance:** Total amount of consumed energy in the plant, both in the form of electricity coming from the grid (or alternative sources) as well as utilities in the form of heat exchange.
- **Energy Optimization and Pinch Analysis:** Depending on the overall design of the process, it might be possible to employ pinch analysis to carry out an optimization of the heat exchanger network employed in the plant, resulting in lower economic costs and environmental impacts.
- **Economic Evaluation:** An economic evaluation of the installation includes the cost of purchasing and installing the equipment of the plant, as well as the operating costs for a given period of time, including energy costs, employee salaries, maintenance, etc. This can be expanded to include design and legal costs, as well as to adjust these values depending on the location of the plant.

Due to the complexities developing this model, it was not directly coded by hand, instead using one of the many professional chemical process simulators available on the market. Each of these simulators may have some challenges, but in general should be capable of completing the previous tasks. In the case of the CooCE project, the Aspen suite was used (Aspen HYSYS, Aspen Energy Analyzer, Aspen process Economic Analyzer, etc.). Figure 2 shows the modelling with Aspen HYSYS of the Biomethanation process.

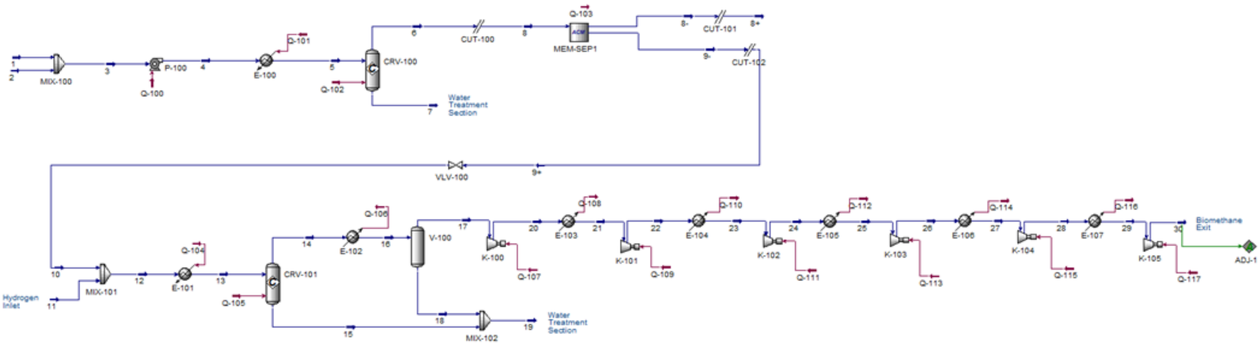


Figure 3. *Aspen HYSYS model of the Biomethanation process.*

B) Supply Chain Modelling Section

The Supply Chain Model is a mathematical representation of the life cycle being studied, and included a series of nodes:

- **Suppliers:** Nodes that represent raw materials / feedstock providers, necessary as the starting point of the process.
- **Production Centres:** Nodes that represent the locations where the raw materials are transformed via chemical processes into the refined products that will be commercialized. Defined by the Chemical Process Model.
- **Clients:** Nodes that represent the final destination that products will reach, receiving the corresponding revenue.

These nodes are defined using geographical coordinates and a series of variables dependent on the location. The nodes are connected via transportation lines, which can be classified in two:

- Those that connect suppliers and productions centers, corresponding to the transportation of raw materials.
- Those that connect production centers and clients, corresponding to the transportation of products.

Once the model is complete, and all the necessary inputs and information is given, the supply chain will be optimized for both economic profitability and environmental sustainability. This model must be developed using an already available commercial programme. There are many different options available, but in this case, AIMMS was used to carry out the implementation.

Figure3 shows the map of an optimized supply chain generated by AIMMS .

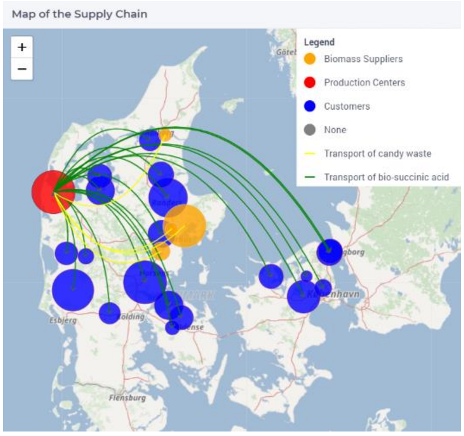


Figure 3. *Map of an optimized supply chain generated by AIMMS.*

The results of the sustainability assessment are in the deliverables section of the CooCE website.

In addition, as part of the training activities of CooCE, Imperial developed an APP. This application allows to assess options to valorise biogas. The app contains three tutorial which allow the user to change data of capacity in a biogas plant and review the changes that it produces in cash flows, payback time and other parameters. This APP can be access following the QR code below:

IMPERIAL APP FOR TRAINING

Figure 4. APP used during the CooCE training

References and links

Aspen HYSISwebsite
CooCE. 20224. Harnessing potential of biological CO2 capture for Circular Economy. https://cooce.eu/
ISO. 2006. International Standard Organisation, SS-EN ISO 14044, Environmental Management – Life Cycle Assessment – Requirements and Guidelines, ISO.

Social sustainability assesment

Toolkit

Undertaking a Social Sustainability Assessment: the case of CooCE

Sustainability assessment that addresses the environmental, economic and social impacts has become established and mandatory for novel technologies involving bioprocesses and need to be assessed across their entire value chain.

Imperial worked on WP5 on Social sustainability assessment. This entails assessing the social and economic impacts of policies, projects, or practices. A variety of methodologies and frameworks have been developed for social sustainability assessment, including Social Life Cycle Assessment (SLCA), which builds on Life Cycle Assessment (LCA). LCA evaluates the potential environmental impacts of a product or process, offering insights into production efficiency and identifying areas for improvement. It covers all phases of a product's life cycle, including raw material extraction, processing, transportation, use, and disposal. But whilst LCA involves gathering data on the primary product and on the entire life cycle of all materials involved in its production, SLCA requires additional data collection related to organisational and social aspects throughout the supply chain. SLCA can also be combined with Social Impact Assessment (SI) to provide a more comprehensive and robust assessment (Diaz-Chavez, 2014). Figure 1 shows a sample of social, economic and policy issues that can be assessed in terms of impacts. Figure 2, in turn, shows they interrelate.

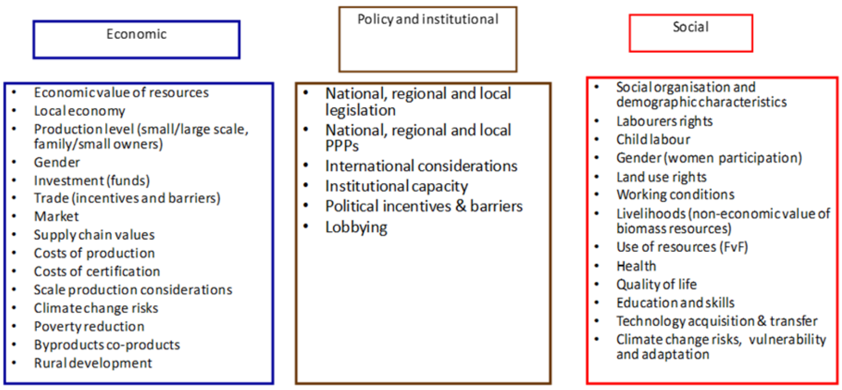


Figure 8 Issues for Impact Assessment (Diaz-Chavez, 2014)

Figure 9 Analysis of a Product System with SLCA and SIA (Dia-Chavez, 2014)

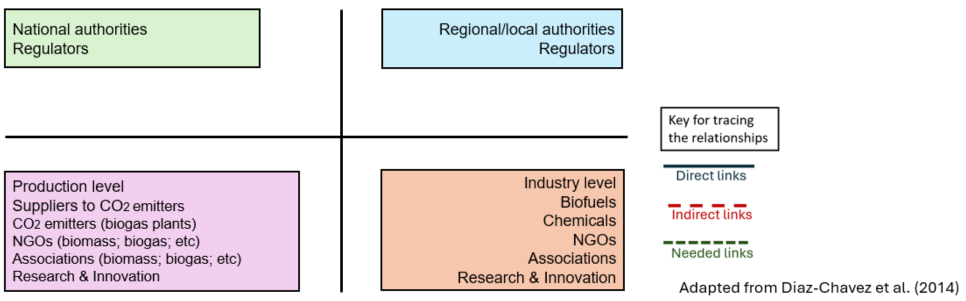
The Social Sustainability Assessment of CooCE was carried out using a composite approach developed by Diaz-Chavez (2014) that combines elements of SLCA and SIA and are applied to a range of thematic parameters for assessment through quantitative and qualitative indicators. A total of 11 parameters were examined in CooCE. They are: Trade of feedstock; Identification of Stakeholders; Policies and Regulations; CO_2 point source; Community Participation; Rural Development and Infrastructure; Job creation and wages; Gender equality; Labour Conditions; Health and Safety; and Competition with other sectors.

Figure 3 illustrates the parameters for Stakeholder Mapping, the criteria and other specifications. Figure 4 illustrates the approach for Stakeholder Mapping, whilst Figure 5 illustrates its application to Greece, one of the countries where CooCE biotechnologies are being developed.

Table 1 Parameter Stakeholders

Parameter	Characteristics/ criteria	Assessment Level	Supply chain stage	Data type and source
Identification of stakeholders along the supply chain	Associations Authorities/regulators Businesses CO_2 emitters Investors Researchers etc	National Local	All	*Qualitative* Desk search Research Partners *Quantitative* Survey

Figure 10 Matrix for Mapping the Stakeholders



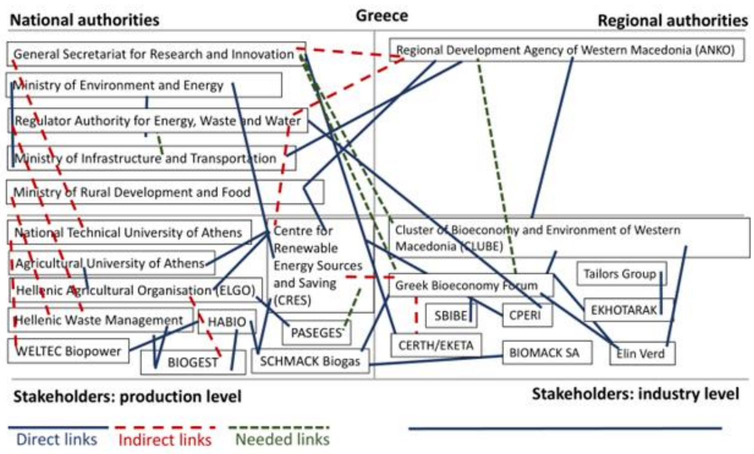


Figure 11 Stakeholders Mapped

A variety of indicators can be used to enable the social assessment, drawn from reputable databases or also from tools for SLCA. Table 1 illustrates indicators and data from the Social Hotspot Database, a tool for Social Life Cycle Assessment, for the parameter *Labour Conditions*

Table 2 Risks Related to the Labour Force

CooCE countries/ Sectors	*Chemicals/plastics*	*Electricity*	*Gas*	*Transportation*	*Water*
	Overall country-sector risk of child labour				
Denmark, Italy, UK	L	L	L	L	L
Greece	M	M	M	M	M
	Overall country-sector risk of forced labour				
Denmark	M	L	L	M	L
Greece	H	H	H	H	H
Italy	M	M	M	M	M
UK	L	L	L	L	L
	Risk of trafficking in persons				
Denmark, Greece, Italy	M	M	M	M	M
UK	L	L	L	L	L

Source: SHDB (2024) Key: L= low; M=Medium; H=High; VH= Very High; ND= No Data; risk level colour is as used in the SHDB

The key results from the analysis of all parameters are then transposed to a Social Sustainability Assessment Matrix, which uses, the evaluation system shown below.

Table 3 Evaluation Criteria for the Overall Assessment

Impact	*Type*	*Evaluation*
Direct	D	Where the project itself produces the impact
Background	B	Where local conditions influence implementation of the project
Positive	+	Project likely to produce a benefit
Negative	-	Project likely to produce impact that will not be of social benefit to country/local community
Neutral	N	Project produces no impact at all

Risk	*Benefit*	*Type*	*Evaluation*
L	L	Low	According to the data and indicators examined, and the likelihood of a problem emerging in the future even where the impact was assessed as positive
M	M	Medium	
H	H	High	
VH	VH	Very High	

The Social Sustainability Assessment Matrix thus provides an overview of the key socio-economic impacts, risks and benefits associated with the implementation of CooCE along with recommendations for mitigating against negative impacts and high risk. Table 1 shows the results for one parameter.

Table 4 Social Sustainability Assessment Matrix

Parameter	Characteristics/Criteria	Type	Impact	Risk	Benefit	Actions/Mitigation	Observations
Policies and regulations	International National	B	- +	M	VH	Ensure stable, coherent, and interconnected policies for energy, transport, and platform biochemicals to encourage investment in the CooCE concept; devise policies specific to CCUS; amend existing EU policy instruments (e.g. *CEAP, CRCF, ETS-I, FuelEU Maritime, PWD, RED III, TEN-E, WDF);* advocate for policies that support the circular economy and prioritise the use of captured CO_2 to reduce competition with other CO_2 sources	Extensive EU policy framework for energy, transport and platform biochemicals but many gaps (no specific legislation for CCUS nor bioproducts obtained through it); normative instruments need to be transposed properly/timely by member states to enable and support the scaling up of CooCE into successful commercial ventures

Overall, this composite methodology enables a comprehensive evaluation of the potential socio-economic impacts and risks associated with implementing novel bio-technological processes and establishing value chains at the local level, such as CooCE's.

References and links

CooCE (2024) Harnessing the Potential of Biological CO_2 Capture for the Circular Economy: https://cooce.eu/

Diaz-Chavez, R (2014) 'Indicators for Socio-Economic Sustainability Assessment', in Ruts, D and R Janseen, (eds) Socio-economic impacts of Bioernergy Production, Springer: Switzerland: 17-37.

SHDB (2024) Social Hotspot Database: http://www.socialhotspot.org/

This Handbook/toolkit was prepared as part of WP5 of the CooCE project and should be cited as follows:

Diaz-Chavez R, Evans Y, Giarola S, Basterrechea P, Zacharopoulos I, Treu L, Morlino M S, Gaspari M Müller B, Porqueddu I and Agostini S. 2024. Best practice handbook/toolkit for the potential of biological CO2 capture for circular economy. The CooCE project. https://cooce.eu/