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CO2CE

Harnessing the potential of biological CO2 capture for the Circular Economy

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Report:
CooCE Stakeholders' Workshop

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1. 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 Introduction

This document reports on the activities and findings of a workshop carried out for the CooCE-ACT project (co-funded by ACT- ERANET, under the European Union's Horizon 2020 grant agreement number 327331 and UK/BEIS). The workshop brought stakeholders together in dialogue, enlisting their views, knowledge, and expertise on the development of CCUS applications and value chains as envisaged in the CooCE concept. The report first introduces the CooCE project, before discussing aims, organisation, and activities of the workshop. It then moves on to present the workshop results, introducing and discussing different topics in turn. The report concludes by summing up the key challenges and outlining the prospects for CooCE.

2 The CooCE concept

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 carbon-intensive, high-polluting and hard-to-abate industries and sectors 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 offer an economic incentive for capturing, converting, and transforming CO_2 into valuable commercial products or materials (e.g. construction materials, fuels, chemicals, and plastics) or into feedstocks for further industrial processing. CooCE will help accelerate the market uptake of its technologies by replicating to CO_2 intensive industries and sectors and creating sustainable supply/value chains. This will require working in collaboration with a broad range of stakeholders, including technology providers, research centres, end-users, clusters, CO_2 intensive industries and state agencies.

The CooCE project will develop, demonstrate, and validate a diverse portfolio of novel and flexible technologies at different TRLs for the chemical and biological conversion of CO_2 into products for long-term storage of CO_2 emissions. CooCE opens a pathway for decarbonisation of businesses in industry, energy, and transportation (air, road, water), thus helping mitigate against climate change. Moreover, by turning CO_2 into valuable bioresources, CooCE will help expand the bioeconomy and the wider circular economy through the sustainable recycling and utilisation of CO_2 which will also help boost the creation of jobs across the economy.

In the CooCE concept, CO_2 will be captured to be converted into (final or intermediate) bioproducts using different technologies (Figure 1). A first product is high purity biomethane, (CH_4>95%) that is obtained from a novel add-on, cost-effective and highly efficient bioprocess of CO_2 hydrogenation, involving the use of excess renewable electricity from wind turbines and/or photovoltaic plants to electrify water electrolysers to generate H_2. This technology enables flexible and seasonal on-site hybrid energy storage, with biomethane being either as a liquid or as compressed gas, the equivalent to LNG that provides a promising alternative for shipping, and CNG that can be used in road haulage and most other vehicles. Also, biomethane can be injected into the natural gas grid, as allowed by legislation in various countries in the EU. Thus, there is a clear market opportunity for CooCE's proposed technology for upgrading biogas to biomethane.

A second CooCE product is BioSA that will be obtained simultaneously with biogas upgrading to biomethane and a biochemical route that uses as feedstock carbohydrates from waste streams. CooCE introduces a novel technology that uses waste streams to produce second-generation bioSA, obviating, for instance, the need for biomass feedstocks that require land for cultivation. The CooCE concept is designed to upgrade biogas in bioreactors, treating a range of carbohydrates containing organic wastes to produce biomethane and bioSA in a separate fermentation reactor. BioSA readily replaces the fossil-based chemical succinic acid that is used for making numerous commodities in chemical, food, agricultural and pharmaceutical industries. There is also growing demand for succinic acid from the industrial, personal care and beverage industries, and increasing adoption of it as a replacement for adipic acid in polyurethane production. As manufacturers seek to increase the renewable content in their products by using more bio-based plastics and polyurethane, this increases the demand for bioSA in a wide range of applications, notably in bioplastics, making it a strong platform chemical. Hence, CooCE's proposed technology for BioSA production has strong market potential.

A third CooCE product comprises biopolymers that will be obtained through bio-catalytic technologies (based on *Cupriavidus necato*r and *cyanobacteria*) that use carbon-rich waste streams for cost-effective conversion into PHAs. These biopolymers are accumulated as storage materials within the cells of microorganisms, serving both as carbon and energy reserve. PHAs possess similar characteristics to common plastics, are biocompatible and biodegradable, and can replace the commonly used petroleum-derived plastics. They are currently produced at industrial scale, being applied to a broad spectrum of end products, such as bioplastics for packaging, prebiotic and nutritional compounds for medical applications, and bio-creams for cosmetics. Together, BioSA and PHAs comprise a high value-add platform of commodity chemicals, proving the building blocks of various biopolymers and bioproducts. In CooCE, they will also be tested for use as a plasticiser in the packaging production process.

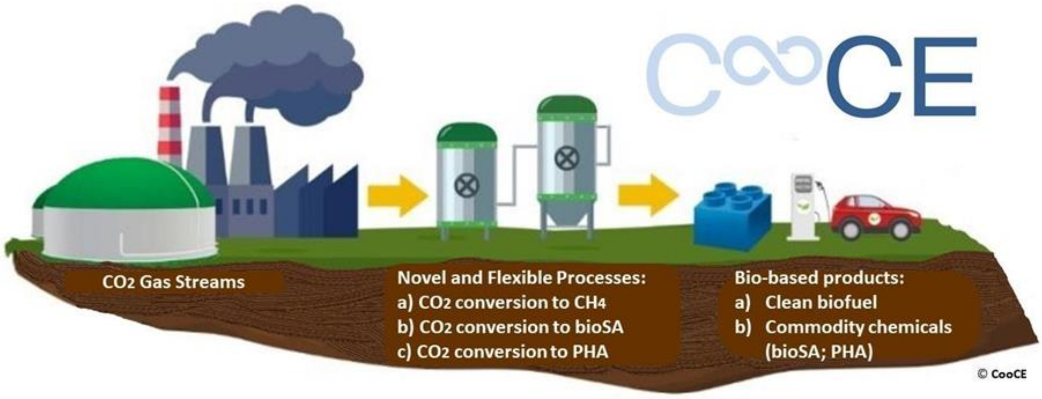

Figure 1 The CooCE Concept

3 The Stakeholders' Workshop

3.1 Aims

The stakeholders' workshop aimed at gathering the views of a diverse range of stakeholders on both the proposed CooCE concept and on wider CCUS issues to examine the benefits and challenges related to the deployment of CCUS technologies and applications at industrial scale through a circular economy approach. The engagement of diverse social actors in proposed techno-innovation projects is an essential requirement for understanding perception and acceptance of new technologies and products as they play a critical role in market diffusion and societal embedment (Jones, et al., 2017; Lynch, et al., 2017; Arning, et al., 2019). Engaging with stakeholders also helps meet the objectives of other tasks across the CooCE project, including the assessment of social sustainability and policy.

3.2 The workshop

The stakeholders' workshop was held as a side event at the 31st EUBCE in Bologna, Italy. This large annual international conference is a highly suitable occasion to recruit potential participants to the workshop from amongst the conference attendants as existing or potential stakeholders in CCUS. The IC team secured a dedicated page within the conference's online platform to disseminate the project and a separate page was set up to publicise the workshop itself, explaining the event, its aims, its format, and the agenda (see Appendix I and II). Conference attendees were able to secure a place at the workshop by signing up directly on the CooCE dedicated page, prior to the event.

The workshop took place on 8th June 2023. A total of 22 stakeholders participated, whilst four project partners led the proceedings, introducing the project to the audience, facilitating or providing support to the facilitators during the interactive sessions. The stakeholders were mostly based in Europe (N=15; Figure 2), representing business, research, and academia

(Figure 3). The workshop opened with an introduction by research partners to the key aims and features of the CooCE project and concept. This was followed by interactive sessions where participants worked in groups to carry out a SWOT analysis of CooCE and CCUS more generally, and presented the results of their discussion to all workshop participants at the end of the exercise. In the first session, the SWOT analysis focused on features of the CooCE concept, whilst the second session entailed a discussion of issues on the industrial-scale deployment of CCUS. In the third session, the SWOT analysis covered CCUS market demand, whilst in the last interactive session, the discussion centred on regulatory frameworks. At the end of the interactive sessions, there followed a final, open-floor debate on the findings and further issues before the workshop concluded.

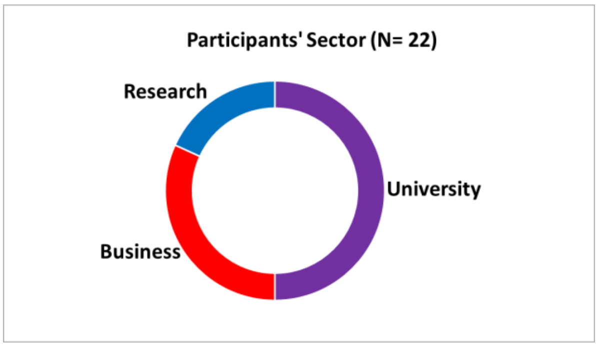

Figure 2 Partipants' Sector of Interest

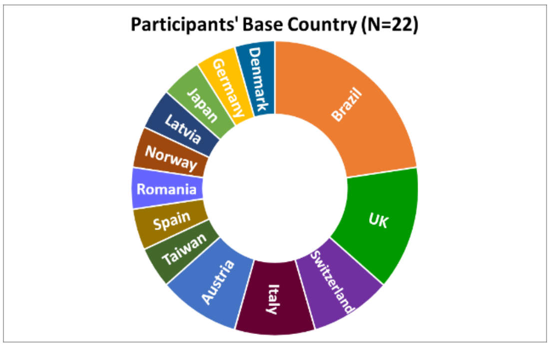

Figure 3 Participants Base Country

Source: Stakeholders Workshop (June 2023)

4 SWOT Analysis of CooCE and CCUS

This section introduces and discusses the results of the SWOT analysis at the stakeholders' workshop, starting with the analysis for the CooCE concept and moving in turn through the other themes examined.

4.1 The CooCE concept

In this SWOT exercise, stakeholders were asked to consider different aspects of the CooCE concept and proposed chain pathways based on their understanding of earlier presentations by research partners when introducing the project (Figure 1). This required looking at feedstocks and inputs, the processes and conversion technologies, along with the intermediate products obtained, namely biofuels, biosuccinic acid and PHAs for bioplastic production. Their responses are summarised in Table 1.

Table 1 SWOT of CooCE

Strengths	Weaknesses
Could be profitable	Bacteria for CO_2 capturing
Environment friendly	Costs
High purity CH_4 (95%)	Energy needs
No need for CO_2 separation/capture	Lack of widespread knowledge/information
Wide range of products that add value to the overall process	High cost of CO_2 capture/transport
Useful production of CO_2	Need for building capacity
	Public perception
	Scale up

Opportunities	Threats
Bio-digestion is quite well known	Extraction costs
Cheaper methods for industrial gases purification	Focus on cheaper CCS technology
Chemicals platform	Lack of renewable electricity (competing uses)
CO_2 obtained from bio-reaction	No regulation framework for CCUS
More environment friendly methods of industrial gasses purification	Policies
Replacement of CO_2 (otherwise produced from fossil fuels)	Quality of the product (industrial standard)
Strong (CO_2 capture/biogas/biomethane upgrade)	Scalability
Upgrade for biomethane is quite well known	
Use of CO2 with H_2 to produce fuels	

Source: CooCE stakeholders' workshop (June 2023)

The results show that, environmentally, CooCE is seen as providing more friendly methods for industrial gasses purification and enabling a useful replacement of CO_2 from fossil fuels with CO_2 obtained from bio-reaction, although energy needs (type and volume) may prove a challenge, particularly given the perceived lack of incorporation of renewable energy for which there may also exist competing uses. Technologically, positive features of CooCE identified by stakeholders were its proposed bio-digestion and biomethane upgrading (accepted as established processes), the fact that the concept that obviates the need for CO_2 separation and can obtain high-purity methane whilst also using CO_2 with H_2 to produce fuels whilst delivering a chemicals platform. On the other hand, the bacteria proposed for capturing CO_2 seen as perhaps not be most appropriate or effective, whilst energy demands (including renewable electricity), the scalability of the concept, the quality of the intermediate products (whether suitable to industrial standards) and the current market and policy focus on cheaper CCS technology all configure notable challenges. Regarding the economics of CooCE, the cheaper methods for the purification of industrial gasses that CooCE entails along with the range of intermediate products proposed both combine to add value to the overall concept and make it profitable, although the high costs attached to CO_2 capture and transportation, and industrial scaling up were seen as important issues. Socially, CooCE will require building capacity across sectors, whilst public perception and the lack of knowledge by wider society of CCUS may impact on CooCE's acceptance. Lack of regulatory frameworks and policies for CCUS are also challenge.

4.2 CCUS deployment

In the second interactive session, participants carried out a SWOT analysis of CCUS deployment at industrial scale, as envisaged in the CooCE concept. Their responses are shown in Table 2.

Table 2 SWOT of CooCE/CCUS deployment

Strengths
Biological processes simpler than fossil/petrochemicals
Circularity
Capture and reduce
Carbon negative
Easier to capture CO_2 from biogas upgrade compared to CO_2 from combustion
Easy to operate

Weaknesses
Contributes to CO_2 emission
Downstream purification of the platform chemicals from the bacteria
High costs
H_2 production
Storage for the bacterium
Micro-organisms growth at large scale

Easy integration	Possibility of not having enough CO_2 in some regions
Diversification of applications (different output products)	Reactor configuration
Simple mechanisms	Technical limitations due to scale-up (e.g., mass transfer/radiation distribution)
	Transporting biogas

Opportunities	Threats
Awareness of industries that can benefit	Competition with conventional technologies in the case of co-derived products
Decarbonisation option for industrial sectors with intrinsic CO_2 emissions	Hard to scale up
Decentralised approach to CO_2	Lack of policies to drive expansion
Increase manufacture units	Leakage of CO_2
Raise public awareness of importance of CO_2 mitigation	New competing technologies (higher yields; efficiencies)
Reach net zero emissions 2050	No policy framework
Reduce investment costs	Processes

Source: CooCE stakeholders' workshop (June 2023)

Participants' comments show that positive aspects of CooCE as regards the environment include its encapsulation of the principle of circularity through capture and recycling of CO_2 which, in turn, opens a pathway for heavy carbon-emitting industrial and energy sectors to decarbonize or lower their emissions thus helping countries around to world meet their commitment to achieving Net Zero emissions by 2050. The CooCE concept itself was seen by some as being potentially 'carbon negative', but others thought that it contributes its own CO_2 emissions which need to be accounted for and abated. CO_2 leakages (during conversion/processing, transportation, storage) and biogas transportation were also highlighted, having implications for sustainability and social acceptance. In economic terms, positive features of CooCE are that it entails a diversification of applications that can deliver a range of products (i.e., biofuels, biochemicals and biopolymers) that will prove useful in diverse industrial sectors and in energy generation and may help reduce investment costs for businesses. But the high costs and difficulties with implementing and scaling up CCUS also comprise challenges. Technologically, biological processes were thought to be less complex to manage than those for fossil fuels and petrochemicals, with a further advantage that CO_2 is easier to capture from biogas upgrading than from combustion. CCUS was also seen as providing a decentralized approach to CO_2 capture and use based on simple processes that can be easy to integrate and operate at business or plant level, thereby stimulating wider take up. Yet, various issues related to CCUS technologies were noted: the processes themselves (i.e., set up and integration); downstream purification of the platform chemicals from the bacteria; H_2 production and storage for the microorganisms and their growth at large-scale; the configurator of the reactor; on the one hand, competition with conventional technologies for co-derived products, and on the other, competition with new technologies reg yields and efficiencies. Further technological issues identified relate to scaling up (e.g., mass transfer/radiation distribution), and the potential lack of availability of CO_2 in some regions. Socially, CCUS was seen as a means to raise public awareness about the importance of mitigating CO_2 emissions. However, the lack of policy frameworks to incentivise the wider take up of CCUS technologies was seen as a clear hindrance to the development of CCUS chains.

4.3 CCUS market demand

In the third interactive session, participants undertook a SWOT analysis of market demand for CCUS technologies and applications and implications for helping expand the bioeconomy. Table 3 shows a summary of their discussions.

Stakeholders reiterated the potential role of CCUS in helping CO_2 intensive industries lower their emissions through progressive adoption of CCUS technologies and applications as well as using CO_2 for the manufacture of a wide range of products, such as bioplastics, for which there is a growing demand, all of which will drive market expansion. In particular, CCUS could provide more revenue streams for local biogas producers via the biorefinery concept (e.g., CooCE). Nevertheless, stakeholders also highlighted some challenges to CCUS market expansion, pointing out that different circular economy pathways for CCUS will entail different costs that are nevertheless expected to be high, and noting the complexity of new markets for biogas producers, the fact that markets tend to develop more slowly in the EU, and that product prices are currently higher than those for products obtained from established technologies. They also observed that the maturity level of renewable energy has implications for integration that may jeopardise sustainability. Moreover, the multitude of stakeholders required to work together in circular economy approaches may operate to hinder or slow down market diffusion.

Table 3 SWOT of CooCE/CCUS market demand

Strengths	Weaknesses
Growing consumers' demand for bioplastics	Multitude of stakeholders involved in such circular economy approaches
Possibility of more revenue for local biogas producers via biorefinery concept	New complex markets for biogas producers

	High costs for CCU circular economy options
Opportunities	**Threats**
Decarbonisation of CO_2 intensive industries/sectors (transport)	Markets develop more slowly in EU than other parts of the world
Potential for reducing CO_2 emissions	Maturity level of renewable integration may jeopardise sustainability
Use of CO_2 as starting point for wide range of products for other industries	Current product prices are higher than for established technologies

Source: CooCE stakeholders' workshop (June 2023)

4.4 CCUS and regulatory frameworks

The final interactive section was dedicated to a SWOT analysis focused on current policy and regulatory frameworks for CCUS and bioproducts obtained through CCUS technologies and application. Table 4 incorporates the contributions by stakeholders.

Table 4 SWOT of CooCE/CCUS regulation issues

Strengths	Weaknesses
Good intentions at EU level	No consistency of regulations within the EU
Impacts still possible on legislative process (early on)	No funding mechanisms for bioproducts or investment
Sustainability and decarbonisation high on EU policy agenda	No recognition of CCUS products as bioproducts
	No regulations on CO_2 status of bioproducts
Opportunities	**Threats**
Carbon Tax and/or credit schemes should develop from multi-region to global scale	Focus on carbon sequestration rather than CCU markets and infrastructure
Policies could target the full CCUS chain on lowering emissions and circularity	Massive investments required for permanent sequestration
EU mandate on Net Zero emissions can help CCUS to develop	Achieving purity/quality standards for commercial use (e.g., food packaging)

Source: CooCE stakeholders' workshop (June 2023)

Stakeholders noted the lack of policy instruments designed specifically for CCUS chains, products and bioproducts, including accounting for CO_2 content in bioproducts, and enforcing standards for commercial use of bioproducts (e.g., food packaging), as well as the lack of funding and investment mechanisms for bioproducts. Current policy instruments are seen to focus exclusively on carbon sequestration and storage to the detriment of CCU infrastructure and markets. Stakeholders noted the favourable, high priority given to decarbonisation on EU policy agendas, acknowledging the enabling role of the EU's mandate on Net Zero emissions in helping develop CCUS chains. Although current regulations lack consistency, it was thought that there should be scope for influencing legislative processes to incorporate CCUS chains, highlighting their scope for enhancing circularity and lowering CO_2 emissions, which would be further enhanced by taxing carbon and operating credit schemes at regional and global scales. But stakeholders also noted the very high volume of investment needed for making carbon capture a permanent feature in heavy-emitting businesses.

4.5 Further Issues Discussed at the Workshop

At the end of the SWOT exercise, further issues about CCUS were raised for discussion by different stakeholders on an open floor, addressed to all participants, including the research team. One issue was about how the principle of circularity (i.e., the 'closed loop' system to minimise environmental impact, associated with sustainability and the circular economy) would be valued in CCUS (i.e., put into practice). The discussion noted that circularity is an intrinsic and important element in the CooCE concept since it helps reduce waste by recycling resources (e.g., capturing and repurposing CO_2, use of wastewater).

Another issue was whether CCUS technologies and applications would prove financially attractive enough for widespread voluntary adoption, that is, in the absence of state intervention (subsidies, incentives, etc) given the current high upfront costs of integration at plant level. The discussion speculated that voluntary adoption of CCUS would depend on the specific technology or application being considered, but CooCE's own technological portfolio could prove attractive for wide take-up in the near future, although it is evidence that state support and availability of financing mechanisms would hasten market diffusion.

A further issue was whether there would be enough CO_2 available to accommodate demand for the uses proposed in CooCE with existing and rising demand for other uses. The discussion noted that the assumption behind the CooCE concept is that the market can accommodate rising demand to enable CooCE technologies to thrive in the market. Stakeholders also queried whether CO_2 transportation infrastructure in the EU is sufficiently developed to accommodate rising demand for CO_2, with discussion noting that development of such infrastructure (i.e., pipelines, road, shipping) is dependent on a range of factors (i.e., infrastructure technology development, policy and regulations, investment and funding, public perception) but that the expectation is that ultimately CO_2 transportation infrastructure will develop in the EU to keep pace with CO_2 demand and CCUS development.

Finally, questions were raised about the prospects for the widespread adoption by the steel industry of CCUS the scope for integrating CCUS into heating plants in the forestry sector and for capturing CO_2 from the natural gas used for domestic purposes. The discussion noted that there is evident potential for these sectors to adopt CCUS, particularly the steel industry (see the discussion by Muslemani, et al., 2020).

5 CooCE:understanding the challenges

The SWOT analsyses conducted at the workshop raised various issues that span the various stages of a hypothetical CooCE supply/value. They range from inputs or feedstocks through to final products. But they also extend beyond, to the market and regulations which naturally will impact potential businesses operating in industry, power supply, CO_2 transport and storage, and H_2 production. Table 5 summarises the key issues identified by stakeholders, that can be classed as advantages and challenges for the CooCE concept, or CCUS more generally.

Table 5 CooCE/CCUS

Advantages	Challenges
CooCE Concept	***CooCE 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

Source: Stakeholders' Workshop (June 2023)

As can be seen in Table 5, many of the advantages are about aspects of CooCE concept, which are also defining features of CCUS, such as carbon capture and the use of CO_2 as feedstock, its suitability to activities in various economic sectors, its decentralised approach, that it addresses policy agendas for curbing carbon emissions, and that it may be driven forward by Net Zero emissions mandates to mitigate against climate change. Features specific to the CooCe concept are the emphasis on circularity to help boost the circular economy, the diverse portfolio of technologies and applications, and the potential for them to become carbon negative and profitable, providing in particular, an extra revenue for the biogas sector. Further advantages relate to technology and processes envisaged in CooCE which are seen to configure an integrated system that is relatively straightforward to set up, run and manage. The varied portfolio of products (intermediate and final) further enhances the scope of CooCE for wide market adoption. Nevertheless, Table 5 also illustrates the challenges confronting CooCE, some of which are specific to the concept itself, whilst others are rooted in the wider context of CCUS development and deployment. They are discussed in turn, under separate headings.

5.1 CooCE/CCUS: energy, emissions, and infrastructure issues

Competing uses for renewable energy and other resources: one obvious way in which CooCe/CCUS might compete with renewable energy is by providing a pathway for power plants and industrial facilities to reduce their carbon emissions and footprint rather than incentivising the phasing out the use of fossil fuels altogether and it might also potentially compete for resources and investment with renewable energy technologies that offer cleaner and more sustainable long-term solutions (Jones, et al., 2017; IEA, 2020; Naims, 2020). Yet, renewable energy integration in certain industries is notoriously challenging (e.g. steel and cement production) and their emissions may not be mitigated by using more renewable energy sources or improving efficiencies, so CCUS provides a cost-effective, competitive option (Pieri, et al., 2018).

Energy requirements: it is widely acknowledged that CCUS techno-processes generally require significant volumes of energy (although these will vary according to specific types of technology or applications (Pieri, et al., 2018; Hepburn, et al., 2019; Naims, 2020; Dziejarski, et al., 2023). Achieving the purported environmental improvements will largely require the use of renewable energy, and H_2 produced mostly from water electrolysis; yet this process also entails high energy usage as well as being expensive, so to offset this, CCUS should also help develop types of renewable energy that can contribute to process efficiency (Naims, 2020; Peres, et al., 2022).

H_2 production: CooCE proposes to produce low-carbon H_2 through CO_2 hydrogenation with use of excess renewable electricity from wind turbines and/or photovoltaic plants to electrolyse water thereby resulting in low CO_2 emissions. H_2 shows great promise for the energy system, since it delivers energy in the form of gas that can be stored in large volumes for long periods of time and deployed flexibly across the system, without emitting carbon at the point of use, although low-carbon hydrogen is more expensive to produce than high carbon alternatives (BEIS, 2019; Kircher, 2021). However, integrating hydrogen into existing CCUS systems increases the complexity of the overall process, entailing interactions between hydrogen and capture compounds that could impact overall reliability, stability, efficiency and effectiveness of CO_2 capture. A further issue is the potential clash between the benefits of using CO_2 for materials and products and using H_2 for energy production or other potential applications (IEA, 2020).

CooCE/CCUS own emissions: this relates to the 'energy penalty' of CCUS (IEA, 2020), where fossil fuel energy is used for capturing CO_2 thereby leading to additional or residual CO_2 emissions whose volume will depend on the specific types of technology deployed, as CO_2 utilisation per se will not necessarily help address climate change (Hepburn, et al., 2019). Ensuring overall emissions reduction may well require using only clean and renewable energy sources for the capture process. Similarly, additional emissions may result from using fossil fuel energy for CO_2 compression and transportation to a storage site along with emissions from pipelines, all of which can be avoided by ensuring the integrity of transport infrastructure through appropriate monitoring and maintenance along with use of low-carbon or renewable energy sources (IEA, 2020).

Biogas transportation and potential CO2 leakage: CooCE proposes to capture carbon on-site for upgrading into biomethane by removing CO_2, which therefore obviates the need for biogas transportation, but biomethane and CO_2 transportation and storage do raise potential risks about the impact of leakages, both on the environment and on human health (Jones, et al., 2017). Addressing these will require monitoring and verification and well as transparent communication with the public to allay their concerns and maintain support (BEIS, 2019; Balaji & Rabiei, 2022). Comprehensive regulatory frameworks are also required to manage CCUS project design, monitoring, and closure procedures to ensure leakage risks are managed effectively and operations meet safety, environmental and quality standards. Technologies that detect and respond to CO_2 leakage in real-time are also required (BEIS, 2019; Balaji & Rabiei, 2022; Bywater, et al., 2022).

Potential shortage of CO_2: circumstances may arise that potentially affect the availability of CO_2 for capture that could jeopardise CCUS projects, particularly if there is increased demand for established and newly-emerging uses (e.g, listed by Pieri, et al., 2018). These include: heavy CO_2 emitting industrial processes reducing their emissions significantly or transition to cleaner technologies; competing uses of CO_2 such as EOR in oil fields, food and beverage applications, and various other industrial uses; cases where the price of CO_2 in the market is higher due to increased demand or limited supply; the availability of suitable infrastructure for capturing and transporting CO_2 to storage wells; cases where policies do not provide sufficient support for CCUS or prioritise other uses of CO_2; lower emissions from energy generators as a result of continuous development of renewable energy technologies. Nevertheless, numerous industrial processes emit substantial volumes of CO_2 as a byproduct that can provide a potentially continuous and significant supply (e.g. energy generation, cement production, chemicals manufacturing), and demand for CO_2 is also still relatively lower compared to the total emissions from various industries (IEA, 2023).

Bacteria use, storage, large scale growth, and platform purification: CooCE proposes to use bio-catalytic technologies to convert carbon-rich from waste streams into PHAs, as part of a growing interest in developing microbe-based CCSU technologies, as microbial carbon capture processes offer much more flexible operational conditions compared to chemical processes, producing the same same chemicals as petroleum-based chemicals at a mild temperature under ambient pressure, consuming less energy and emitting less CO_2, although such technologies have mostly been developed at lab scale (Ahn, et al., 2023). Attendant issues are: the need for appropriate storage conditions (e.g. temperature, humidity, nutrient availability) and quality control to prevent risk of contamination to ensure that bacteria remains viable and active to function effectively, all of which require consistency for large volume production; the cost of maintaining and monitoring storage systems (Ahn, et al., 2023; Oneyaka & Ekwebelem, 2023).

5.2 CooCE/CCUS: deployment and market issues

Costly investment: it is widely acknowledged that CCUS technologies are costly, with high upfront costs being a key factor preventing the deployment of carbon capture in industry, along with the substantive upfront capital expenditure is needed to develop the infrastructure for T&S of CO_2 which will all need to decrease to make CCUS deployable at scale in the medium-term (BEIS, 2019; Warren, 2019; IEA, 2020; UNECE, 2021; Peres, et al., 2022). CCUS is not yet a viable investment for businesses operating in most industrial sectors particularly, for instance, cement and steel, where carbon capture costs are much greater than can be incentivised at current EU ETS allowance values (BEIS, 2019). Also, emissions recycled through CCUS across industry have to meet ETS costs, although exemptions should apply (Kircher, 2021). Additionally, costs will vary considerably between different industrial sectors, as will the ability of each sector to pay for carbon capture, depending on the particular technologies used and the specific applications proposed, along with locally contingent factors, such as labour and energy costs (BEIS, 2019; Warren, 2019; Naims, 2020; UNECE, 2021). There is also concern about the apparent incongruence between the aims of CCUS (e.g. reducing emissions and mitigating climate change) and broader sustainability goals, since CCUS is predicated on the continued use and availability of fossil fuels, thereby delaying the transition to renewable energy and a low-carbon future (Jones, et al., 2017).

Lack of funding mechanisms: major challenges for potential investors in CCUS are the repayment period for capital financing and accessing capital for building the capture plant, whilst CO_2 storage risks are said to be one of the most challenging element of investing in CCUS, since it is a risk that has to be managed over the long term (BEIS, 2019). Instead, the development of CCUS at industrial scale requires sustainable business models that can stimulate private investment across a broad range of investors and support cost reductions, along with financing mechanisms that provide flexible incentives appropriate to each relevant industrial sector that can help drive efficiency and cost reductions, and are relatively quick to implement (BEIS, 2019; IEA, 2020; Muslemani, et al., 2020). Also, higher shares of climate finance for climate change mitigation from governments and supra-national organisations could be channeled towards CCUS, as current estimates suggest that it will be considerably more expensive to meet the temperature targets set in the Paris Agreement without CCUS (Warren, 2019) and virtually impossible to meet Net Zero goals without CCUS (IEA, 2020; ECIU, 2021).

Scalability: CCUS technological development has been gathering pace in recent years, with several processes and applications available from middle to high TRLs, but in general, it is still at early stages (Jones et al, 2017; Pieri, et al., 2018; Arning, et al., 2019; Hepburn, et al., 2019; Dziejarski, et al., 2023). The development of efficient and cost-effective CCUS technologies for industrial scale deployment depends on a variety of factors, particularly: the upfront high costs of developing and implementing them; building a comprehensive infrastructure network for CO_2 and T&S which can be costly and slow to achieve; energy requirements; sufficient state and industry support and incentives that remove uncertainty and help secure funding and investment; competition for resources with other climate change mitigation technologies and energy efficiency measures; regulatory frameworks; stakeholder engagement; public perception (BEIS, 2019; IEA, 2020).

Complex market for biogas producers: the complexity of the biogas market for CCUS derives from various factors: variability in biogas composition (based on feedstock and digestion process) may affect CCUS efficiency and feasibility, as different gasses may require specialist separation and purification methods; biogas impurities must be removed prior to carbon capture, which adds complexity of the process and may require further treatment; the specific characteristics of the biogas (e.g.,composition and flow rate, will largely dictate the choice of CCUS technology; biogas production and upgrading have their own costs to which will add those of CCUS technologies, thereby increasing overall costs; regulatory frameworks for biogas and CCUS may vary widely between regions and countries, conditioning the feasibility and financial attractiveness of mixing biogas production with CCUS; integration of CCUS processes with existing biogas production and distribution systems may entail technical challenges (e.g. specialised equipment, materials, expertise) and demand resources for ensuring reliable operation, monitoring and maintenance. Moreover, the economic viability of integrating CCUS with biogas will be conditioned by the scale of the operation, local energy prices, policy incentives, while the availability of funding Incentives, carbon pricing mechanisms, and emissions reduction targets will help shape up the business case for such integration. Overcoming these challenges demands a comprehensive understanding of both the biogas and CCUS sectors (Cordova, et al., 2022).

Slow market expansion in EU: a series of challenges historically have combined to slow down market expansion of CCUS in the EU, namely: regulatory and policy frameworks for CCUS lagging behind those for renewable energy sectors; weak incentives and financial mechanisms (e.g. carbon pricing, subsidies) relative to other regions; CCUS technologies are less mature than technologies for renewable energy; public perception/social acceptance related to concerns about safety and environmental impacts; investor uncertainty about the financial viability of CCUS projects and the regulatory landscape; complexity of integration and implementation (e.g., capture and T&S); significant investment needed to build the necessary CCUS infrastructure; oversight by the EU regarding CCUS development relative to renewable energy, energy efficiency and other decarbonisation strategies. However, recent policy reorientation (e.g. the 2019 European Green Deal, the Clean Energy Package) make provisions for channeling resources towards CCUS research and pilot projects (Bolscher, et al., 2019; JCR, 2022).

Quality standards for commercial use: CCUS processes and products may need to meet a variety of standards to be fit for commercial deployment, although the standards will likely vary between countries and regions. Standards may apply to the quality of captured $CO_{2;}$ standards for diverse utilisation pathways and storage site; standards for transportation pipelines and storage facilities; standard requirements for monitoring technologies, measurement accuracy, frequency of monitoring, and reporting protocols; standard requirements potential environmental and health impacts of CCUS operations, with requirements for emission controls, air quality monitoring, and health and safety protocols for workers; standard guidance on the need to meet national and international regulatory requirements (e.g. reporting on emissions; processes for issuing permits; legal frameworks); transparency requirements for reporting project information, safety measures, and potential environmental impacts for building public trust and support (Pieri, et al., 2018; Bolscher, et al., 2019; Naims, 2020; Greenfield, 2022).

5.3 CooCE/CCUS: policy and societal issues

Lack of policies for CCUS/its bioproducts: it is well-established that techno-innovations require supportive policy frameworks and instruments to encourage their successful deployment and widespread adoption (BEIS, 2019; Naims, 2020; Kircher, 2021; Greenfield, 2022) and although several countries have already developed substantive legal and regulatory frameworks for CCUS (BEIS, 2019; Greenfield, 2022;), there is a need for wider, coherent, integrated and coordinated policy development for CCUS, and also for bioproducts obtained through CCUS technologies (Naims, 2020). A combination of factors may operate to hinder the formulation and advancement of effective policies which are likely to impact the rate of market expansion. These include technological complexity of both CCUS and bioproduct technologies that demand substantive multi-stage investment (research; development; deployment); doubts about formulating policies because of concerns about potential risks linked to CO_2 storage and unforeseen consequences of bioproduction; lack of public demand for supportive policies due to poor or no understanding of CCUS and bioproducts; lack of a strong business case for the economic viability of CCUS and bioproducts, even though the bio-based origin of products may justify a higher seling price compared to fossil-based options; technologies tend to evolve much more rapidly than the pace of policy development and enactment; the need for engagement of all stakeholders in policy-making is essential to the success of CCUS and bioproducts, yet deliberations can be time consuming, thereby slowing down the whole process (Naims, 2020; UNECE, 2021; Greenfield, 2022). However, the higher prices of bio-based products that result from subisiding fossil fuels and excluding negative externalities in conventional fossil counterparts remain central challenges to the development of effective regulations and policies for the bioeconomy/bioproducts (Morone & Imbert, 2020; Kircher, 2021; Gould, et al., 2023).

Lack of consistency in EU regulations: quite clearly, it is to be expected that EU members states will have different interests and approaches to developing CCUS, which will be conditioned by their own historical development trajectories that will have produced their current energy mixes, economic priorities and levels of technological development, all of which may make it challenging to achieve harmonisation and consistency in legislation. The multiple stages involved in CCUS means that different policies and regulations may apply to each stage, leading to fragmentation across the entire value chain. Similarly, as CCUS is applicable to various sectors, each of which may have unique features and issues that make it difficult to develop consistent regulatory frameworks. Also, the relative recency and complexity of CCUS technologies means a lack of precedent in terms of regulatory frameworks, leading to uncertainties and inconsistencies in emerging legislation, as do potential interpretational differences of CCUS (Bolscher, et al., 2019; JCR, 2022).

Low public knowledge about CO2-based technologies/public perception: public perception of CCUS technologies (benefits, barriers and risks) is also crucial for their successful deployment since it informs social acceptance (the extent to which they are endorsed or rejected by key social actors), which can exert strong influence on policy and industry and impact on development and deployment (Jones et al., 2017; Lynch, et al., 2017; Arning, et al., 2019; (UNECE, 2021). Research has shown that the public in general has little knowledge of CCUS, and that the perceived toxic nature of CO_2 raises central concerns about the risks to human health (related to use of products) and the environment (leakage), with some skepticism also about its effectiveness as a long-term solution for mitigating climate change, in contrast to a perception that a key benefit of CCUS is reducing dependence on fossil resources (Arning et al., 2019). It is therefore vital to develop a clear understanding of the factors and the role of diverse stakeholders that shape social acceptance of CO_2 (Jones, et al., 2017). Essential too is ensuring transparency in communication initiatives and activities on CO_2 use and providing comprehensive and reliable information to dispel misconceptions, and raise public interest and trust in CCUS (Arning, et al., 2019).

Multitude of stakeholders: the involvement and collaboration of broad range of stakeholders in the design, implementation and monitoring of projects of different kinds (i.e., environmental, social, economic) has been an established requirement for their success, gaining greater impetus in pursuit of sustainable development and sustainability aims, and more recently also, in the expansion of the circular economy and bioeconomy (Morone & Imbert, 2020; Bicchielli, et al., 2021;Hoes, et al., 2021; Kircher, 2021; Gould, et al., 2023).

Stakeholder engagement remains imperative also in the CCUS context, but the myriad of stakeholders that are expected to be engaged may entail delays in the industrial-scale deployment of CCUS technologies and associated infrastructure, because of potential challenges in attempting to align diverse and conflicting views, aims and interests and obtain concerted action from developers, investors, operators, researchers, consumers and civil society, local and central government agencies and policy-makers (Jones, et al., 2017; Pieri, et al., 2018; BEIS, 2019; Naims, 2020).

6 CooCE: harnessing CO_2 for sustainable value chains

The results of the SWOT analysis demonstrate the value of gauging and understanding how stakeholders at the forefront of CCUS see its potential development trajectories (Hoes, et al., 2021). Together, these findings delineate a complex picture regarding the actions, measures and policies needed to bolster CCUS development. From the perspective of stakeholders, the CooCE concept exhibits positive features in its proposed chain pathways and products (intermediate/final), but ensuring their viability will require addressing 'sustainability challenges' (Hoes, et al., 2021) that may otherwise jeopardise the successful roll out of value chains (Figure 4).

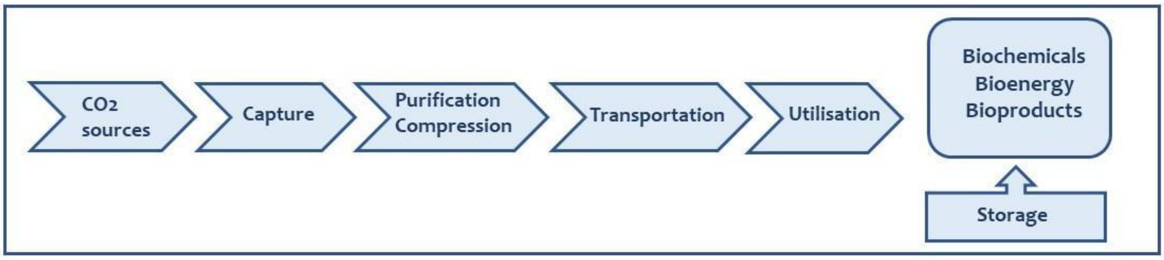

Figure 4 CooCE's Conceptual Chain

Although often discussed separately here, it is clear that the issues raised by stakeholders are all interlinked and cut-across environmental, economic, social and policy dimensions (Pieri, et al., 2018; Naims, 2020). Indeed, as has been argued, the success of CCUS projects such as CooCE hinges on employing a holistic approach (Pieri, et al., 2018) that addresses and integrates all issues according to the specificities of each pathway in their attendant contexts (Hepburn, et al., 2019; Naims, 2020), takes on further issues affecting associated chains (e.g. biofuels: Panoutsou, et al., 2021), and configures them according to prevailing policy landscapes to ensure the establishment of sustainable value chains that help expand the circular (bio)economy (Morone & Imbert, 2020; Bicchielli, et al., 2021; Hoes, et al., 2021; Kircher, 2021; Peres, et al., 2022; Naims, 2020; Gould, et al., 2023).

A holistic approach will be employed in the Integrated Sustainability Assessment of CooCE (to be carried out in the later stages of the project) which will discuss its potential impacts across all these dimensions and identify the most sustainable pathways. It is essential to examine these dimensions so that CooCE can help drive sustainability transformations of industrial and energy systems (Naims, 2020). The implementation of CooCE is predicated on harnessing CO_2 capture and use to help expand a circular economy grounded on sustainable chains that produce valuable products (Jones, et al., 2017; Kircher, 2021; Peres, et al., 2022).

Overall, the CooCE concept and techno-processes provide a viable and effective route for the decarbonisation of industrial and energy sectors, helping secure their long-term competitiveness and economic success whilst enabling countries to meet their commitments to reducing their carbon emissions towards Net Zero and mitigating climate change. However, the evolving landscape for CCUS development face challenges that need to be overcome through a combination of measures: better articulation and interplay among stakeholders across all sectors; greater commitment to decarbonisation of the economy by businesses and government; effective state support; stable and coherent policy and regulatory frameworks to enable industrial-scale deployment of CooCE/CCUS; fostering viable markets for CCUS technologies and products; and ensuring widespread social acceptance.

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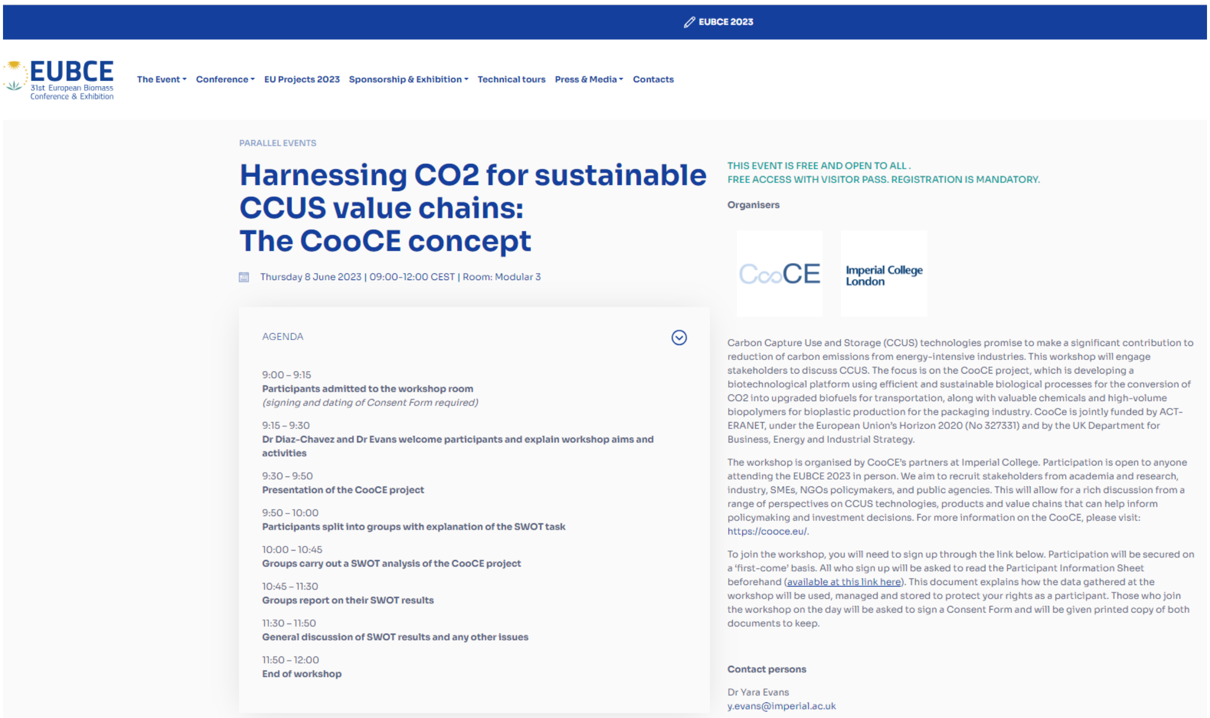
2. Appendix I

The CooCE's workshop page at the EUBCE 2023 platform



EUBCE 2023

EUBCE 31st European Biomass Conference & Exhibition

The Event · Conference · EU Projects 2023 · Sponsorship & Exhibition · Technical tours · Press & Media · Contacts

PARALLEL EVENTS

Harnessing CO2 for sustainable CCUS value chains: The CooCE concept

Thursday 8 June 2023 | 09:00-12:00 CEST | Room: Modular 3

AGENDA

9:00 – 9:15
Participants admitted to the workshop room
(signing and dating of Consent Form required)

9:15 – 9:30
Dr Diaz-Chavez and Dr Evans welcome participants and explain workshop aims and activities

9:30 – 9:50
Presentation of the CooCE project

9:50 – 10:00
Participants split into groups with explanation of the SWOT task

10:00 – 10:45
Groups carry out a SWOT analysis of the CooCE project

10:45 – 11:30
Groups report on their SWOT results

11:30 – 11:50
General discussion of SWOT results and any other issues

11:50 – 12:00
End of workshop

THIS EVENT IS FREE AND OPEN TO ALL.
FREE ACCESS WITH VISITOR PASS. REGISTRATION IS MANDATORY.

Organisers

CooCE · Imperial College London

Carbon Capture Use and Storage (CCUS) technologies promise to make a significant contribution to reduction of carbon emissions from energy-intensive industries. This workshop will engage stakeholders to discuss CCUS. The focus is on the CooCE project, which is developing a biotechnological platform using efficient and sustainable biological processes for the conversion of CO2 into upgraded biofuels for transportation, along with valuable chemicals and high-volume biopolymers for bioplastic production for the packaging industry. CooCe is jointly funded by ACT-ERANET, under the European Union's Horizon 2020 (No 327331) and by the UK Department for Business, Energy and Industrial Strategy.

The workshop is organised by CooCE's partners at Imperial College. Participation is open to anyone attending the EUBCE 2023 in person. We aim to recruit stakeholders from academia and research, industry, SMEs, NGOs policymakers, and public agencies. This will allow for a rich discussion from a range of perspectives on CCUS technologies, products and value chains that can help inform policymaking and investment decisions. For more information on the CooCE, please visit: https://cooce.eu/.

To join the workshop, you will need to sign up through the link below. Participation will be secured on a 'first-come' basis. All who sign up will be asked to read the Participant Information Sheet beforehand (available at this link here). This document explains how the data gathered at the workshop will be used, managed and stored to protect your rights as a participant. Those who join the workshop on the day will be asked to sign a Consent Form and will be given printed copy of both documents to keep.

Contact persons

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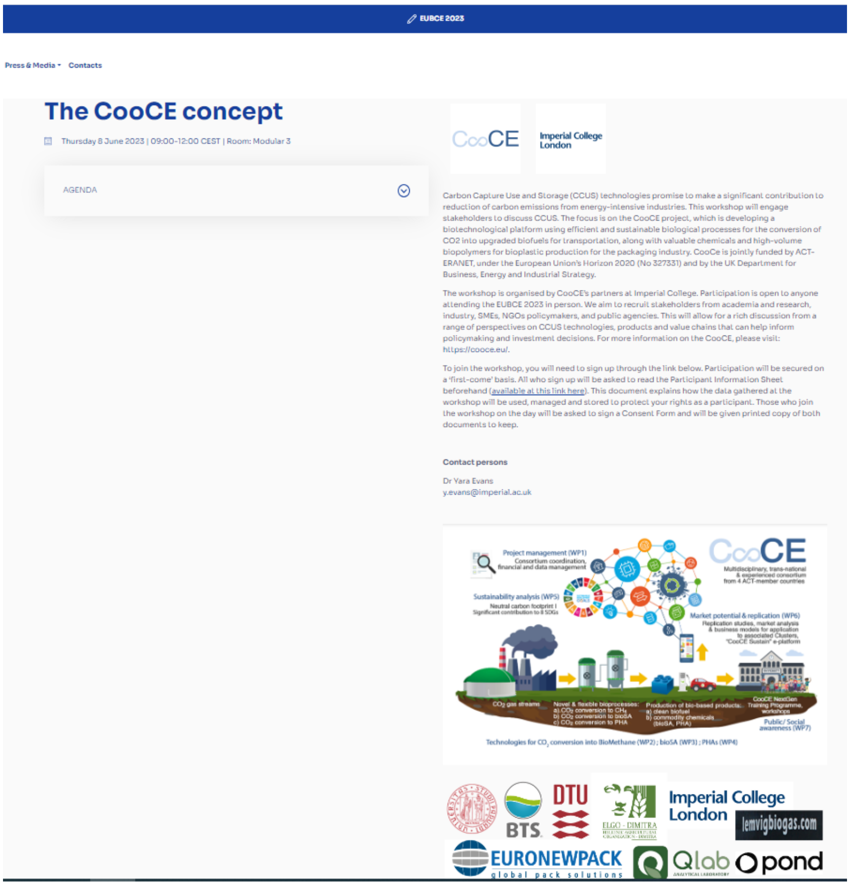

EUBCE 2023

Press & Media · Contacts

The CooCE concept

Thursday 8 June 2023 | 09:00-12:00 CEST | Room: Modular 3

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Contact persons

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3. Appendix II

At the workshop

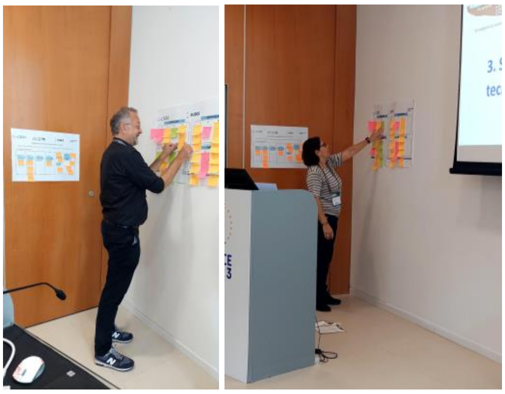
Professor Tomas Morosinotto – *UDP*
Dr Evans and Dr Diaz-Chavez *Imperial College*

Professor Tomas Morosinotto – *UDP*

Dr Diaz – Chavez and Dr Giarola *Imperial College*

Dr Rocio Diaz-Chavez - *Imperial College*

Workshop debate



Participant and Dr Yara Evans

Workshop discussion

Workshop discussion