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Solutions for a circular biobased industry

CO2SMOS USE CASES SHORT- AND LONG-TERM PLANS

DELIVERABLE 1.8

[CARTIF]

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CO2SMOS is an EU-funded project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101000790.

Executive Summary

The overall goal of the CO_2SMOS project, funded by the EU H2020 programme, is to boost the development of a set of innovative cost-competitive CO_2 conversion technologies (gas/liquid fermentation–biorefinery processes, intensified electrocatalytic processes and bio-based/organic catalysed processes) to transform biogenic CO_2 emissions produced by bio-based industries (e.g., in fermentation processes) into a set a of high added-value chemicals with direct use as intermediates for bio-based products within the BBI's value chain.

In particular, Deliverable 1.8 takes a look back at the main results of the activities in WP1, serving as a recap of the main outcomes. Additionally, it elaborates on some of the most relevant aspects that can condition the short and long- term strategies of the use cases, such as the landscape of sustainability initiatives at EU level and the resulting drivers and opportunities, the replication potential and finally the issue of circularity evaluation and a methodology for circularity assessment.

The evaluation of the sustainability landscape has shown that there are a number of action plans in place for the achievement of a carbon-neutral, regenerative EU economy, with several ambitious targets in terms of GHG emission reduction and resource use. As a result of these initiatives, there is a number of regulations and incentives that can significantly impact the project's activities. At the same time, this is a great opportunity for industries committed to sustainable business models, which can thrive in this new situation. Additionally, the incentives for the development of CCU technologies, and the opportunity to obtain valuable chemicals out of CO_2 emissions, have made it possible to replicate the project technologies using CO_2 from several value chains, being biogenic CO_2 emissions (i.e. from bioethanol production and food and beverage industries) the most technically and economically feasible.

In consequence, the use cases have adopted bold strategies to adapt to this changing environment, committing to the development of circular, low carbon operations in the short to mid-term and reducing material and energy consumption through the development of disruptive technologies, such as the integration of CCUs in their production processes.

Regarding the evaluation of circularity, it has become a relevant topic in the transition from linear to circular business models, as the starting point of any action plan is the evaluation of the current status of the system. Currently there are several methodologies available for this type of assessment, using different metrics and with different levels of assessment (material, product, company…). For CO_2SMOS, the Circular Transition Indicators methodology has been explored in detail as it provides an assessment framework considering different indicators relevant to the project particularities, and can be coupled with the LCA for the holistic evaluation of the performance of the project's solutions.

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List of abbreviations

BBI	Bio-Based Industry
CAPEX	Capital Expenditure
CCU	Carbon Capture and Use
CE	Circular Economy
CTI	Circular Transition Indicators
C2C	Cradle to Cradle
CSR	Corporate Social Responsibility
EMF	Ellen MacArthur foundation
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MCI	Material Circularity Index
OPEX	Operational Expenditure
PCDS	Product Circularity Data Sheet
RTO	Research and Technology Organisation
SLCA	Social Life Cycle Assessment
SME	Small and Medium Enterprise
TRL	Technology Readiness Level
WP	Work Package

1.Introduction

The overall goal of the **CO_2SMOS** project, funded by H2020, is to boost the development of a set of innovative cost competitive CO_2 conversion technologies (gas/liquid fermentation–biorefinery processes, intensified electrocatalytic processes and bio-based/organic catalysed processes) to transform biogenic CO_2 emissions produced by bio-based industries (e.g., in fermentation processes) into a set a of high added-value chemicals with direct use as intermediates for bio-based products within the BBI's value chain.

The project will tackle the development and optimisation of a CO_2 conversion technological toolbox allowing for the production of innovative biobased chemicals and biobased materials. The proposed technologies will be tested and validated from lab (TRL 3-4) to pilot scale (TRL 5), and the obtained molecules will be validated into final applications for the formulation of high-performance biopolymer renewable chemicals.

The **WP1** of the project has several main objectives such as the characterization of the feedstock used (biomass and biogenic CO_2 emissions), the definition of stakeholders and project end-users' requirements (bio-based industries, chemical sector -polymer and renewables chemicals) and specifications, or the study of regulatory barriers for the use of CO_2 in chemicals production or the CO_2SMOS circularity assessment by means of specific methodology developed and its application in user cases.

Within this WP, **Task 1.6** deals with the assessment of CO_2SMOS use cases and establish a method to estimate the circularity and regenerative capacity potential of the industrial value chains developed in CO_2SMOS. In particular, subtask 1.6.2 will be carried out in parallel to Subtask 1.5.1 and in coordination with T1.3, via the methodology developed in T1.6.1. Solid targets and KPIs to be achieved in short term, as well as providing a first approach, from an industrial point of view, regarding: a) circularity and regenerative capacity of the biogenic CO_2 emissions into added value-chemicals as well as b) potential replicability and future aimed industrial plants as end-users of the CO_2SMOS technologies.

This deliverable serves as a recap of de different outcomes in WP1, elaborating on some of the most relevant aspects for the use cases, such as the landscape of sustainability initiatives at EU level, replication potential and finally a methodology for circularity assessment that uses D1.7 as starting point.

1.1. Contribution from the partners

Table 1. Partners' contributions to the deliverable.

Partner name	Contribution
CAR	Deliverable orchestration, contributions to the core of the deliverable and final quality check and review.
HERA	Contributions to the core of the deliverable and final review.
NVMT	Short-long term strategies for the use cases and final review + quality check
AVNT	Short-long term strategies for the use cases. Review + quality check.
NADIR	Short-long term strategies for the use cases.

1.2. Related project activities

Table 2. Related project activities.

Activity	Connection
WP1	(R) Stakeholders' requirements and market needs are collected from T.1.1 D.1.2. Vision on circularity and sustainability provided from Industrial cases partners inside the consortium (R) Other feedback regarding circularity and sustainability provided from external stakeholders (T.1.1) (R) CO_2 feedstock and potential value chains (from D.1.5) (R) KPI targets to be achieved in long/short term (from D.1.3 and D1.3 extended version) (R) Regulatory barriers for CO_2 transformation (feedback from D.1.6) (R) Circularity indicators (from D1.7)
WP2	
WP3	
WP4	(P) Information about industrial scale and other industrial requirements to design the scaling-up roadmap
WP5	(P) Background for standardization
WP6	(P) Information for replicability studies
WP7	(P) and (R). LCA indicators are related with sustainability and circularity, therefore D.1.8 could set the basis for LCA approach

(P) Information provided, (R) Information received

2. Overview of the EU sustainability and circularity landscape

Transitioning from the current linear consumption model where goods are continuously used and disposed of to a circular system where materials are kept in use in closed loops is key to make a more efficient use of resources, reduce the number of products that end up in landfills (zero landfill approach) and reduce the environmental footprint of the economy, as the products are kept in use for longer. Currently, circularity at global level has been estimated to be 8.6 % [1] so there is still a long way to go to achieve a fully circular and regenerative system.

In this context, the EU has made circularity one of the key strategic aspects to achieve environmental and economic goals in the transition to a more sustainable economic system. Circularity is also a key aspect for the CO_2SMOS ecosystem of industries, RTOs and SMEs. A review of the main initiatives has been conducted to set the foundations for the short- and long-term strategies for the partners regarding circularity and sustainability, as each of these initiatives set out target values for emissions, circularity metrics and goals for a more efficient use of resources.

This section has a strong link with D1.6, where relevant legislative and non-legislative initiatives were identified as part of the study. As part of the WP1 recap performed in this deliverable, the review of the initiatives has been expanded to include the most recent actions.

Climate Target Plans

Climate action has steadily sped up in the last years, becoming a top priority for EU policies and regulations and a top concern for the civil society overall, with environmental issues topping the lists of the most severe risks for the upcoming years [2]. This has resulted in more demanding mid and long-term objectives compared with the previous goals.

In this context, the EU has set out targets that will deliver the required reductions while showing that increased climate ambition, economic prosperity and sustainable growth can go hand in hand (Reference executive summary climate target plans).

The most relevant target is the achievement of climate neutrality for European economies by the year 2050, and a 55 % reduction by 2030, which represents a significant increase in the ambition of the goals with respect to the previous one (40 % by 2030) [3].

Relevant outcomes for CO_2SMOS: efforts towards the reduction of greenhouse gas emissions (at least 55% by 2030, and a goal of becoming climate neutral by 2050) that will support the wider development and implementation CCU technologies.

Circular Economy Action Plan (CEAP)

The Circular Economy Action plan for a cleaner and more competitive Europe was released in 2020 following the adoption of the European Green Deal to support the transition towards the circular economy and the neutrality of the EU economy. The goal of the CEAP is to make sustainable products more widespread in the market while reducing the generation of waste. It focuses specifically on 7 key value chains [4] (Figure 1).

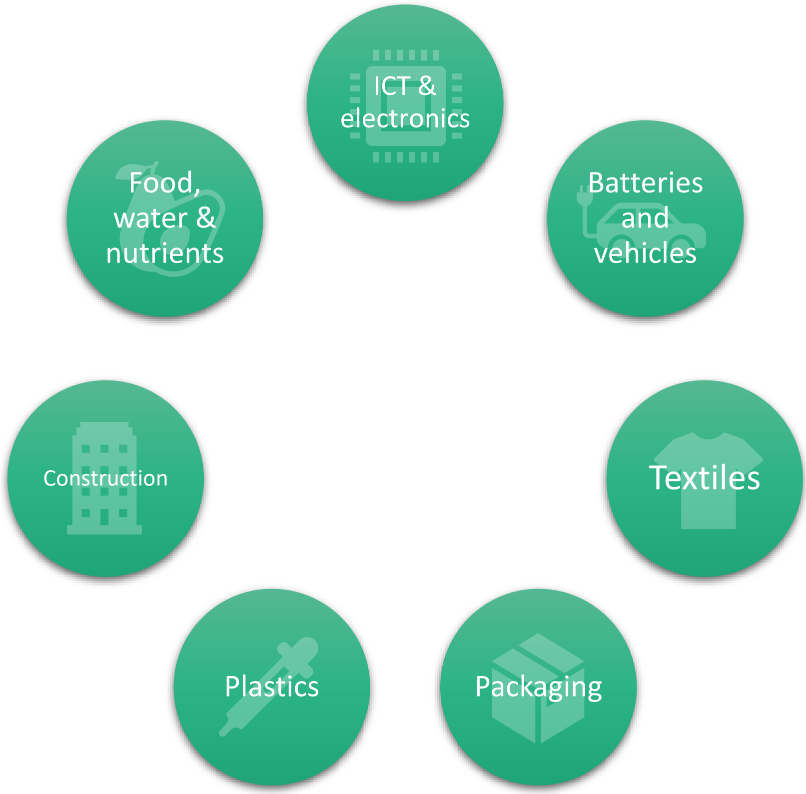

Figure 1. Key value chains for the CEAP. Adapted from [4].

The CEAP pays special attention to waste reduction, setting up reduction targets for specific waste streams, thus increasing process circularity and minimising the content of harmful substances across the value chain of products.

Another key aspect is the implementation of a market for secondary raw materials, boosting the recovery of valuable materials from waste, building trust on the use of these secondary raw materials and reducing the need for primary raw materials.

Relevant outcomes for CO_2SMOS: Incentives for increased recycled content in products and regulations towards reduced content of substance on concern, standards for the reuse of waste streams.

Sustainable Products Initiative

Adopted by the EC on the 30th March 2022, this initiative revises the previous Eco-design Directive to ensure that the new products placed on the EU market are more sustainable in the path towards a circular EU economy with reduced environmental footprint. Key product categories include textiles, ICT and electronic products, furniture, steel, cement and chemicals.

The regulation deals with aspects such as the product durability, reliability, reusability, upgradability, reparability, disassemblability, maintenance, energy and resource efficiency, life cycle thinking and waste prevention and reduction.

It is based on 6 overarching product sustainability principles [5]:

- Regulations to increase producers' responsibility for providing more circular products and intervening before products can become waste (for example providing products as a service, providing maintenance service or ensuring spare parts availability to extend product lifespan);
- Implementation of sustainability labelling and/or transparent disclosure of information to consumers and users on B2B and B2C communications;
- regulations for setting mandatory sustainability requirements on public procurement;
- inclusion of social aspects throughout the product lifecycle as part of sustainability principles and requirements;
- implementation of circularity strategies in production process, increase recycled content, track and trace methods for materials, especially for hazardous substances in such processes;
- Measures to ban the destruction of unsold durable goods.

Relevant outcomes for CO_2SMOS: incentives for the implementation of circular strategies and to foster the use of secondary raw materials in process industries could benefit the use of CCUs with CO_2 as secondary raw material.

Bioeconomy Strategy and Action plan

One of main goals in the abovementioned CEAP is to strengthen the bio-based sector, contributing to the development of a sustainable bioeconomy that can contribute to the 2030 Agenda. As a result, the EU developed the Bioeconomy action plan, with the main objective is to upscale the biobased sector, unlocking new business opportunities and new markets for biobased products.

The action plan has been developed around 5 strategies [6]:

- Guaranteeing food safety in the face of the challenge of reconciling population growth and the climate threat for the coming years.
- Sustainable management of natural capital to prevent ecosystem degradation.
- Cutting down the dependence on non-renewable energy and resources.
- Mitigation and adaptation to climate change
- Fostering the EU competitiveness in the bioeconomy sector.

Relevant outcomes for CO_2SMOS: Funding and investment opportunities for innovation in the bio-based sector, supporting the development of bio-based products, biorefineries, standards and labels.

IPCC AR6 WG3

The 6th Assessment report from working group 3 from the Intergovernmental Panel on Climate Change is about to be published, and is included as part of this overview since it is expected to include relevant information about CCUs and the use of CO_2 as feedstock in the production of renewable products, building blocks, fuels and chemicals as relevant strategies in the pathway towards limiting warming well below 2ºC [7].

The report is also expected to include a mention to relevant CE related strategies to reduce waste generation and the consumption of resources.

Relevant outcomes for CO_2SMOS: Carbon Capture and Utilization is recognized as playing a crucial role in the production or renewable products, fuels and chemicals.

Communication on restoring carbon cycles

It is the first step of the European Commission towards regulating carbon sinks, removals and recycling.

The main objectives include [8]:

- By 2028, any ton of CO_2 captured, transported, used and stored by industries should be reported and accounted by its fossil, biogenic or atmospheric origin.
- At least 20% of the carbon used in the chemical and plastic products should be from sustainable non-fossil sources by 2030, in full consideration of the EU's biodiversity and circular economy objectives and of the upcoming policy framework for bio-based, biodegradable and compostable plastics. This target is totally aligned with CO_2SMOS aim to convert biogenic CO_2 and renewable bio-based feedstock into intermediate products to produce chemicals and biopolymers.

It is to be expected but yet unknown to what extent the reporting of the CO_2 origin will lead to certification schemes that would label CO_2-based products against alternatives. Key actions on carbon cycles include:

- Develop methodologies and carry out an integrated EU bioeconomy land-use assessment, with the aim of ensuring consistency of aggregated national and EU policies and targets, and provide technical assistance to Member States to carry out national assessments in support of their bioeconomy policies.
- Supporting industrial CO_2 capture, transport, use, and storage in its Horizon Europe work program (2023/24).
- Launch a study on the development of the CO_2 transport network.

Relevant outcomes for CO_2SMOS: Support CCU technologies at EU level and implementation of standards and requirements for recycled carbon content.

EU taxonomy for sustainable finances

The EU taxonomy defines a classification system for sustainable activities, starting from the very beginning setting up a common language for the definition of “sustainable”. The regulation entered into force in 2020 with the goal of incentivising investment in projects with sustainability at the core. To this end, it defines 6 environmental objectives [9]:

- Climate change mitigation.
- Climate change adaptation.
- Sustainable management and protection of water resources.
- Transition from linear to circular economy.
- Pollution prevention and control.
- Protection and restoration of biodiversity ecosystems.

In this way, future investments targeting *green* financing should substantially contribute to at least one of the six environmental objectives, and do no significant harm to the rest of them [10]. The EU taxonomy Identifies part of CCU activities as sustainable, including hydrogen production, but there is not an explicit inclusion of all CCU activities, including CO_2-to-chemicals. This would support a wider implementation of projects aiming to produce BioCO_2-based chemicals.

Relevant outcomes for CO_2SMOS: Improved access to *green* financing for CO_2-to-chemical projects, although CCU activities are not explicitly included.

3. Use cases' strategies to reach short and long-term objectives

Stakeholders of the Project (including those inside the CO_2SMOS consortium) could be classified into 3 user cases categories, depending on their particular situation towards the bio-feedstock (CO_2) and the final bio products generated in the CO_2SMOS platform.

- Bio-feedstock (CO_2/bio-feedstock) supplier and end user (bio-refinery). NOVAMONT
- Intermediate user/technologist (renewable chemistry or renewable polymers industry) and bio-feedstock supplier. AVANTIUM
- End-user (final polymer or polymer compound manufacturer/recycler) NADIR

It is therefore expected that short/long term plans are different depending on the type of the industry.

Industrial partners vision on circularity and sustainability is described in the specific interviews carried out in M7 and collected in D.1.2. Stakeholders requirements and market needs.

Please describe how you're targeting circularity and sustainability in your industry. NOVAMONT
Novamont is the international leader in the bioplastics sector and in the development of biochemicals and bioproducts obtained from the integration of chemistry, agriculture and the environment. Novamont's products and value chains are conceived and designed to provide unique and sustainable solutions for specific environmental and social problems closely related to water and soil quality. Moreover, Novamont is a certified B Corporation (https://bcorporation.eu/about-b-lab/), it operates responsibly, sustainably and transparently towards people, communities, territories, the environment, cultural and social goods and activities, entities and associations and other stakeholders. Novamont has adopted a Sustainability Policy aimed to: - Ensuring that processes, products and workplaces do not entail risks to the health and safety of employees or of the community, and reducing every form of pollution as much as possible; - Adopting a management approach that is based on the principle of Life Cycle Thinking (LCT). Pursuing actions to mitigate and improve the environmental and social profile of its activities and of its products, by: (i) choosing or developing processes and systems that allow reducing energy and material consumptions, (ii) using renewable energy sources, (iii) carefully designing products from an eco-design perspective throughout their life cycles, and (iv) purchasing products and raw materials that most respect the environment (green purchasing); - Reducing to a minimum greenhouse gas emission, the use of water resources and their quality deterioration along the whole value chain; - Contributing to mitigating the contamination of the soil and of the oceans; - Contributing to maximizing efficiency in the management of organic waste in urban and metropolitan areas, by encouraging biological recycling; - Guaranteeing respect for human rights along the whole value chain, including the supply chain

Novamont promotes a circular bioeconomy model in which all activities, starting from extraction and production, are organized in such a way as to use renewable resources or recycled materials, creating a system in which the products maintain their function for as long as possible, while keeping waste to a minimum.

Novamont Research activities are mainly focused on the development of new increasingly sustainable processes and new bio-based polymers and chemicals.

Novamont's involvement starts with sustainable raw material production and procurement, with the through the selection and exploitation of oleaginous dryland crops able to grow in marginal lands, with low environmental impact and reduced water consumption.

Such crops help recovering soil fertility, contributing to decarbonisation. Novamont, moreover, has also successfully managed the supply chain being able to give to all products and by-products an added value. This fully integrated supply chain has been proven in different national and EU financed projects such as COMETA and First2Run.

Novamont is also highly involved into research innovation activities to demonstrate how emerging feedstock, such as sub-products and waste, could be complementarily and synergistically integrated in the future supply of the biorefineries.

Beyond COSMOS, there are other EU projects like Scalibur, Waystup and Deepurple, which are based on the valorization of wastes at a demonstration level to reach this purpose (i.e. sugars recovered from biowaste and wastewaters; and recovery of waste cooking oils).

The biomaterials produced by Novamont from renewable resources are at the basis of biodegradable final products (e.g., compostable packaging, biodegradable in soil mulch films) that at the end of their life could be converted into compost as nutrient for the farmland or biodegraded in soil closing a virtuous carbon cycle and improving the quality of soil and water.

NOVAMONT VISION

Using biogenic CO_2 as feedstock for the preparation of biobased building blocks and biopolymer will enable Novamont to develop an integrated biorefinery capable of transforming CO_2 into bioproducts, accelerating its transition to a nearly zero waste integrated biorefinery.

Please describe how you're targeting circularity and sustainability in your industry. AVANTIUM

Avantium has two business units focused on renewable chemistries and renewable polymers.

By 2030 Avantium will become a circular business and will tackle the circularity challenge with the following approach:

- Design products with renewable materials that are responsibly and ethically produced.
- Develop products that are durable and recyclable creating the highest possible value for the longest possible time while consuming the smallest amount of material possible.
- Develop partnerships within the circular value chain to "close the loop".
- Develop new business models to extend the use of our technologies or products.
- Develop licensing models for our renewable and sustainable technologies, scaling the production and enabling economies of scale. This will enable Avantium to generate more circular impact.

Avantium products and processes are basically supported by two business areas: i) renewable chemicals and ii) renewable polymers. The renewable chemicals business unit develops innovative plant-based chemicals and materials from non-food resources. It is mainly supported by a demonstration plant based on PlantMEG™ technology opened in 2019 for up-scaling and commercialization. The plantMEG™ (mono-ethylene glycol), is a sustainable and cost-effective plant-based alternative for fossil-MEG, made by Avantium RAY plants-to-glycols technology that provides brands with a sustainable, recyclable, and innovative ingredient capable of attracting environmentally conscious consumers. The MEG market is projected to grow from 28 million tonnes to 35 million tonnes in 2035. On the other hand, the renewable polymers business unit has developed a technology to commercialize novel polymers to produce bio-based materials. In December of 2021 Avantium took a positive final investment decision on the construction of its FDCA Flagship Plant and on April 20 2022 Avantium celebrated the First Piling Ceremony for this FDCA Flagship Plant at the Chemie Park Delfzijl site in the Netherlands. The World's first commercial FDCA factory is set to produce 5 kilotonnes of FDCA (furandicarboxylic acid) per annum, the key building block for the 100% plant-based, recyclable plastic material PEF (polyethylene furanoate).
AVANTIUM VISION Avantium believes in a fossil-free future. At the moment over 350 Mtons of plastic are produced annually, with an annual increase around 3%, which would lead to an annual production of over 1 Gton by 2050. In order to meet these demands, especially when moving away from fossil resources, all sustainable carbon sources should be explored, especially CCU.

Please describe how you're targeting circularity and sustainability in your industry. NADIR
NADIR S.r.l. activities are focused on two business segments: manufacturing of custom equipment based on proprietary atmospheric plasma technology and development of innovative and tailor-made polymeric compounds. One of the most relevant activities in Polymeric Compounds segment is to help our customers in development project focused on the production of polymeric compounds having innovative properties. In this respect, Nadir policy is to submit to its customer an evaluation about the feasibility of the substitution, entirely or partially, of fossil raw materials with biobased materials. Sustainability of material is becoming one key point not only for big industry but also for SME, that are the typical customers of NADIR looking for innovative products and technologies. Some of NADIR customers are already aware about the possibility to use innovative and sustainable polymers: recyclable, re-usable, biodegradable-compostable or obtained from biobased sources. In this context, also from Nadir's customer point of view, the attention to non-fossil based polymeric materials is increasing in different areas of application ranging from automotive to fashion, involving us in R&D projects focused on the possibility to find sustainable alternatives to the polymer material normally used. Thanks to this approach Nadir is becoming an important ring of a more sustainable value chain for many Italian and European SMEs.

Other than consulting activities targeted to the needs of its customers Nadir is also developing its own innovative materials; as an example, Nadir recently registered a mark, Greenpolyohm™, related to a new polymeric electroconductive material composed for more than the 40%, by non-fossil carbon.
NADIR VISION Nadir believes in the future of fossil-free polymers that, also thanks to proper modifications, will reach several targets of processability, mechanical properties and active properties, replacing the major of the existing fossil-based materials.

Information collected from the online polls developed within T.1.1. indicated that the majority of companies are committed with decarbonisation and CCUs (specifically to CO_2-based products). The CO_2SMOS technologies are recognized for them as potentially implementable in their industries.

Several of the respondent stakeholders explained their ongoing/planned investments in the CCUs aimed to produce biobased products. Those not generating CO_2 in their processes are very favourable to introduce biobased products produced by third parties in their value chains.

4.Replicability

The replicability potential of a technology refers to its capacity to be reproduced (in the same or different framework) and it is highly dependent on: upscaling capability, environmental and economic cost (CAPEX and OPEX) and performance related to the targeted products within the targeted sector. Flexibility of the technology to be adapted to other sectors provides an extra advantage towards future replicability.

All these factors will be assessed in the evaluation of the replicability of the CO_2SMOS technologies, to be tackled by WP6, however, at this point of the project, and within the activities already developed in WP1, it is already verified that the replicability potential of the technologies being developed is very promising. CO_2SMOS toolbox technologies are suitable to be implemented along several CO_2 value chains.

Biogenic CO_2 value-chains

According to the results of D.1.5: Preliminary CO_2 sources, there is great potential for CO_2SMOS solutions implementation among the BBI industries. Form the eligible sectors (within the CO_2SMOS call) , the most favourable for CO_2SMOS implementation were identified:

- Fermentation bio-refineries.
- Bioethanol production (specific case of fermentation bio-refineries)
- Biogas/biomethane generation,
- Food and beverage industry.

Several highlights that could hinder/promote the CO_2SMOS replicability in the sector of the Bio-based industry are:

- High quality/purity biogenic CO_2 sources are not always available for its use, since they are currently recycled into the main manufacturing process (i.e. wine and breweries) or sold to third parties for specific and restrictive utilization purposes requiring the achieved quality (food-grade CO_2 for food packaging, greenhouses, etc.).
- There is a significant amount of non-classified fermentation facilities (bio-refineries similar to Novamont) that are defined as first-of-a-kind plants in continuous development (with strong effort and investment in R+D). This sector is considered very promising for the future implementation of the CO_2SMOS solutions. At the same time, they form a very heterogeneous group.
- Biogas to biomethane sector (non-waste management driven plants) is also a growing source of high concentration biogenic CO_2 to be considered for future replication and up-scaling projects in analogous sectors to BBI's. the main limitation for CO_2SMOS development is their relatively small size.

Alternative Biogenic CO_2 sources

During the activities developed in WP1, other sectors with potential replicability were identified. :

- Waste management industry including wastewater treatment were biogas is generated (out of the scope of the project but with a high contribution to the biogenic CO_2 generation. Business model for this sector would be similar to the biogas sector previously described.
- Biomass/biogas combustion sources. Generating high dilution CO_2 streams. Upgrading of CO_2 to the downstream specifications will be necessary (carbon capture and conditioning)
- Biomass gasification: Also generating streams with low CO_2 concentration. Carbon capture technologies and further purification are necessary to produce concentrated CO_2 that could be used as a feedstock (according with the future CO_2SMOS platform inlet requirements).

Other CO_2 value chains

Along the interactive sessions carried out within T.1.1, not only BBI industries feedback but additional external stakeholder's insight was collected, giving adjunctive idea of the overall potential for future replicability:

- Non BBIs are also possible recipients of the CO_2SMOS toolbox solution, as non-biogenic CO_2 emitters and polymers consumers. Big companies or Corporates representing Oil & gas, steel, cement and chemical sectors are providing excellent synergies towards industry decarbonization, including CCUs, and being at the same time also potential recipients of intermediate or final products generated by the CO_2SMOS environment. Indeed, from the interactive polls described in D.1.2 we confirmed that CO_2SMOS solutions were considered by respondents as potentially applicable in a 94% of the answered internal and external stakeholders. In addition, fossil-based industries are replacing progressively their fossil fuels/raw materials by recycled, biofuels or biomaterials, and therefore, a considerable amount of this non-biogenic $C0_2$ wil change into biogenic.

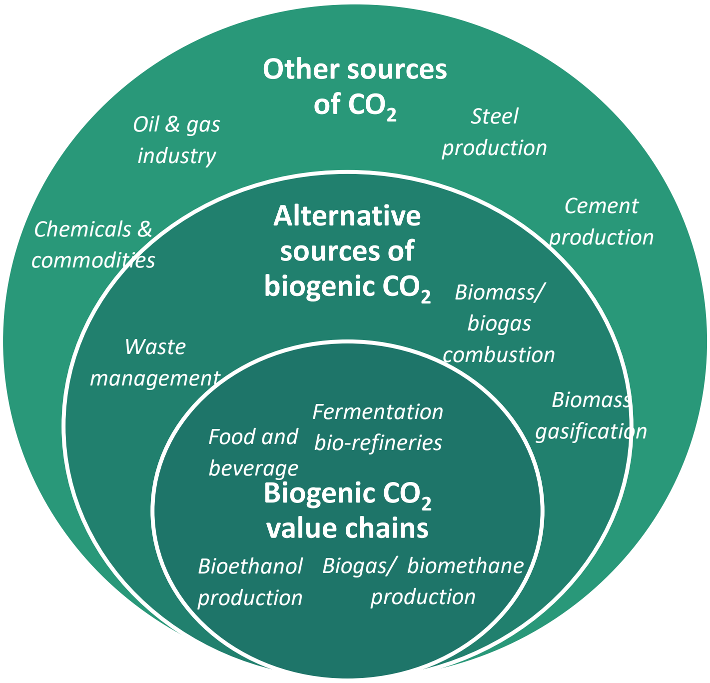

Figure 2. Replicability potential based on the sources of CO_2 (own elaboration).

5.Circularity assessment

This section addresses the issue of circularity assessment, as introduced as part of deliverable 1.7. The methodology will be further addressed in this deliverable D1.8, along with a brief overview of existing methodologies already in place for the measurement of circularity.

5.1. Review of circularity evaluation methodologies

Environmental assessments have been in use for a long time, with the life cycle assessment methodology well-stablished thanks to the ISO standards 14040 and 14044 defining the framework for this type of evaluation. Despite the existence of the ISO framework, LCA of low TRL technologies evaluation is not a trivial issue: learning curves, literature and other assumptions should be made, however, at the end of the day, no fair comparisons are possible between low and high TRL environmental life cycle analyses. In this sense, specific Guidelines for CCUs and low TRL technologies have been recently developed [12].

More recently, economic and social aspects have been included in the life cycle thinking framework (LCC and SLCA, respectively) to address the 3 dimensions of sustainability in a quantitative, science-based way, although there still is a lack of consensus and no standard is still in place for LCC and SLCA.

With the rise of the concept of circular economy, circularity evaluations have come into play, being one of the current hot topics in sustainability research. Several methodologies and approaches have been developed, but there is no standard method, and the applicability of the different tools and methods varies across the different product life cycle stages. Just as an example, most of the metrics focus on the extraction of raw materials, the manufacturing stage and the end-of-life (EoL). On the contrary, aspects related to design and use are currently out of the scope of most of the methodologies, so a relevant part of products' life cycle is still underrepresented in these methods (Figure 3).

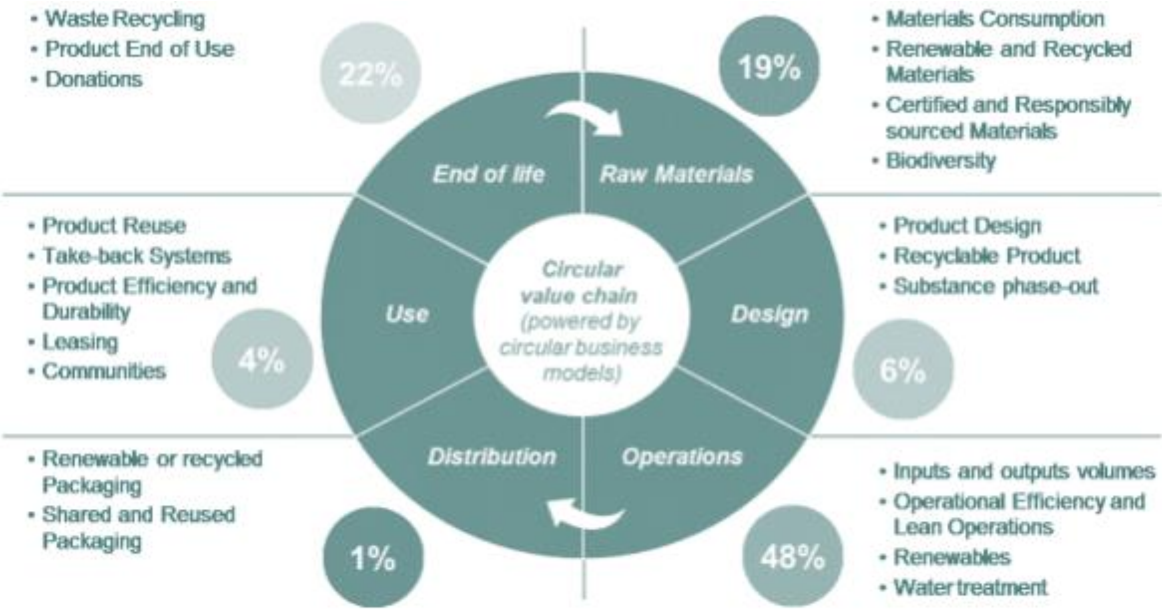

Figure 3. Review of the most common circularity metrics along the life cycle of a product. Adapted from [11].

Some of the most relevant methods and frameworks for the assessment of the level of circularity are introduced in the following paragraphs.

Material Circularity indicator by the Ellen MacArthur Foundation

The Ellen MacArthur Foundation (EMF) is a leading organization in the field of circular economy, committed to promoting circularity in different sectors of the economy and has built a wide network of stakeholders to discuss the potential of circular economy.

The EMF has developed a methodology for the quantification of circularity that was first released in 2015. After several iterations, the methodology now has evolved into a framework for the evaluation of the level of circularity/linearity of a product, encompassing also bio-based raw materials and composting process as circular materials/processes that directly contribute to increase product circularity. The core concept is the material circularity indicator (MCI) that ranges between 0 (linear) to 1 (circular) based on the material content (primary/secondary raw materials in the final product) and the length and intensity of the use compared to the intended lifetime for average products in the market [13]. The approach can be adapted throughout the supply chain considering the material losses across material/product life cycle – which is currently limited or subjected to data availability.

The framework suggests to combine this indicator with additional metrics, such as risk indicators for the supply chain, material toxicity, energy use, water use…

The EMF recently published a tool for the evaluation of circularity of businesses, Circulytics, which is based in three principles: design out waste and production, keep materials in use and regenerate natural resources. Circularity measurement is based on products and materials (recycled, reused, primary), circular economy strategies for service-based companies, water, energy, financial aspects…

In this methodology, a company provides answers for a set of indicator questions, leading to a scorecard on circular economy performance, at the company level that can support decision making activities related to circular economy strategies.

GRI disclosure standards

The global reporting initiative (GRI) is an independent organization that supports businesses and organizations to develop CSR strategies and integrate sustainability in their activities. It has developed a set of standards for corporate reporting grouped in three main categories: Universal (general standards applied to reporting activities), sectorial (for specific sectors) and topic (used for reporting of specific categories, i.e. waste, energy, water…)

As an example, *GRI 306: Organisation disclosure*, deals with the organizations' significant actual and potential waste-related impacts, providing the framework for the description of the inputs, activities, and outputs that lead or could lead to these impacts.

In particular, the standard indicator 306-2a deals with actions, including circularity measures, taken to prevent waste generation in the organization's own activities and upstream and downstream in its value chain, and to manage significant impacts from waste generated [14].

Product Circularity Datasheet (PCDS)

The product circularity datasheet (PCDS) belongs to the Circularity Dataset Initiative, that is led by the Luxembourg Ministry of the Economy. The main goal of the PCDS is to evaluate how circular a product is and to provide information about the circular path it is designed and manufactured for.

For each product, it targets to define an internationally accepted dataset that will describe the relevant information related to circularity in standard statements that serve as decision-making support for consumers and manufacturers [15].

The PCDS has three main components:

- A data template containing standardized and trustworthy statements on the product circularity.
- A third-party verification process to validate the content of the PCDS (audit system).
- A standardized data exchange protocol based on decentralized data storage (IT system).

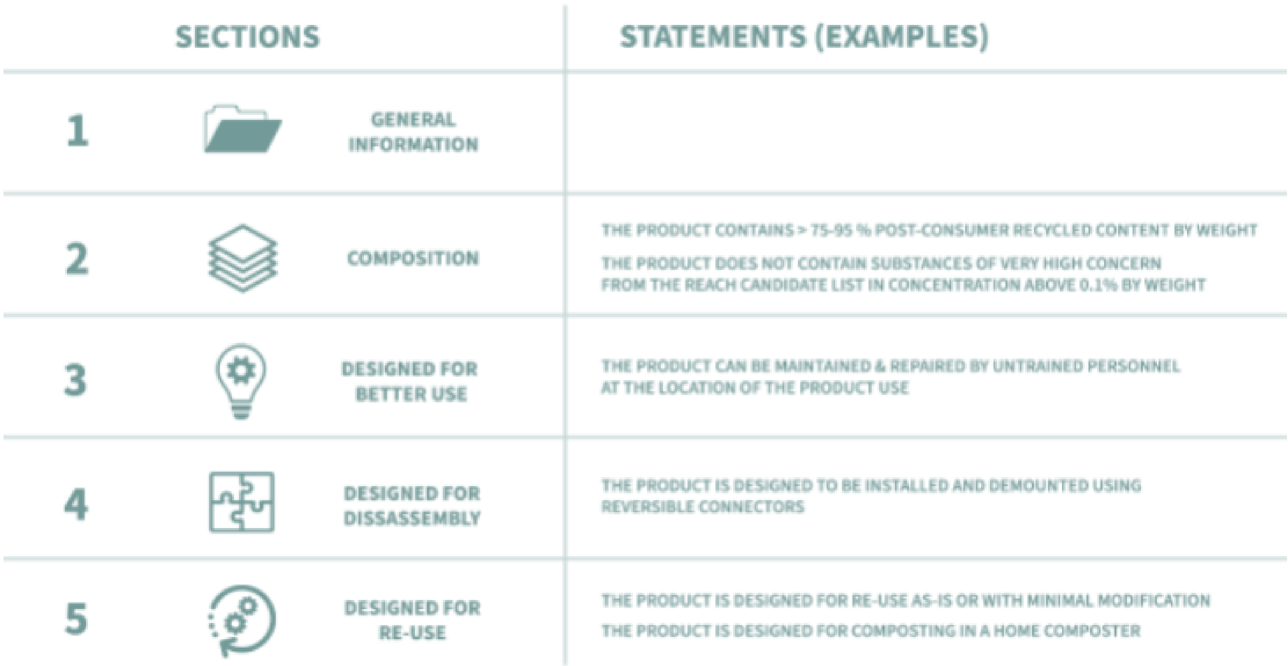

Figure 4. Structure of the PCDS template. Adapted from [13]

The methodology is still under development and has limited applicability for CO_2SMOS as it has a strong complex-product focus, paying special attention to the operation and EoL stages.

Cradle-to-cradle certification.

This certification was developed by the Cradle-to-Cradle Product Innovation Institute as a global standard for circular products. The standard was first developed in 2005, and now has turned into a consolidated standard that is applicable for different product categories and addresses several dimensions of circularity and sustainability. The certification includes 5 main categories [16]:

- Material Health.
- Product Circularity.
- Clean air and climate protection.
- Water and soil stewardship.
- Social fairness.

The Product Circularity category focuses on products with extended lifespan through increasing the number of uses, evaluating the level of achievement in this category through different performance indicators such as the content in renewable materials, availability of information for proper end-of-use management, cycling rate, design for disassembly…

Based on the results of the evaluation, the certification has 4 possible levels of achievement: Bronze, Silver, Gold and Platinum.

CTI method form the World Business Council

The Circular Transition Indicators (CTI) were developed by a roundtable of companies that are part of the World Business Council for Sustainable Development (WBCSD). The goal of the method is to evaluate the circularity of companies, for different product categories and applicable across the value chain.

This method is aligned with the definitions of circular economy in the EMF approach, and defines a set of indicators for the evaluation of aspects related to circularity of businesses. It is based on the evaluation of material flows from the perspective of the inputs (raw materials, components…) and the outputs (design for disassembly, repairability, biodegradability…). Table 1 shows a list of the main indicators for the CTI methodology [17].

Table 3. List of CTI circularity metrics. Adapted from [13].

***Close the loop* metrics**	***Optimize the loop* metrics**	***Value the loop* metrics**
% circular inflow	% critical raw materials	Circular material productivity
% circular outflow	% recovery type	CTI revenue
% water circularity	Onsite water circulation	
% renewable energy		

CIRCelligence

The CIRCelligence methodology was developed by the Boston Consulting Group as a self-assessment tool for companies to address their level of circularity. It follows a bottom up approach with indicators at three levels: process, performance and headline [18].

It combines quantitative and qualitative data and combines metrics such as material use, with dedicated questionnaires to obtain data from the value chain, although the amount of available information for this methodology is limited.

ISO/TC 323

In the pathway towards the standardisation of circularity assessments the technical committee ISO/TC 323, Circular economy, aims to cover all aspects of a circular economy including public procurement, production and distribution, end of life, circularity strategies, product data sheets as well and the evaluation of the circularity footprint.

In particular, the ISO/WD 59020.2, which is under preparation, will introduce a framework for measuring circularity.

5.2. Development of the methodology for the CO_2SMOS project

In previous activities of the WP1, some **indicators to evaluate circularity and sustainability** had been identified:**. Full process KPIs** were defined *in D1.3: Report on selected evaluation indicators*. This deliverable was created in two versions (public and confidential) in order to be used as an internal tool to guide the CO_2SMOS project advance and development. Technical, environmental and social KPIs were listed as part of the general framework for the evaluation of the performance of the project. In this deliverable, additional KPIs have been defined to address circularity-related aspects such as the intensity of material and energy use (Table 4), as well as indicators devoted to the assessment of the level of circularity.

Table 4. List of circularity-related KPIs[1]

Technical KPI	Definition	Rationale for the KPI definition
Materials Intensity rate	ton of produced product / ton of input materials	Production yield rate
Renewable material rate	ton of renewable materials / ton of input materials	Renewable material rate
Energy intensity	total energy consumed / ton of produced products	Energy used for the production of final products
Renewable Energy Use	renewable energy in inputs / total energy in inputs	Renewable Energy rate
Waste intensity	ton of produced wastes / ton of produced products	Waste production per final product
Recycled waste rate	ton of recycled wastes / ton of total wastes	Rate of recycled waste at plant level
GHG Emissions	kg of GHG emissions / ton of produced products	To indicate the average GHG emissions per produced product
Net Fresh Water Use	m^3 of net freshwater inputs / ton of produced products	Net freshwater use per final product.

According to the **feedback provided by the stakeholders** in the meetings and interviews, various indicators are relevant to assess the circularity and sustainability of the developed materials.

- Final biogenic CO_2 conversion yield to specific biochemical/bio-based chemical and bio-based materials. Effort should be dedicated to design efficient processes to reach high conversion yields that enable upscaling at higher TRLs towards successful application and business development, as well as replication strategies.
- Upscaling potential of the developed value chain is of a paramount importance for the majority of biogenic CO_2 producers, since, in general, it is expected a high potential of exploitation of biogenic CO_2 streams from innovative industrial partners".
- CO_2 source: Low purity/richness sources might require specific pre-treatment to condition the targeted stream to be introduced to the CO_2SMOS system. Specific requirements should be defined (Tech#1-Tech#5) in order to better evaluate purification needs and environmental/economic impact of CO_2 pre-treatment.

[1] Gate to Gate approach referred to industrial plant level.

- Final purity/richness of the bio-based product: high dilution materials or products consisting of different materials irreversibly added together would require additional environmental and economical effort to be introduced in the market.
- Other relevant process indicators related with the LCA (to be assessed at later stages of the CO_2SMOS project) are water footprint, toxicity, resources depletion, eutrophication potential, acidification potential, etc
- Properties of the developed materials should be at least similar, or superior to their counterparts (sometimes the newly developed products show improved performance compared to the existing solutions). These parameters should be defined by the final end-users of:
    - Building blocks.
    - Final bio-based product: they should ensure a similar workability, recycling capacity (number of cycles before degradation), less wastages, etc

To complement these lists of indicators, D1.8 tackles the assessment of circularity in CO_2SMOS as a key aspect to determine how regenerative these new processes are, later having the possibility of merging this study with the LCA results to build a holistic set of indicators and evaluate the performance of the project.

The first step is to address the level of circularity of the material flows at product level (Figure 5). To this end, the framework defined by the CTI will be used (See section 5.1), in particular the metrics in the "Close the loop" category [17]. These indicators will be complementary to the ones defined in Table 4 above.

Figure 5. Input and output flow categorization referred to the product system boundaries. Adapted from [13].

The percentage of material circularity is defined as the weighted average between the circularity of the inputs and the outputs. The % circular inflow is calculated from the ratio between the amount of renewable and secondary materials compared to the total amount of material inputs:

$$\% \, circular \, inflow = \frac{mass \, renewable \, inflow + mass \, recycled \, inflow}{total \, mass \, of \, all \, inflow} * 100 \qquad Eq. 1$$

Flows that are both renewable and come from secondary sources should only be accounted once, avoiding double-counting issues. Linear inputs are those that come from virgin raw materials. On the contrary, circular inputs are those that come from secondary raw materials or from renewable sources, for example from reused, remanufactured or recycled sources.

For biogenic inputs, according to the CTI framework, they can be considered circular if they come from sustainably managed sources through natural regenerative cycles after extraction. In the same way, for the quantification of the % circular outflow, the methodology defines the following formula:

$$\% \, circular \, outflow = \frac{\% \, circ \, outflow \, A * amount \, A + \% \, circ \, outflow \, B * amount \, B}{total \, outflow \, (amount \, A + amount \, B)} \qquad Eq. 2$$

The % circular outflow can be defined from the potential for recovery for each of the outputs and the actual level of recovery using the following formula:

$$\% \, circular \, outflow = \% \, recovery \, potential * \% \, actual \, recovery \qquad Eq. 3$$

In general, most of the outputs can be categorized based on 2 general rules:

- If the outflow is fully recoverable, then the recovery potential is 100 %.
- If the outflow is not recoverable, then the potential is 0 %.

For the technical outflows, that can consist of (by-)products or waste, the company must determine the recovery potential and the % actual recovery. As a general rule if detailed information is not available, the methodology provides the following criteria: if a technical material keeps a functionality equivalent to the original in its second life in a technically and economically feasible way, it's circular. On the contrary, if it's downcycled or turned into a fuel or burned it, it is linear.

- For bio-based products, biodegradability and potential content of substances of concern are the common criteria used for the calculation of the recovery potential or circularity index:
  - Biodegradability: The % recovery potential is the weighted average of the % biodegradability of its components or compounds, under the condition that it is possible for the consumer to separate bio-based resources from technical components at end of life. Biodegradability is not linked to the bio-based origin of materials, since they are different, separated concepts, so other circular end-of-use strategies need to be considered in this scenario, for example for non-biodegradable, biobased materials.
  - Substances of concern: Only consider a product to have recovery potential if its levels of substances of concern abide with existing regulations. In general, certified biodegradable materials are proven to be non-ecotoxic and free of harmful substances by independent external parties following strict regulations such as EN 13432.

In addition, bio-based products that substitute total or partially other fossil / non-renewable based products which required specific properties such as durability and extended life time, may be also considered as products with a relevant percentage (%) of circularity since they actually replace non-renewable products by others that they do are, and at the end of their life cycle can be recycled and/or reutilized.

Finally, the % recovery shows the amount of outflow that is recovered at the end of use. This indicator requires primary data from the company. If a given company keeps control and tracks its product flows after they leave your facility, this data should be available.

If no data is available, information from existing standard or regulations on recovery rates can be used to perform the calculations.

For bio-based outflows, they can be considered recoverable if they biodegrade as designed during the end of life (for biodegradable biobased materials only) , as well as if existing reuse/recycling/remanufacturing strategies (e.g. in the case of non-biodegradable biobased materials) such as chemical and mechanical recycling allow to keep the bio-based materials in use for longer and with retained value.

Valorisation of bio-based products through energy recovery would only be considered circular under certain criteria stated by the methodology, such as the lack of other viable end-of-life options beside landfill, the sustainable origin of the product and that the product is free of substances of concern. It should also be considered the potential use of the CO_2 resulting from the energy recovery in the production of new materials, as this is a key differential aspect from the project.

Landfill and incineration of bio-based products that are part of mixed-waste streams is considered linear with 0 % recovery potential.

6.Conclusions

Deliverable 1.8 provided an overview of some of the drivers/constraints that can steer the short and long-term strategies of the use cases, while collecting and summarising the most relevant outcomes of the different activities in WP1.

The wide range of initiatives in the field of sustainable development and circular economy, developed as an answer to the climate emergency, address a number of critical aspects to limit global warming well below 2 ºC. These initiatives define different sets of targets that can condition the trajectories of the use cases in terms of emissions, use of resources, sourcing, product development and marketing, product design and end of life management strategies. At the same time, they have resulted in a thriving ecosystem for industries related to the development of sustainable products, providing great opportunities for business development and a great replication potential for CO_2SMOS' core ideas.

In this context, the use cases have defined strategies to adapt to all these changes, committing to the development of circular, low carbon operations in the short to mid-term and reducing material and energy consumption through the development of disruptive technologies, such as the integration of CCUs in their production processes. In addition to this, the potential increased value of CO_2 emissions as a source of secondary raw materials has resulted in a number of CO_2 sources that are suitable for the replication of CO_2SMOS' technologies, with processes with biogenic CO_2 emissions being the most promising in terms of technical and economic feasibility.

Finally, with the rise of the Circular Economy concept, several frameworks and methodologies have put circularity metrics in the spotlight as a key tool to evaluate how regenerative a process is, and accordingly develop roadmaps and specific action plans for the implementation of CE-related strategies that allow to increase the circularity of the processes, reducing the consumption of virgin raw materials and minimising waste generation.

In consequence, the deliverable presents a list of general indicators related to the circularity of the developed technologies, as well as a definition of specific indicators to evaluate circularity based on the CTI methodology.

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CO2SMOS

Solutions for a circular biobased industry

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