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List of abbreviations

CCU – carbon capture and utilisation

CHP – combined heat and power (generation)

CO – carbon monoxide

CO2 – carbon dioxide

ETS – emission trading scheme

EU – European Union

GDP – gross domestic product

GHG – greenhouse gases

H2 – hydrogen

LCA – life cycle assessment

N2 – nitrogen

OCAP – Organic CO_2 for Assimilation by Plants

R&D – research and development

RED – Renewable Energy Directive

SCOT – Smart CO2 Transformation

EXECUTIVE SUMMARY

Overview

The goal of the study and findings in this report assess the **social and economic impact** of implementing a carbon capture and utilisation (CCU) hub at the North Sea Port industrial zone in East Flanders, Belgium. The CCU hub is one of the most ambitious initiatives of its kind in Europe and a pioneering endeavour on a global scale. It is expected to help sustain the local and regional economy, create new jobs, foster economic and innovation linkages, while helping an ecosystem of related industries near and far to reduce their carbon emissions and achieve broader climate and environment goals.

The study revolved around a mix of investigative methods including *desk research, interviews* and *case studies.* Interviews took place between June 2019 and February 2020 with experts and those involved in current activities in the Port, as well as outsiders with expertise in CCU and potential markets and customers of CCU tech/products. The data was analysed and used in case studies, scenario analyses and in the scoping of CCU value chains.

The study focuses on the socio-economic but also **technological and innovation-oriented impacts** of developing the CCU hub and associated activities in the North Sea Port including those on competitiveness, economic costs and benefits, employment generation, new knowledge-creation, new linkages, recognition and visibility benefits, technical knowhow and technological advances in the region, local clusters, and any new capabilities, spin-offs and spill-overs resulting from **CCU value chains**.

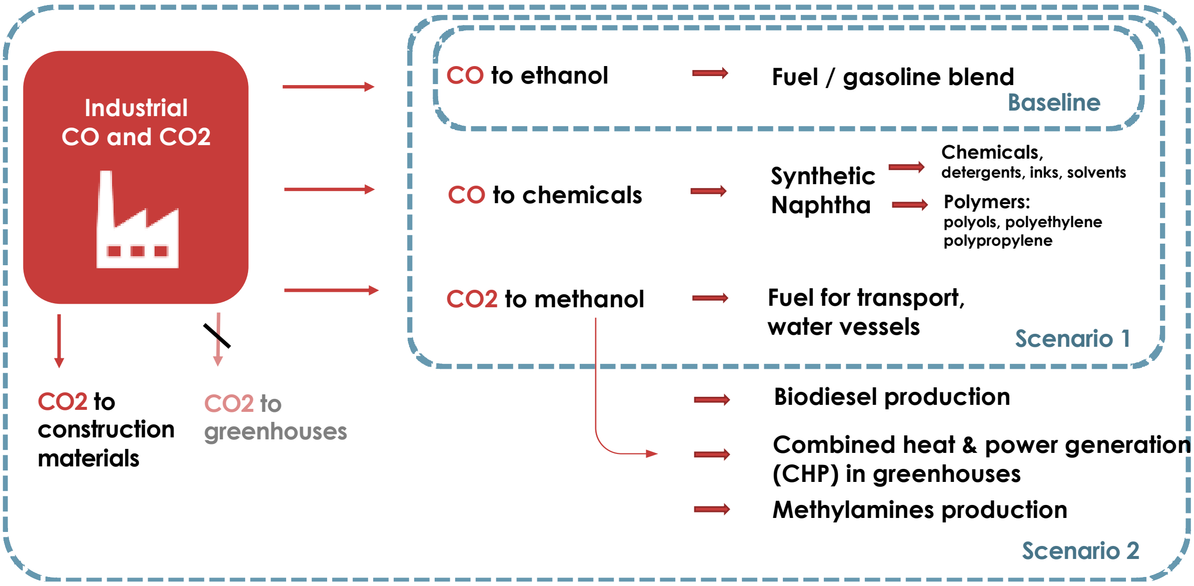
Broadly, it is understood that the more value chains that can be launched within the CCU hub, the greater the overall observed impact. But CCU practices are relatively new and in many cases technologies and value chains are in the R&D and piloting stage, so evidence of actual impacts and lessons from examples on the ground are still scarce. Indeed, until now, the social and wider economic impacts of the CCU projects and technologies have been largely under-investigated.

Nevertheless, **seven strong case studies** guided by **three clear scenarios** have been derived according to their genuine feasibility and based on evidence from the study and benchmarks in Europe and abroad. The scenarios are outlined in Chapter 4 and the case studies are analysed and discussed in sections of the report with a full account of each in the Appendix.

Value chains and scenarios explored

Three scenarios of CCU cluster development in the North Sea Port and beyond have been put forward in this study. These include the baseline scenario where the current state of play will continue, while two other scenarios are based on the various parameters and permutations of new value chains and boundaries of the CCU hub activities outreach, as analysed within the study. The geographical boundaries of the scenario stay within the North Sea zone that is shared between East Flanders of Belgium and Zeelandic Flanders on The Netherlands side, due to the proximity of key players involved in the CCU hub.

CCU value chains covered in the scenarios



Cases and their value chain

	Case study	Value chain covered
Case 1	LanzaTech project for bio-ethanol production, Shougang China	CO to ethanol
Case 2	George Olah Renewable Methanol Plant, Iceland	CO2 to methanol
Case 3	ThyssenKrupp demonstration project for methanol and chemicals, Duisburg Nord Rhein Westphalia	CO2 to methanol, ammonia, other chemical
Case 4	CO2 based polyol production at Covestro	CO2 to polyol and polyurethane
Case 6	Evonik & Siemens artificial photosynthesis (electrolysis and fermentation)	CO2 to specialty chemicals
Case 6	Carbstone technology by Orbix, Belgium	CO2 to construction materials
Case 7	Organic CO_2 for Assimilation by Plants (OCAP), Netherlands	CO2 to greenhouses

Recommendations going forward

New technologies present opportunities but usually come with their own economic challenges. Green technologies are special in that the environmental sustainability mission does not always immediately translate into commercial viability.

Economic obstacles faced by CCU projects mainly concern (i) the price of the product, and (ii) high investment cost of CCU projects.

(i) High price of product

Recommendations:

Promote public procurement instruments for CCU-based products/services, e.g. public transport and shipping services can specify recycled carbon-based fuels in their green procurement products; construction of public buildings or infrastructure can specify procurement of carbonation-based construction materials.

Promote other schemes that will boost demand for CCU products and fuels, e.g. setting specifications for fuel blends, carbonation-based construction materials, recognition under the local green product labelling, etc.

Set examples to follow, e.g. public transport companies (train, water shipping) can shift to CCU-based fuel use which would create a secured market for the CCU fuel and help in further rolling out to a wider market.

(ii) High investments cost

Recommendations:

Ensure diverse EU funding schemes for upscaling and commercial projects in CCU and related technologies such as green hydrogen. Today, many CCU technologies have been developed in labs; they need incentives and direct support to move to the market.

Dedicate special support instruments for industrial symbiosis projects. It can be a purely public funding or co-funding of the new facilities, or a combination of public and private financial instruments with favourable financing conditions.

CCU technology is still emerging as a commercially viable field. Promising innovations such as growing bacterial protein from waste CO2, boosting algae farming with industrial CO2, CO2-based specialty chemicals, and numerous other examples need some maturing to scale them up and make them more efficient, ensuring high- quality and safe products, while reducing dependence on high energy and resource inputs, and developing efficient and less costly gas separation, hydrogen production and other auxiliary technologies.

Recommendations:

Encourage carbon-intensive industries that have little room to manoeuvre in cutting their carbon emissions, to invest, introduce and integrate carbon-recycling technologies that can also generate additional value in their local economies.

The EU should sustain its leadership in CCU technologies by continuously supporting technology development, commercialisation, upscaling as well as R&I in novel carbon-recycling possibilities. Technological barriers that exist now can find solutions via R&I and testing efforts. All these are needed to de-risk the required CCU development trajectories, to explore alternative processes and find economic and environmental optimisations at different scales and with different process setups.

The environmental performance of CCU technologies remains a complex and debated issue. This is because such performance could be unique to each CCU project and depend on a combination of many factors, including (i) the availability of renewable energy as a guarantee of the climate mitigation potential of CCU products that require energy for production processes, as well as (ii) lack of comprehensive LCA assessment methodology for CCU.

(i) Availability of renewable energy

Recommendations:

Policy and investment support are highly recommended in expanding renewable energy production, scaling up existing capacities and launching new renewable energy production capacities, which for CCU projects can be off-grid installations, however overall greening of the electricity grid should be the ultimate aim.

Addressing the cost of the renewable energy to encourage its competitiveness against fossil-based energy should be a priority policy objective. Wider deployment is one of the ways to cut production costs and prices (which has been seen with the wind energy deployment). Redistributing fossil fuel subsidies[1] to support renewable energy development, as well as using carbon tax revenues for investment in clean energy production facilities, could also be part of the policy support package.

(ii) Lack of a commonly recognised, comprehensive LCA assessment

Recommendations:

Development of a comprehensive LCA guideline for assessing the environmental impact of CCU projects, as well as common recognition of methodologies across Europe and possibly internationally need to be facilitated on an EU level. For CCU, it is necessary to calculate the CO2 avoided rather than the CO2 used in the process. The methodology should focus not only on climate mitigation and GHG reduction, but also cover other impacts related to ecosystems, water, land use, air, energy, materials and waste.

LCA results should become a basis for fair recognition of CCU technologies in the European Emissions Trading Scheme, in as much as they lead to a net reduction of CO2 emissions over the whole life cycle. LCA should also become a basis for demand-boosting instruments for CCU products (e.g. procurement, product certificates and labels, minimum fuel blending quotas, etc.).

Addressing regulatory gaps is vital because there is presently no proper framework conditions to help CCU technologies reach wider acceptance and become more competitive and commercially viable.

Recommendations:

Develop a regulatory framework that incentivises both the permanent sequestration of CO2 into, for example, polymers or construction materials by the mineralisation as well as temporary sequestration in CCU fuels. The regulatory setting should assure comprehensive LCA methodology for CCU as a precursor for other regulatory measures (addressed below), and securing an even playing field with bio-based and traditional products.

Ensure that CCU is ultimately recognised under the EU Emissions Trading Scheme in order to allow a breakthrough for CCU technologies. Namely, along with the carbon storage via mineralisation, the accrediting of GHG emissions avoided and/or carbon negative emissions should be considered under the EU-ETS.

A smart carbon-pricing system should be introduced to push CCU projects into profitable areas. Carbon taxation should be applied with a warrantee of an international level playing field – within Europe and with border-tax adjustments between the EU and the rest of the world.[1] Carbon taxation should also be sensitive to various types CCU products: e.g. carbon tax for CCU fuel could be paid by the CO2 producer, while if it is a CCU product with a longer lifetime (e.g. polymers, construction material) the carbon tax would be paid by the product user. At the same time, benchmarking against footprints of currently used (e.g. fossil-and bio-based) products should be considered in calculating carbon tax.

Ensure full implementation of the revised Renewable Energy Directive (RED II), which includes mandatory targets for CO2-based fuels, via rapid and fair adoption of the required Delegated Acts[1]. At the same time, encourage members states and regions to consider concrete strategies and plans on deployment of CCU technologies in achieving the 2030 and 2050 climate targets and the new EU Green Deal goals.

Ensure that standardisation bodies (CEN and national bodies) work hand in hand with industry in developing required standards for the new CCU industry (e.g. standards for the quality of captured CO2). Align policy and regulatory development around industrial symbiosis and CCU, such as on standards development, reporting, indicators, and for promoting CCU by building favourable framework conditions for industrial symbiosis.

Policy implications

This study has demonstrated that the environmental, economic and social benefits of CCU technology deployments could be promising for the local economy, while their wider diffusion can offer solid input towards addressing global climate change imperatives. This study, however, also showed that there are a number of obstacles that prevent the CCU initiatives from easily and quickly penetrating current industrial and economic systems. Addressing these obstacles would need favourable framework and market conditions that can be created by carefully designed policy measures and incentives.

With the proliferation of the circular economy in the EU there are growing calls for carbon removal via re-use and storage in products. Yet, CCU is still not well understood and embraced by a wider policy and economic community and often not regarded as a promising approach for GHG reduction. There are several challenges that prevent CCU technologies from gaining wider diffusion: economic barriers related to the cost of CCU technologies and products, technological challenges requiring further improvements, testing, piloting, research and innovation, ambiguity and lack of understanding of CCU technologies' environmental performance, and policy barriers that are mainly due to uneven playing fields, lack of favourable framework conditions and limited political support.

These obstacles are interlinked and to great extent reinforce each other, which means resolving them would require a **comprehensive approach** and favourable framework and market conditions, measures and incentives.

CCU, from challenges to strengths

CCU is the process of capturing polluting CO and CO2 emissions and either using them directly as a carbon resource or transforming them into a new product through biological or chemical processes. CCU has the ability to transform most polluting industries, diversifying outputs and turning a liability into a strength.

Current challenges facing the sector:

- While the technology has already been successfully demonstrated, the efficiency of chemical processes and innovation in new pathways have to be increased. Doing so will not only increase the economic viability of CCU but will also offer alternative applications for this resource.
- If commercial success is to be achieved, funding will play a primary role in order to negotiate the economic obstacles. Collaboration between public and private organisations is an essential part of the future of CCU technology, as this will allow to overcome the current financial barriers for large-scale commercialisation.
- Considering the role of the public sector in supporting the implementation of CCU, regulations should reflect the necessity for our current society to move from fossil fuels to CO2. Ensuring conformity of legislative changes with the low-carbon agenda at each level of government will be a challenge that needs to be addressed.
- The lack of information in terms of the societal perception of CCU technology is the final issue that needs to be addressed. Diffusing knowledge on the benefits and risks of CO2-based products will go a long way to underling its potential to a wider audience.

From challenges to strengths:

- CCU has been identified as a potential driver of growth in the future EU low-carbon circular economy. CO2 is a future replacement for fossil hydrocarbons.
- CCU can facilitate the European energy transition. For example, while the transition to low-carbon energy sources is in full swing, intermittent/insecure supply continues to be a major obstacle for these renewable options. Synthetic fuels may be the solution required to address this problem, enabling a riskless and sustainable transition.
- The most straightforward benefit of CCU is the reduction of carbon emissions. Not only does the utilisations of CO and CO2 allow for long-term storage in new products, it also greatly diminishes the addition of 'fresh' hydrocarbons into the current economy.
- Utilisation of carbon emissions can be commercialised globally (a benchmark non-EU case is the Shaugang project in cooperation with LanzaTech).

1 Introduction

1.2. CCU as one of the responses to climate change

Greenhouse gas emissions from fossil fuels have increased by 2.7% annually over the past decade and are now 60% higher than in 1990. To avoid the worst effects of climate change, global warming should be limited to at least 1.5°C, which requires the 2017 CO2 emissions level to be cut by at least 50% by 2030 and then achieve carbon neutrality by 2050[1]. *Carbon capture and utilisation (CCU)* has been attracting attention worldwide as its main goal is to turn waste CO2 and CO emissions into valuable products (chemicals, fuels, construction materials), and to contribute to climate change mitigation. CCU is the process of capturing polluting CO and CO2 emissions and either using them directly as a carbon resource or transforming them into a new product through biological or chemical processes. CCU has the ability to transform most polluting industries, diversifying outputs and turning a liability into a strength.

The Smart CO2 Transformation (SCOT) collaborative project[2] has identified the following areas of strength:

- CCU is a potential driver of growth in the future EU low-carbon circular economy. CO2 is a future replacement for fossil hydrocarbons.
- CCU can facilitate the European energy transition. For example, while the transition to low-carbon energy sources is in full swing, intermittency continues to be a major obstacle for these renewable options. Synthetic fuels may be the solution to address this problem, enabling a riskless and sustainable transition.
- The most straightforward benefit of CCU is the reduction of carbon emissions. It offers a long-term solution by storing them in new products and largely stops new or 'fresh' hydrocarbons from entering the economy
- Utilisation of carbon emissions can be commercialised globally (some non-EU cases, such as the Shaugang project, in cooperation with LanzaTech, have established a case for this).
- Carbon emissions are a 'renewable' resource, low in cost and non-toxic.

The main candidates for potential application of CCU as sources of CO and CO2 are power plants, oil refineries, biogas sweetening, ammonia producers, cement, iron and steel producers, electricity generation, fossil-fuel power plants, and waste incineration plants. For each industry emitting CO and CO2 there are different carbon-capturing systems being developed. However, the level of maturity among different capturing systems varies across industries. As an example, power plants and refineries are well advanced in implementing carbon emission capturing, while such industries as steel and iron are still in transition mode.

The CO2 emissions can be used directly in several industries like food and beverage as a carbonating agent, preservative and packaging gas. It can also be used in the pharmaceutical industry as a respiratory stimulant or as an intermediate in the synthesis of drugs (Kokal & Al-Kaabi, 2010).

CO2 can be processed and converted into fuels and different chemical products. Such outcomes can be achieved through "carboxylation reactions where the CO2 molecule is used as a precursor for organic compounds such as carbonates, acrylates and polymers, or

1 IPCC 2018, Global Warming of 1.5°C – Special Report, Intergovernmental Panel on Climate Change, available at: https://www.ipcc.ch/sr15/

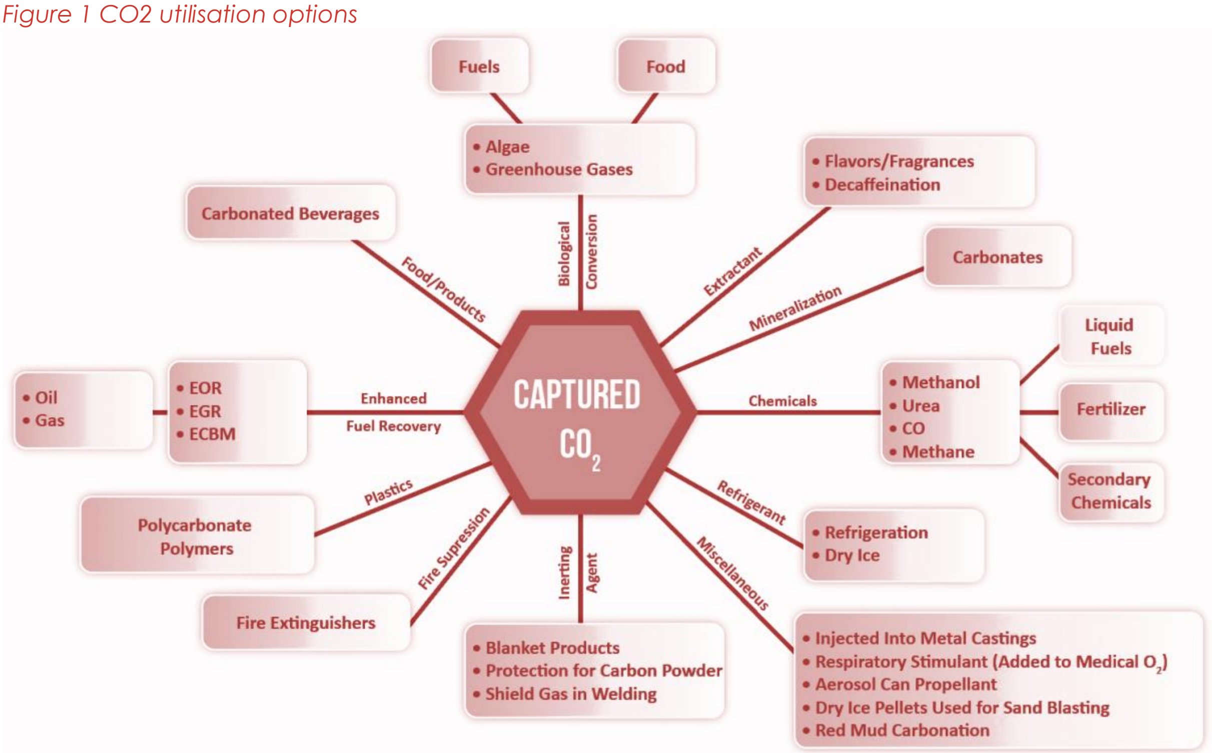
2 http://www.scotproject.org/CO2-utilization

reduction reactions where the C=O bonds are broken to produce chemicals such as methane, methanol, syngas, urea and formic acid" (Styring, et al., 2011; Yu, et al., 2008; Markewitz, et al., 2012).

Another way to use CO2 emissions is in mineral carbonation, a chemical process where CO2 reacts with a metal oxide, such as magnesium or calcium, which in turn forms carbonates (Metz, et al., 2005; Li, et al., 2013). Binding the CO2 to construction materials like concrete, bricks and stones is being increasingly looked into. Some greenhouse-based farms have started applying CO2 sink methods to increase production. Another way to apply CO2 emissions is through the cultivation of microalgae, which is used in the production of biofuels, feed for livestock, colourants and vitamins (Styring, et al., 2011; Brennan & Owende, 2010; Li, et al., 2008).

Various examples of CO2 utilisation are shown in Figure 1.

Figure 1 CO2 utilisation options



Source: https://s3platform.jrc.ec.europa.eu/carbon-capture-and-utilization

While CCU is certainly promising in the context of the shift towards a green and circular economy, there are a **few challenges** that need to be addressed to capitalise on this innovative technology:

- While the technology has already been successfully demonstrated, the efficiency of chemical processes and innovation in new pathways have to be increased. Doing so will not only increase the economic viability of CCU but will also offer alternative applications for this resource.
- If commercial success is to be achieved, funding will play a primary role in order to negotiate the economic obstacles. Collaboration between public and private organisations is an essential part of the future of CCU technology, as this will help to overcome the current financial barriers for large-scale commercialisation.
- Considering the role of the public sector in supporting the implementation of CCU, regulations should reflect the importance of society's move from fossil fuels to CO2. Ensuring

the conformity of legislative changes with the low-carbon agenda at each level of government will be a challenge that needs to be addressed.

- The lack of information in terms of the societal perception of CCU technology is another issue. Diffusing knowledge on the benefits and risks of CO2-based products will go a long way towards underlining its potential to a wider audience.

1.1 The context and objectives of the study

The North Sea Port plays a major role in East Flanders' economy as well as in the Belgian economy, in terms of industrial activity and as an intermodal centre facilitating commodity flows. The port contributes to the prosperity of the region and generates a net value of €26.4 million and revenues of €106 million. The total added value of the North Sea Port is estimated at €14.5 billion.

In 2018, gross domestic product (GDP) ***in East Flanders*** *reached €56 billion, or 12% of the national output. GDP in the city of Ghent alone was €27 billion, accounting for 49% of the region's total and 6% of Belgium's GDP.*

At the same time, as one of the biggest marine and inland water transports hubs in Europe and host to one of the largest steel and chemical facilities, the port and its industrial community are high contributors to the region's overall environmental burden, including greenhouse gas emission, other air pollutants (nitrogen, sulphur, etc.), various waste streams, etc.

In an effort to reach its sustainability and climate objectives, East Flanders has been focusing on cutting industrial CO2 emission in the region. One of its flagship initiatives was the launch of a unique consortium with the ambition of transforming Ghent's North Sea Port area into a *hub for carbon capture and utilisation (CCU hub)*. This has underscored East Flanders' ambition to become a leading region in the deployment of CCU technology.

The City of Ghent, the Development Agency of East Flanders, Ghent University, Bio Base Europe Pilot Plant and North Sea Port in 2018 carried out the preliminary study to expand the port area of Ghent-Terneuzen into a CCU hub. Several exploratory initiatives and a pilot programme have been pursued together with local industry and other actors. The vision now is to create a viable CCU hub/cluster in the North Sea Port industrial zone, which can create new value chains, activities, and involve local, and possibly external industrial actors. While previous assessment studies have focused primarily on technological, technical and financial aspects for the potential CCU hub, **this assignment is investigating the socio-economic aspects.**

The overall **objective** of the study is to assess the social and economic impact of the potential implementation of a CCU hub in the North Sea Port industrial zone. More specifically, the study investigates the following:

- Identification of the market opportunities for new economic activities and creation of new value chains including e-fuels, maritime and land transport, chemical and biochemical products, building materials and other.
- Envisaged socio-economic impact (both positive and negative) of developing a CCU hub on companies present in the North Sea Port industrial zone, including new economic activities, new revenues and costs, new value chains, new business models, new collaborations, new R&I activities, new markets and increased competition from others. Selected companies from other regions, potential members of the hub, as well as other non-industry actors are also covered.
- The wider/aggregated socio-economic impact on the East Flanders region in terms of competitiveness, employment, the labour market, education, collaboration, new R&I opportunities, and other spill-overs, as well as externalities in terms of economic and environmental costs.

- Socio-economic obstacles and opportunities for the realisation of an industrial cluster based on the reuse of CO/CO_2 and renewable energy, including the cross-border circumstances revolving around further development of a CCU hub in the North Sea Port industrial zone.

This study is structured in the following way:

Section 2 will explain the scope of the study including the CCU value chains covered and industries captured under these value chains. It also presents the analytical scope of the study, types of impacts that constitute the analytical framework. A methodological scoping sub-section presents the study approaches used in the collection of evidence for further analysis, as well as the design for scenario selection and analysis.

Section 3 summarises the analyses and findings (evidence collection, interviews, case studies, as well as desk research) on each type of CCU value chain targeted in the study.

2 Scoping the study

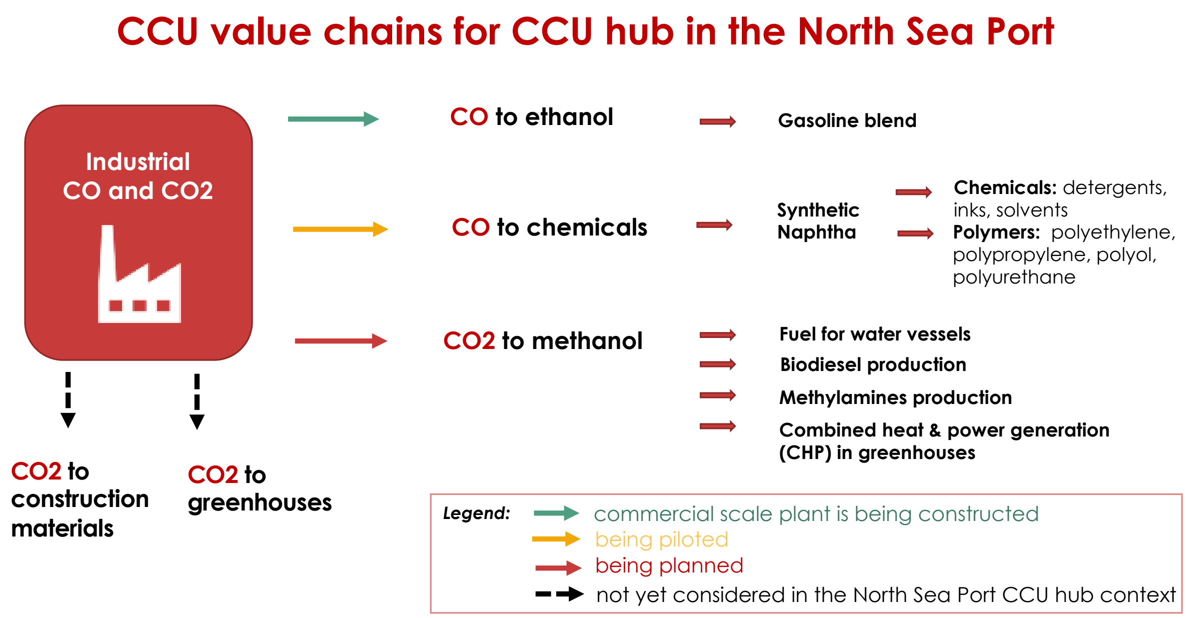
2.1 CCU value chains covered in this study

The territorial scope of this assignment covers the industrial ecosystem in and around the North Sea Port zone which includes the areas of Ghent and Terneuzen. Moreover, in this study we also consider a wider ecosystem with potentially relevant players (industries, clusters, research, service organisations) from East Flanders, nearby Zeelandic Flanders in the Netherlands, and potentially relevant companies from neighbouring regions in Belgium.

In the context of the CCU hub in the North Sea Port, this study has analysed several CO2 and CO utilisation options that can potentially turn into value chains for the local economy. Their selection has been dictated (a) by ongoing projects working towards launching value chains in the North Sea Port area (i.e. CO to ethanol by LanzaTech, CO to synthetic naphtha and polymers by Dow, and methanol by Engie), and (b) by the availability of technologies in the national or European markets, which include CO2 based chemicals and polymers, carbonation of construction products, and CO2 enrichment of greenhouse farming, as well as additional possibilities for methanol application, such as in the production of biodiesel, synthesis of methylamines, in the combined heat and power generation in the greenhouses[3].

The figure below presents the value chains that have been scoped and addressed in the evidence-gathering and analysis parts of this study.

Figure 2 CCU value chains covered in this study



Source: authors based on scoping discussion

[3] It has to be noted that the analysis of opportunities for methanol was initially focused solely on water shipping, due to its vast potential in this area. The discussion of opportunities for methanol use in the combined heat and power generation at greenhouses came in later stages of the study. At the same time, the consultation with stakeholders from the Flemish agri-sector has identified a lack of feasibility for direct feeding the CO2 to greenhouses, while suggesting the possible potential for methanol in combined heat and power generation. Section 4 explains the final scope of the scenario analysis.

The industries covered under these CCU value chains include:

- Steel producer
- Renewable energy supplier
- Chemicals producer
- Industrial biotechnology
- Fuel suppliers (bio-gasoline, biodiesel)
- Construction materials manufacturers
- Transportation and shipping
- Greenhouse based agri-sector companies
- Other service providers

It has to be noted that while the evidence-gathering and analysis has focused on all above-listed value chains, the scenario analysis included only the value chains deemed to be realistically viable in the context of the CCU hub in the North Sea Port (e.g. the CO2 to greenhouses value chain, as well as CCU-based polyol production option have been excluded from the scenario analysis). In the analysis of the downstream part of the methanol value chain, it included use of methanol as fuel in water transport, biodiesel production, methylamines synthesis, as well as in the CHP generation in greenhouses.

2.2 Analytical scope – social and economic impacts

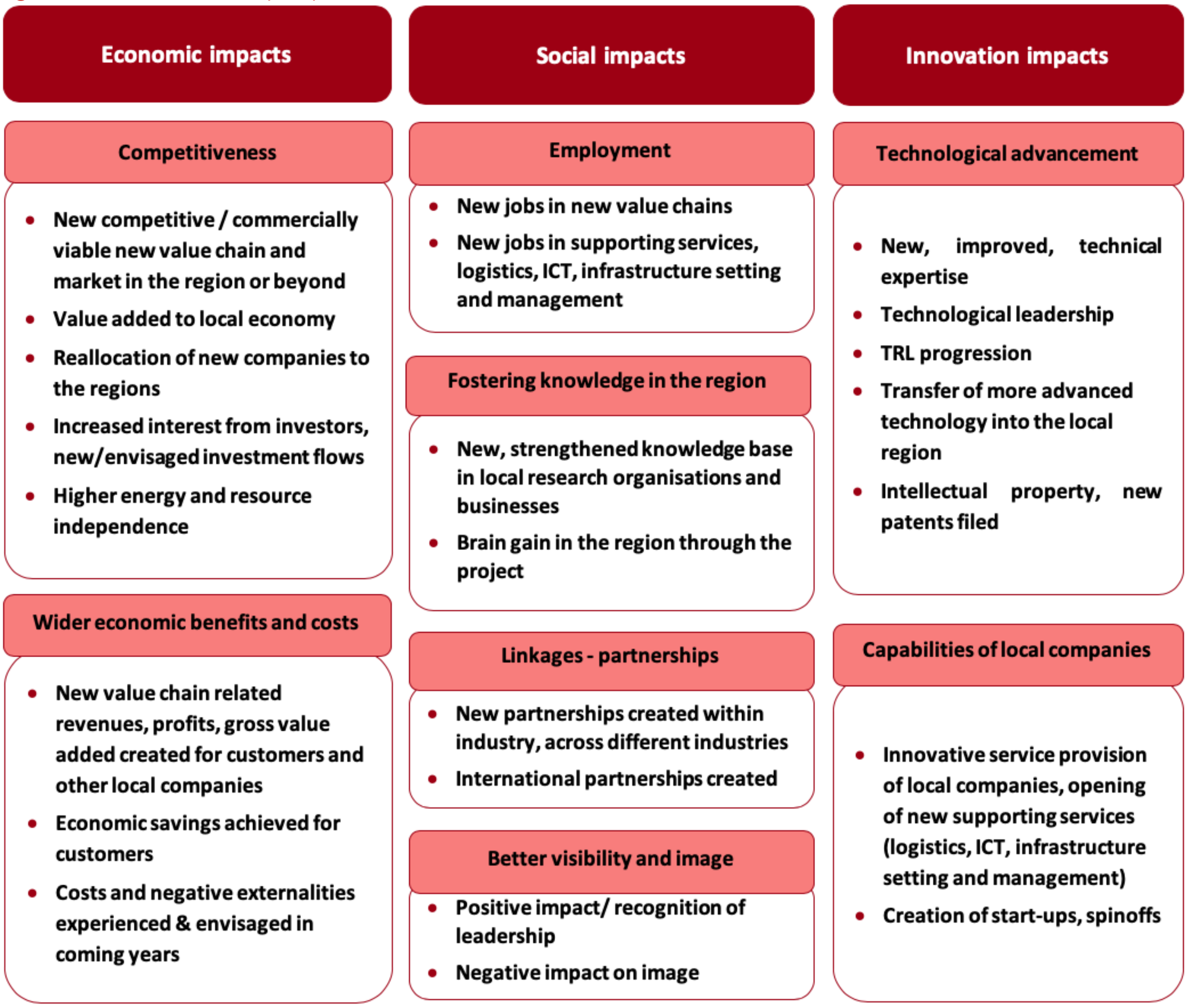
The analytical scope of this study is focused on analysing *social and economic impacts*. Following the objectives presented in Section 1.1. the socio-economic impacts have been studied along several dimensions, including competitiveness, economic growth, employment, skilled human resource mobility, education, new cooperation links, and R&I opportunities.

In order to structure the analysis, the following categories of impacts have been identified:

- **Economic impacts** including:
  - Competitiveness
  - Economic cost and benefits
- **Social impacts** covering:
  - Employment generation
  - New knowledge fostering
  - New linkages creation
  - Change of image and recognition of industry
- **Technological and innovation** impact covering:
  - Technological advancement in the region, local cluster
  - Capabilities of local companies

The figure below presents details on all impact categories and their respective elements which also guide the exploratory and evidence finding work in this study.

Figure 3 Overview of key impacts that have been addressed



Source: authors elaboration

In other words, in the analysis of potential socio-economic impact of the CCU hub and various CCU value chain developments, we have tried to investigate whether any of the listed impacts can be achieved, and if so, how prominently.

Each CCU value chain to be established in the North Sea Port can potentially demonstrate various degrees of impact on each of the listed categories. Indeed, the more value chains launched within the CCU hub, the greater the overall observed impact.

Since this is an ex-ante impact assessment study, the measurements have been based on evidence in the practical examples of CCU value chains available elsewhere, through findings of other research and investigations including theoretical studies, as well as via consultations with stakeholders, collecting their insights and experiences.

2.3 Methodological scope

The approach to the study includes a mix of research methods including *desk research, interviews, case studies and a survey.*

2.3.1 *Desk research*

The literature on CCU has been growing over the past decade because of growing interest in the different technologies and their relevance in the intensifying climate change mitigation discourse. While the body of research and literature on CCU topics has quickly expanded, the majority of studies address technical aspects and the testing of new technologies and processes. Furthermore, a number of studies carried out life cycle assessments (LCA) of selected CCU technologies, where the key focus is on environmental impacts derived from the consumption of raw materials, energy necessary for production, emissions and waste generated during the production, as well as the environmental effects of its transportation, use, and consumption. All these are attributed to the final product.

The social and wider economic impacts of the CCU projects and technologies have been largely under-investigated. Studies assessing social impact of CCU projects have been practically missing until now, something common for all the industrial symbiosis schemes (Pieri et al, 2018). The economic viability of CCU projects has been addressed in some studies to a varying extend (e.g. in technical feasibility studies of specific projects, or in theoretical modelling studies where parameters are modified).[4] However, the impact on the local economies of CCU projects and technologies are rarely analysed. In a few cases, reference to new jobs created is mentioned in studies or project presentations. However, a more systematic and in-depth analysis is lacking in the literature and ongoing research. One of the examples of research projects where this aspect is addressed in a more holistic way is Carbon4Pure project[5]. The project has a component which aims to deliver an evaluation of social benefits by performing a social return on investment analysis and quantification of social benefits/impacts linked to the Sustainable Development Goals. However, no results have been produced at the time of the implementation of the present study, therefore only general insights have been shared via interview by the project experts.

2.3.2 *Interviews*

Interviews were one of the key instruments for collecting information from various stakeholders that engaged in CCU-related activities, research or actors engaged in markets that have relevance to CCU products. Interview data was used in case studies, scenario analysis, as well as the scoping of the CCU value chains for this study. All these helped in building a better understanding of potential opportunities and challenges for the CCU hub and its specific value chains.

The strategy in this study was focused on identifying and contacting the most relevant interviewees, which included the following groups:

(i) *Professionals who are active in the CCU initiative in the North Sea Port* or well informed about it. This includes members of the CCU hub consortium, as well as additional knowledgeable actors, such as professors/researchers at Ghent University, experts involved in previous technical assessment studies of the CCU hub possibilities. Each of them have been pursuing research, technical assessments or piloting activities that will form part of CCU hub. They shared technical information,

[4] The economic characteristics of the individual components of a CCU value chain have not been extensively studied. Most of the studies have been performed in the context of CCS (rather than CCU), and thus the majority of them focus on carbon capture (primarily) and carbon transportation. However, there are no studies estimating the potential costs that are linked with carbon utilisation (due to either retrofitting/modifying an existing plant in order to receive recycled CO2 or installing a new plant) (Piery et al 2018).

[5] https://www.carbon4pur.eu funded under H2020 programme

as well as critical insights on the feasibility, possible impact and barriers faced or envisaged in the current policy context.

(ii) *Outsiders to the North Sea Port CCU hub initiative*, but who are involved, engaged in other CCU projects or relevant research activities in other countries. These actors have a good understanding or experience of CCU. Most of these actors also represented projects that were selected as case studies or had relevance to those.

(iii) *Actors that represent potential markets for CCU products* (e.g. shipping, greenhouse farming) or traditional value chains (e.g. methanol). The discussion with these actors focused on their assessment of opportunities, potential barriers and drivers related to the application of CCU products or technologies in the markets and value chains they represent.

2.3.3 *Case studies*

Case studies is another important source for evidence for the present study. Real cases of the CCU projects, observations from the practices, insights and data collected during these projects provide significant input into the analysis and understanding of impacts that can potentially be created in CCU hub in the North Sea Port zone.

In the selection of the cases, the main principle was to capture the value chains that either have been promoted and discussed within the CCU hub or have very good chances to be launched. The table below presents case studies that have been targeted for this project:

Table 1 List of case studies selected and analysed for his study

	Case study	**Value chain covered**
Case 1	LanzaTech project for bioethanol production, Shougang China	CO to ethanol
Case 2	George Olah Renewable Methanol Plant, Iceland	CO2 to methanol
Case 3	ThyssenKrupp demonstration project for methanol and chemicals, Duisburg Nord Rhein Westphalia	CO2 to methanol, ammonia, other chemical
Case 4	CO2-based polyol production at Covestro	CO2 to polyol and polyurethane
Case 6	Evonik & Siemens artificial photosynthesis (electrolysis and fermentation)	CO2 to specialty chemicals
Case 6	Carbstone technology by Orbix, Belgium	CO2 to construction materials
Case 7	Organic CO_2 for Assimilation by Plants (OCAP), Netherlands	CO2 to greenhouses

2.3.4 *Survey*

The survey targeted companies that can potentially be part of the CCU hub located in East Flanders and mostly in the North Sea Port zone. These included the following sub-sectors:

- Chemical companies that can potentially revisit their production technologies to integrate CO and CO2-based production of new chemicals, material, polymers, etc. (13 companies)

- Companies that are potential procurers of the CCO based new chemicals, material, polymers, fuels as a substitute to their traditional fossil-based materials. This included:
  - Manufacturers of products from plastics, polymers and chemicals (28 companies)
  - Inland shipping and cruise companies with the presence in the North Sea port (22 companies)
  - Agro-farms specialising on greenhouse based vegetable cultivation.

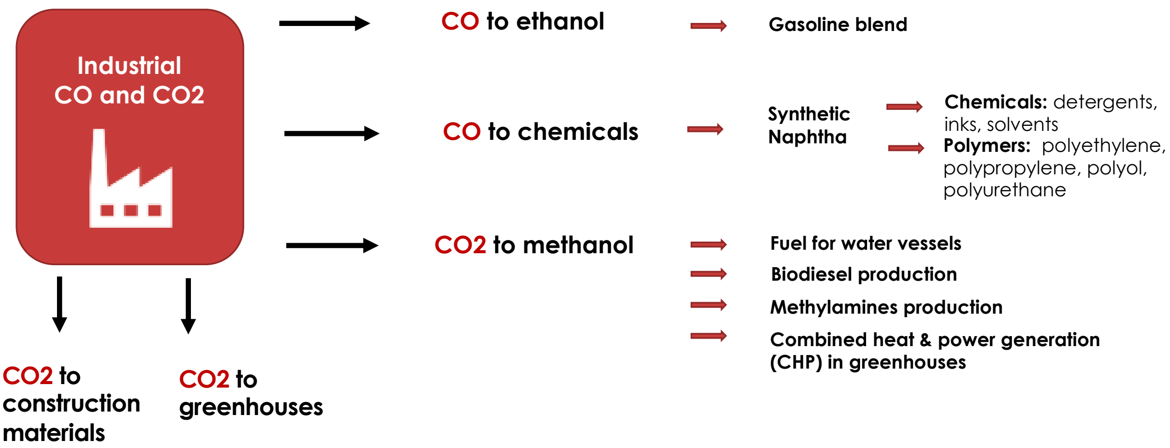
The purpose of the survey was to understand their perception of opportunities, cost and benefits offered by involvement in CCU on: a) their company and b) on the region in general. Two contact channels were envisaged: email survey and when a company requested it, an interview-based survey. A special letter of invitation/introduction was issued by the Development Agency of East Flanders and accompanied the questionnaire.

The survey experienced a lack of response from targeted companies, despite repeated reminders over the phone and emails, and forwarding the requests to alternative email addresses. Due to this challenge, the scenario analysis has to take an adjusted approach where estimates of CCU technology and product uptake are based on informed assumptions about market potential and how open the wider community of companies would be to new developments in this area.

3 CCU hub value chains – analysis and findings

In the context of the CCU hub development in the North Sea Port industrial zone, this study has analysed several CO2 and CO utilisation options that can potentially turn into value chains for the local economy.

Figure 3 CCU Value chains that have been analysed



This section describes each type of value chain and related technologies and present analysis and finding based on the interview consultations and case studies.

3.1 CO to ethanol

3.1.1 Technical description of the value chain

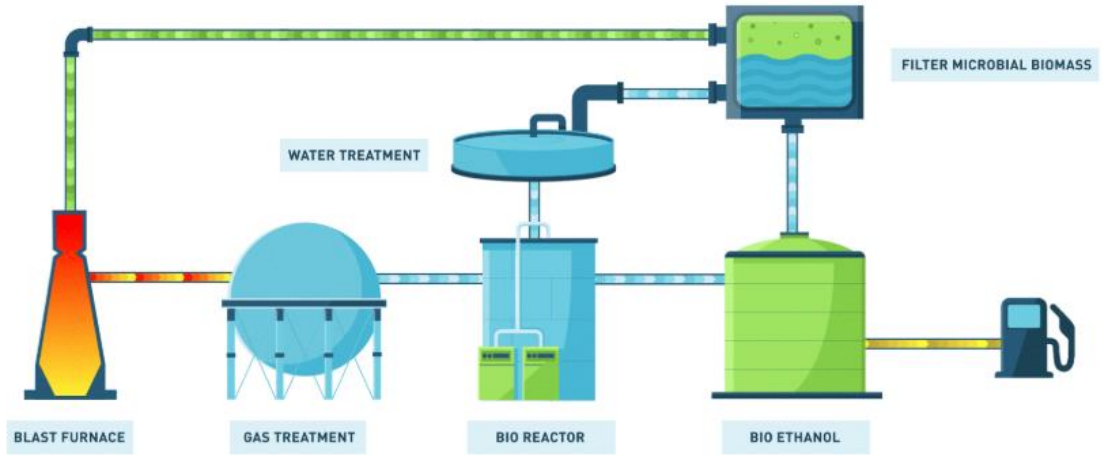
Ethanol or ethyl alcohol is a clear colourless liquid that is biodegradable, low in toxicity and causes little environmental pollution if spilt or released. Ethanol is a high-octane fuel and has replaced lead as an octane enhancer in petrol. The process of blending ethanol with gasoline oxygenates the fuel mixture so it burns more completely and reduces polluting emissions. The most common blend is 10% ethanol and 90% petrol.

In the EU, bioethanol is produced from wheat (1.66 billion litres), corn (1.61 billion litres), sugar beet (1.24 billion litres), other cereals (0.44 billion litres), and lignocellulose and other feedstock (0.24 billion litres)[6] .

However, a new method has been developed to produce fuel ethanol using fermented waste emissions from industry. This type of ethanol's performance in fuel-blending applications is indistinguishable from sugar-derived ethanol as it meets all specifications of ASTM International D4806, the active standard for qualifying ethanol used in blending with gasoline for automotive engines. Ethanol can be used as a low-carbon fuel and can be converted downstream to jet fuel, diesel, plastic and other household products. In Figure 4 below we illustrate the way bioethanol is produced under this CCU scheme.

[6] European Biomass Industry Association data from 2016

Figure 4 CCU-based bioethanol production process



Source: Steelanol project

This technology developed by LanzaTech uses microbes that feed on carbon monoxide to produce bioethanol. The general principle of syngas fermentation is that micro-organisms fix gaseous carbon by reducing CO and/or CO2 to liquid products such as ethanol. The syngas fermentation process consists of three steps: syngas pre-treatment and conditioning; the actual fermentation of the syngas in a bioreactor; product separation and work-up. Some other chemical co-products can be developed by applying the same method such as 2,3-butanediol, which can be converted to butadiene, an important chemical intermediate in the production of nylon and synthetic rubber, as well as to other major bulk commodity chemicals such as methyl ethyl ketone.

A unique aspect of the process is the ability to utilise gas streams with a range of CO and H2 compositions to produce ethanol and diverse other high-yield products. Ethanol demand in Europe could be met by processing 46% of the European steel waste gases, according to one estimate[7].

There are additional advantages that, in turn, can reduce additional pressure caused by other feedstocks. Replacing bio-based ethanol with waste-gas fermentation, for example, can reduce the land footprint of ethanol by 2 million hectares, reducing pressure on biodiversity in and outside of Europe.

3.1.2 CO to ethanol value chain – findings [8]

CCU-based bioethanol is an important value chain in the North Sea Port CCU hub initiative. There has been a substantial effort invested and progress achieved in setting up this value chain, the first such production facility in Europe. An EU-funded project, called Steelanol[9], combines the strength of ArcelorMittal, a major steel producer, and LanzaTech, a leading technology provider, to build and launch the new CCU facility. The commissioning and first production are expected by the end of 2020.

This technology is rather new in the market. At the time of writing, only one commercial unit is up and running, a plant developed by LanzaTech at a steel mill in China. This facility has been

[7] CORESYM (2017) 'CarbOn-monoxide RE-use through industrial SYMbiosis', prepared by Metabolic, available at https://www.metabolic.nl/publications/coresym-carbon-monoxide-re-use-through-industrial-symbiosis/

[8] Interviewees included: LanzaTech US and China representatives, ArcelorMittal

[9] http://www.steelanol.eu/en

selected as a case study, while feedback from the interview with LanzaTech experts gave some insights into the overall challenges and drivers for this technology which are summarised below:

Overall challenges and opportunities:

- The comparative baseline for CCU-based ethanol is plant-based bioethanol. Bioethanol is a biofuel for cars and has been promoted in the EU as a climate benign alternative to fossil fuel. Its competition with food (as it is mostly produced from wheat, corn, sugar-beet, and other cereals, but only marginally from agricultural waste) has attracted criticism in recent years. The sale price of bioethanol has also dropped, discouraging some producers from producing it.
- Life cycle assessment (LCA) of the ethanol produced via LanzaTech fermentation shows that its greenhouse gas emissions are at least 70% lower than that of conventional fossil gasoline. This can make the CCU-based bioethanol a viable alternative to current biofuels. However, the carbon emission reduction or avoidance capacities of this technology is not yet recognised under all existing climate policy instruments. The fuel from this process is currently undergoing assessment in Europe but is recognised in India, China and California. The potential of the environmental characteristics of all types of fuel must be fully understood so stakeholders can consider the impacts of different fuels and their role in the future energy mix.
- Nevertheless, the new technology has received significant interest across many countries. The projects that have been initiated so far have received strong political support and public co-funding of facilities.
- During the period 2021-2030 the share of advanced biofuels will increase in line with the revised Renewable Energy Directive (RED II) based on the following scenario (in real terms): 2% from 2021 to 2024; 5% from 2025 to 2029; 7% from 2030. To achieve the target share of renewable energy in the transport sector, the focus is on a mandatory biofuel content of 14% by 2030. Companies that supply diesel and/or petrol will have to demonstrate that the volumes released for use by consumers on an annual basis contain a nominal percentage of sustainable biofuels. This minimum content will be 7% for first-generation biofuels and 7% for advanced biofuels. These figures boost the prospect for CCU-based ethanol uptake in the Belgian market. Similar prospects are also offered in the biofuel markets of other EU member states.

Social and economic impact

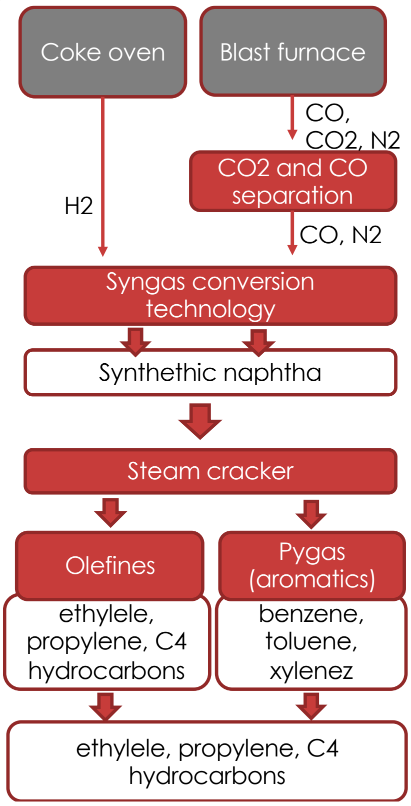
- The projected cost of production of CCU-based bioethanol is said to be competitive with the lowest-cost bioethanol available today. There are no premium price-related issues that are typically associated with ‘green products’ of this nature. This means there is no additional costs passed on to ethanol consumers or intermediary markets that blend it with gasoline.
- A new CCU-based bioethanol plant creates new permanent jobs needed to operate the facility and short-term jobs during the construction phase. For example, the Chinese facility previously mentioned created 130 permanent direct and indirect jobs, wile over 1000 people were involved in the construction phase. In the Ghent project, construction of the new installation will create up to 500 temporary jobs and about 30 permanent positions for operations.
- The arrival of a new ethanol producer with significant production capacities will also boost the need for logistical, tanking, and blending services, as well some new jobs created in companies distributing/exporting transport fuel; more tankers, more fuel-tanking facilities and more staff needed to handle the increased capacity.
- Introduction of an ethanol plant will cause no losses or replacement of existing jobs locally, regionally or at the national level.

3.2 CO and CO2 to chemicals and polymers

3.2.1 Technical description of value chain

Production of chemicals and polymers (e.g. plastics, resins) is one of the most promising areas for the CCU technologies. These value chains are well regarded because they have a higher potential (in comparison to fuels) in locking the carbon emissions in products.

Figure 5 CO to polymers value chain



There are several ways of producing CCU-based polymers. One of them is via the production of **synthetic naphtha from CO**. Fossil-based naphtha is a traditional feedstock in the production of polymers, as well as chemicals used in inks, detergents, agrochemicals, lubricants, etc. CCU-based synthetic naphtha is produced by converting exhaust CO together with H2. From the synthetic naphtha, several chemical products can be produced, such as ethylene and propylene and other derivatives (ethylene oxide/ethylene glycol and propylene oxide/propylene glycol). Through a process of *steam cracking*, several *olefins* can also be produced:

- *Ethylene* is the starting material for the preparation of a number of two-carbon compounds including ethanol (industrial alcohol), ethylene oxide (converted to ethylene glycol for antifreeze and polyester fibres and films), acetaldehyde (converted to acetic acid), and vinyl chloride (converted to polyvinyl chloride). In addition to these compounds, ethylene and benzene combine to form ethylbenzene, which is dehydrogenated to styrene for use in the production of plastics and synthetic rubber.
- *Propylene* is the second most important starting product in the petrochemical industry after ethylene. It is the raw material for a wide variety of products. Manufacturers of the plastic polypropylene account for nearly two-thirds of all demand. Polypropylene end uses include films, fibres, containers, packaging, and caps and closures. Propylene is also used in the production of important chemicals, such as propylene oxide, acrylonitrile, cumene, butyraldehyde, and acrylic acid.
- *C4 hydrocarbons*, which include butadiene, 2-methylpropene/isobutylene, n-butenes and higher olefins, are used to make rubbers (e.g. for car tyres, chewing gum), as well as fuel ethers, lubricants, detergents, agrochemicals.

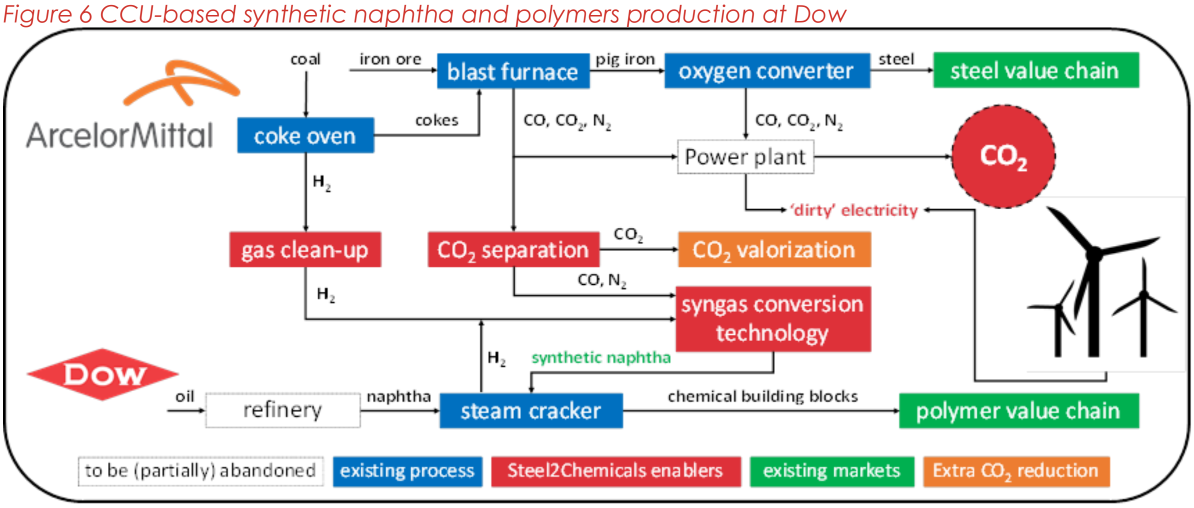
Pyrolysis gasoline (Pygas) is another naphtha-range product with a high aromatics content. It is a by-product of high temperature naphtha cracking during ethylene and propylene production. Also, it is a high-octane mixture which contains aromatics, olefins and paraffins ranging from C5s to C12s. These substances are used in to produce polymers, such as rubber and plastics used in food packaging, automotive parts, CDs, furniture, sports equipment, textiles, construction materials, and in the production of chemicals used as solvents, detergents, and for pharmaceuticals.

Another technology that can draw interest, which is being successfully piloted, is **CO2 to polyol and polyurethane**[10]**.** This technology makes it possible to use CO2 as raw material and chemical building block for polyol, which is an essential component in the manufacture of polyurethane. Polyurethanes made with CO2-based polyols can be tailored to a wide range of everyday items including soft furnishings, insulation and structural foams, clothing, shoes, adhesives and protective coatings. It was estimated that adoption of this technology could reduce fossil resource depletion by up to 15% compared to conventional polyols[11] (von der Assen & Bardow, 2014). Furthermore, CO2-based polyurethane products demonstrated the same or better performance than conventional products[12]. With a current global polyols market of about 6.7 Mt/a, a demand of 0.12 Mt/a of CO2 for polymer applications is estimated if the European polyol market continues to grow at the expected rates (Fernández-Dacosta et al 2017).

3.2.2 CO and CO2 to chemicals and polymers – findings[13]

CO to polymers is one of the value chains that has attracted strong interest in the North Sea Port industrial zone. A number of research and testing initiatives involving local players Dow, ArcelorMittal, Ghent University, as well as other international partners, have resulted in well-working solutions that can separate and clean the CO and CO2 from the industrial exhaust gases, synthetise naphtha and produce polymers. The figure below illustrates the process.

Figure 6 CCU-based synthetic naphtha and polymers production at Dow



Source: Dow

As a result, two parallel projects have received in 2019 public support to develop and test the technologies:

- *Steel2Chemicasl project*[14] focused on piloting synthetic naphtha production in a mobile plant. The project aims to valorise CO produced in the steelmaking processes. Currently,

[10] Examples are innovations from Econic http://econic-technologies.com/ and Covestro https://www.covestro.com/en/company/strategy/attitude/co2-dreams

[11] Niklas von der Assen and André Bardow, 2014, life cycle assessment of polyols for polyurethane production using CO2 as feedstock: insights from an industrial case study, Green Chem., 2014, 16, 3272-3280

[12] http://econic-technologies.com/product-potential/

[13] Interviewees: DOW, Covestro, Recticel, SouthPole (Carbone4Pure project), ThyssenKrupp, Evonik (Rethicus project)

[14] https://ispt.eu/projects/s2c/

CO is used for energy generation and it thus produces CO_2. The investigation is essentially focused on a reaction between renewable H_2 and CO to produce synthetic naphtha. This is evaluated as feedstock for the Dow steam cracker in Terneuzen, which produces building blocks for a host of chemical products. This will be applied as substitute feedstock for the chemical industry and the quality will be validated at Ghent University. The research will not only focus on CO and its reactions, but also on sustainable H_2 (the second important component in synthesis gas), integrated CO_2 and N_2 capture, separation of CO, CO_2 and N_2, establishing technical performance, economic feasibility and impact on the environment when production is scaled up. Lastly, robustness and replication possibilities within the steel industry are being researched and the project will help to prepare for demonstration[15].

- The *Carbon2Value project*[16] focuses on studying two CO valorisation value chains: (1) ethanol as a drop-in transportation fuel (via biofermentation to ethanol) and (2) synthetic naphtha as a drop-in chemical building block (via Fisher Tropsch catalytical conversion to ethylene). The objective is to demonstrate a cost-efficient solution for the separation of CO_2 and CO from steel waste gas from the blast furnace. A pilot line of carbon-rich gases will come through two streams, one rich in CO and another in CO_2 that could be valorised into promising chemical building blocks in the future. Reuse of any by-products will also be looked into as replacements for fossil fuels and to reduce GHG emissions.

At Dow synthetic naphtha will be an input material for downstream production of various polymers and chemicals. Technically, it is not different from the traditional naphtha and therefore no changes in the downstream value chains are needed. The table below summarises the types of products produced from naphtha. Around a third of the 6 million tonnes of annual feedstock are ethylene-based products and a sixth are propylene-based products.

Table 2 Polymer and chemical production at Dow

Input materials			Products	Volume % of feedstock of 6mln tonnes
Naphtha *to be replaced by CCU-based* ***synthetic naphtha***	**Ethylene**	**Ethylene oxide** **Ethylene glycol** (Previously Ethylbenzene to Styrene and Propylene to Cumene to Phenol)	Polymers (plastics): food packaging Chemicals: coatings, solvents, detergents, adhesives, inks, pharmaceuticals, chemical synthesis	**~1/3** of feedstock goes to ethylene production (2mln tonnes)
	Propylene	**Acrylic acid** **Propylene oxide** **Propylene glycol**	Polymers (plastics, rubber): disposable nappies, food packaging, engine coolant automotive, marine industry, bathware, Chemicals: solvents, detergents, adhesives, inks, pharmaceuticals, engine coolant, paints, lacquers, coating, chemical synthesis,	**~1/6** of feedstock goes to propylene production (1mln tonnes)

Source: discussion with Dow

In the frame of this study the existing practices on **CCU-based polyol** has been investigated as part of a wider analysis. Although for Dow it was noted that CO- or CO_2-based polyol

15 https://ispt.eu/news/steel2chemicals-paving-the-road-for-reducing-millions-of-tons-of-co2-emission/

16 https://www.carbon2value.be/en/

production is not the most promising in terms of market volumes and the CO2 reduction potential in comparison to other polymers produced at their premises.

There are currently no CO2-based polyol projects in the North Sea Port, but the Belgian company Recticel, located in East Flanders, in its bedding product area uses CO2-based polyol supplied by Covestro, a German company which produces specialty chemicals for heat insulation foams and transparent polycarbonate plastics.[17] The commercial name of this polyol is CardyonTM, an innovative product containing up to 20% of CO2, and indicates comparable or better properties than conventional ones made of crude oil. The polyol value chain has been considered in this study because of its downstream potential; namely, transforming polyol to polyurethane foam and the manufacturing of matrasses from the CardyonTM already taking place in East Flanders.

Furthermore, ArcelorMittal, Ghent University and Recticel were among the partners in the EU-funded project Carbon4Pur, which is developing a new generation of CCU-based polyols and polyurethanes with a lower CO2 footprint and higher process-energy savings[18]. Thus, in the long run, launching the upstream part of the polyol value chain in North Sea Port could become a reality.

Overall opportunities and challenges

Opportunities:

- Shifting from sourcing fossil-based naphtha to CCU-based synthetic naphtha offers significant potential for locking carbon emissions from the steel industry into Dow's polymer and chemical products, one of the largest manufacturers of such products in Europe. Dow already has a well-established market and links with customers_for polymers. Unlike new product launches, there is no need to invest in market building efforts or to change/create the business model.
- CCU-based products such as polymers are expected to benefit from a higher level of 'acceptance' in the public and policy discourse compared to CCU fuels. It is clear that these products capture and bind carbon, while fuels are largely seen as temporary storage for carbon emissions (resulting in fast CO2 release when burned). Dow believes that capture of carbon in materials is better than in fuels, especially if the materials also have end-of-life recycling opportunities.
- It was noted that DOW's technology has a simpler production chain, less steps in comparison to other CCU products, e.g. electrolysis-based methanol. There is no need to make significant changes at the established polymer production facilities, except for installing a catalyser for converting CO and H2 into naphtha.
- The existing example of CO2-based polyol demonstrated a successful case of market uptake of the product. This case has shown the growing demand for sustainable products, provided that the performance of such products is equally high. Belgian producer Recticel has confirmed that their company is willing to expand production of their branded CO2-based mattresses if the input of polyol increases. They are also open to collaborating with additional suppliers of similar so-called "green input materials".
- Among the key success factors of Recticel's new product are enhanced fire resistance and heat generation, as well as reduced volume and toxicity of smoke produced. Its carbon sink features add to the product's market image (it contains 6-10% of its mass as carbon

17 https://www.covestro.com/en/company/strategy/attitude/co2-dreams

18 https://www.carbon4pur.eu/

dioxide and uses 15% fewer fossil resources compared to conventional polyols). Manufacturing cost savings, as well as a reduction of harmful chemical handling in the processing stage are additional advantages noted by the technology owner.

- A critical feature of the projects analysed here is that they involve a wide network of partners from many industries and scientific organisations. Collaboration and open dialogue among different industries is key to progress in the area.

Challenges:

- Often higher costs and premiums applied to these novel CCU-based products is a persisting barrier. CO2-based polymers are still more expensive to produce, although they might have superior quality (e.g. polyol) which can offer an advantage in terms of its competitiveness. Despite increasing awareness among companies and consumers, not all are consciously making choices for more sustainable products such as those developed through CCU methods.
- In the context of the CCU hub in the North Sea Port, establishment of a new value chain of CO2 to polyol might take some time. Typical new product development, demonstration and commercialisation can take around 10 years.

Socio-economic impact

- Many positive outcomes of the product put up by Covestro and Recticel are related to the R&I and testing stage of the product development. Over the longer term practices, greater emphasis on the impacts of commercialisation will be key.
- An important impact of introducing CCU-based production lines at Dow is related to creation of employment. According to Dow's calculations, 50 to 100 jobs can be created at the upstream end of the value chain that will integrate the synthetic naphtha production from blast furnace gases. A considerable impact is also envisaged in the 'greening' of existing jobs at the company in the segments where the production process does not change. That is where synthetic naphtha is converted into chemical building blocks which are then further converted into polymers, as well as at companies further down the value chain (manufacturers of final products from polymers). In addition, a few indirect jobs could be created at the logistics, supporting facilities, and other adjacent service providers.
- Research and experimental projects implemented to date have strengthened the expertise and knowhow within all project organisations. New researchers were hired to grow the research team at Dow which also helped to strengthen the expertise.
- It is expected that the activities implemented as part of the *Steel2Chemicasl and Carrbon2Value projects* will allow to bring the technology of CO to synthetic naphtha to a higher level of readiness thanks to establishing a demonstration plant, that is TRL 6. Further activities on pre-commercialisation will allow it to move to TRL 7.
- The projects initiated in the North Sea Port area have received publicity with significant regional and national recognition of the benefits and prospects they might bring. In general, Dow and other partners are very active in industrial symbiosis initiatives (e.g. Smart Delta Platform, ISPT, etc.), and the university-business-public sector partnership model has been well deployed.
- The overall impression is that the projects have contributed to the positive image of Dow and ArcelorMittal. Both are rather large players in their sector. Carbon-emission-reduction initiatives are a very important element of their company strategies and implementing pioneering technology in CCU reinforces that effort, as well as the image of the region as a whole.

3.3 CO2 to methanol

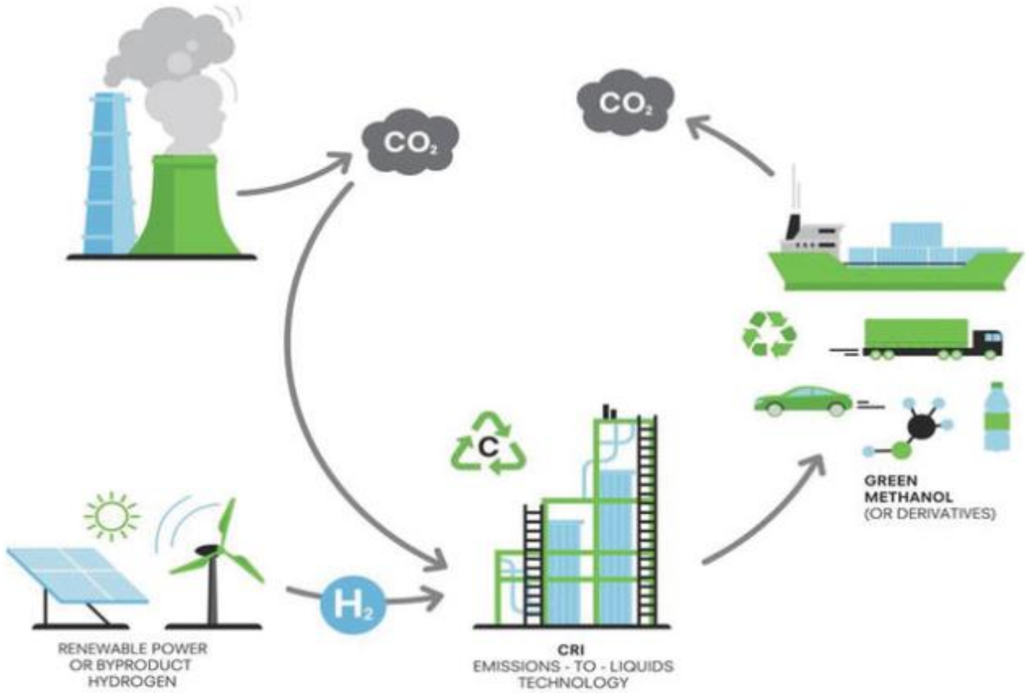
3.3.1 *Technical description of the value chain*

Methanol has been widely targeted as a CCU product. At the moment CO2 to methanol is one of the most advanced CCU value chains in terms of shifting from R&D to commercialisation.

Methanol (CH3OH) is a clear liquid chemical that is water soluble and readily biodegradable. In industry, methanol is most commonly produced using natural gas as the principal feedstock. Methanol is used to produce building materials, foams, resins, plastics, paints, polyester and a variety of health and pharmaceutical products. Methanol also is a clean-burning, biodegradable fuel. It can be used as an alternative for powering vehicles and ships, cooking food and heating homes.

Methanol can be made from a wide array of feedstocks. The process involves the creation of synthesis gas, which is a mixture of CO, CO2 and hydrogen gas (natural gas is most often used in the global economy). Using mature gasification technologies, synthesis gas can be produced from organic waste. Synthesis gas can also be produced by combining waste CO2 from manufacturing or power plants with hydrogen produced from the electrolysis of water using renewable electricity. The figure below presents the CO2 cycle for methanol production.

Figure 7 CO2 cycle for methanol production



Source: Al-Saydeh & Zaidi, 2018

Methanol is also a key component of many other chemicals, where the largest scale application – in terms of volume – is processing it into formaldehyde, which is further treated to form resins, glues and various plastics, and for the production of acetic acid (essentially used in the production of polyester fibres and PET plastics). Methylamines production is another high potential area for methanol use. [19]

Methanol is used to produce light olefins (ethylene and propylene), the base product for the plastics industry, which are created by steam cracking naphtha. Olefin production using CO2 can fully substitute low-cost ethane or more expensive naphtha (An et al., 2008; Zhou et al., 2016).

Special attention has to be given to the usage of methanol as an energy option:

- *Automotive fuel* – an alternative transportation fuel, which is easy to distribute. Methanol is a high-octane fuel that enables very efficient and powerful performance in spark ignition engines. Engines optimised for methanol could provide an energy-based efficiency gain of 50% over a standard (port fuel injected, non-turbo) gasoline engine in a light-duty vehicle. The power-producing qualities of methanol are well known, and it is used in several motorsports. While methanol has a low cetane rating, it can also be used in combustion ignition engines as a diesel fuel substitute. Dual-fuel heavy-duty engines operating on diesel and methanol can improve efficiency and dramatically reduce emissions for trucks, buses, and off-road vehicles.
- *Marine fuel* – methanol can be used as a fuel in ships. It is sulphur free, has low emissions and methanol-based fuel can be a cheaper and better alternative to marine distillate fuel It also rates higher on the International Martine Organisation's (IMO) energy efficiency design index (EEDI) than LNG and diesel.
- *Fuel cells* – provide a cleaner and efficient way to convert fuel into electricity. Due to its varied potential, fuel cell technology is used in a wide variety of applications, such as automobiles, back-up generators, and as a storage unit for electricity. Direct methanol fuel cells (DMFC) offer portable power for various applications and allow for easier transportation. Moreover, DMFC is CO2 neutral, thus emitting fewer emissions and making it more environmentally friendly.
- *Biodiesel manufacturing* – in the process of making biodiesel fuel, methanol is used as a key component in a process called transesterification (i.e. methanol is used to convert the triglycerides in different types of oils into usable biodiesel fuel).
- *Electricity* – electricity generation through methanol usage. Methanol can be a better and more sustainable replacement to oil as a fuel for back-up generators. Methanol's low heating value, low lubricity, and low flash point makes it a superior turbine fuel compared to natural gas and distillate, which can translate to lower emissions, improved heat rate, and higher power output. Recent methanol-to-power demonstration projects have established the viability of this technology.
- *Boiler/cookstoves* – many developing countries still consume a lot of biomass, wood, etc. for cooking, which in turn generates significant air pollution. Methanol-based fuels a viable and potentially greener alternative. It is cheaper than ethanol and can be used by most ethanol stoves since the methanol stoves work on the same principle as ethanol.

Methanol can help to reduce the environmentally damaging emissions from wastewater treatment facilities. Through a process known as denitrification, water treatment facilities convert excess nitrate into nitrogen gas, which is then vented into the atmosphere, that way eliminating its ability to cause algal blooms in watersheds and block oxygen and sunlight from reaching marine life below the surface. Methanol is the most common organic compound

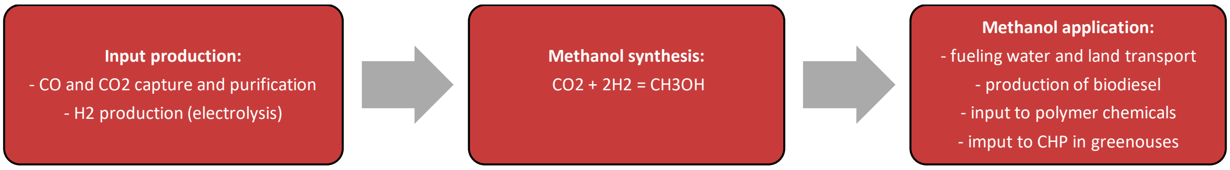
[19] https://www.methanol.org/about-methanol/

used in denitrification, accelerating the activity of anaerobic bacteria that break down harmful nitrate.

3.3.2 *Methanol value chain – consultation findings*[20]

The CCU-based methanol production is actively explored in the CCU hub. The methanol value chain has been central in this study and a large share of interviews focused on discussing challenges around CCU-based methanol production and its market viability. Stakeholders representing the producers and consumers perspective have been consulted, as well as the experts that have been researching and analysing the methanol and sustainable fuel issues.

The consultations have focused on upstream and downstream sections of the methanol value chains starting from CO and CO2 capture, purification, H2 production, methanol synthesis, and its application.



The following findings have been identified:

Input production (CO and CO2 capture and purification):

- It was stressed that in any CCU value chain, where emissions are based on fossil fuels, the separation and purification of the CO and CO2 gas is necessary. Steelwork waste gases consist of multi-component mixtures of carbon monoxide, hydrogen, nitrogen, carbon dioxide, methane, and/or moisture. Nitrogen and sulphur components are also present, for example NOX, HCN and H2S, COS, respectively. These are quite problematic for chemicals production and present a downside for the use of waste gases when compared to syngas from natural gas. This is also an issue for CO2 enrichment in greenhouse farming, which leads to regulation of the CO2 sources in some countries. For this reason, the purification processes for steel mill waste gases are one of the key issues for the environmental and economic outcomes of the process.
- Purification and gas separation challenges are mostly technical, and they are being resolved by special R&D and testing activities that all interviewed stakeholder had to implement in their project. While the main knowledge about the processes are there, testing and adjustments would normally be needed for various sources of CO2 (i.e. steel plant, coal power plant, cement plant, waste incineration plant, chemical plant) as the content of the gas mix varies.
- While requiring adoption of a specific technology and additional chain to the overall production system, there is little in the way of potential job creation; it can mostly be handled by automated processes or integrated into current duties.

Hydrogen production via water electrolysis:

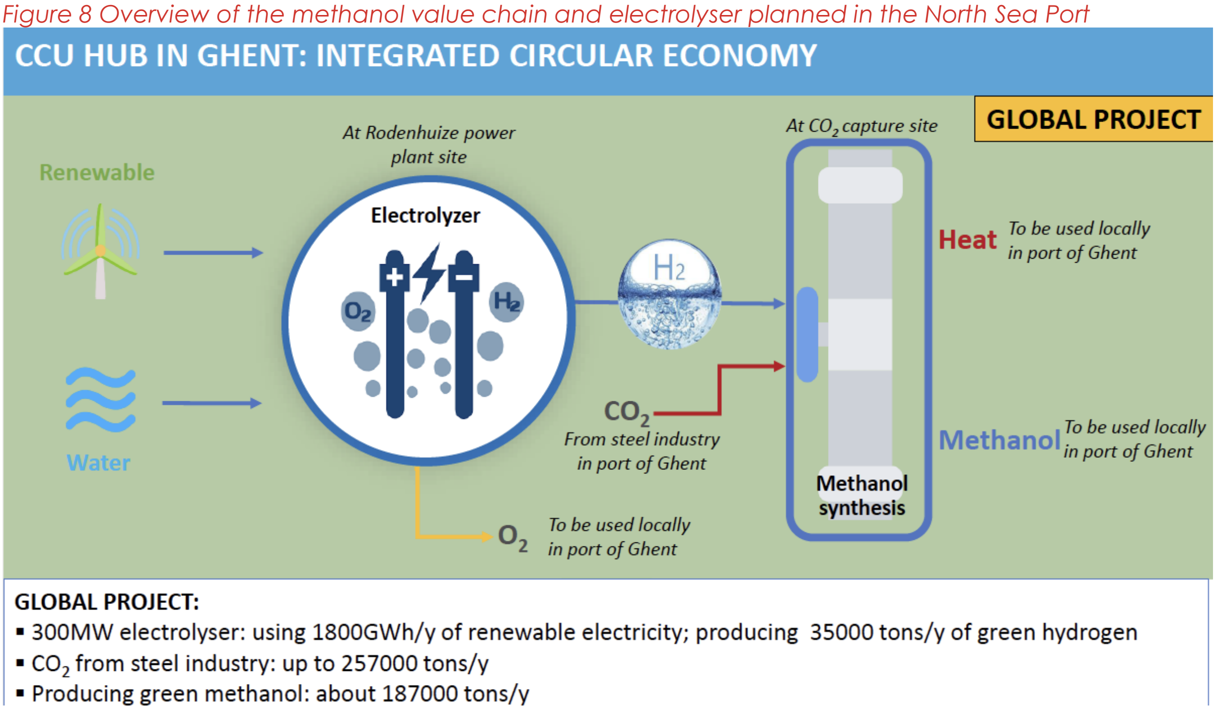
- CCU-based methanol production requires hydrogen inputs, which makes it a key molecule in this process. How the hydrogen is produced will be a determining factor in the environmental and economic results. There are a number of methods for hydrogen

[20] Interviewees: representatives of Arcelor Mittal, ENGIE, Carbon Recycling International, Thyssen Krupp, Vloot, BBE PP, Antwerp University CBRB, CITBO, Methanol Institute, Cooperaive binnenvaart ondernemingen, Proeftuin Zwaagdijk

production. But considerations in the CCU hub must be given to so-called water electrolysis, which is the electrochemical conversion of water to hydrogen and oxygen.

- The electrolysis process requires electricity and the main challenge here is to maintain environmental neutrality through renewable energy sourcing. CRI has mitigated this issue by selecting Iceland (which has a 100% green energy grid) as the location for its pilot project. Similarly, ENGIE is keen to build its pilot 63 MW electrolyser and a commercial scale 300MW electrolyser using renewables – an offshore wind farm being built close to Zeebrugge. The proximity of this wind farm is one of the factors that makes the North Sea Port a prime location for CCU-based methanol production using his technology.
- Operating and maintaining the electrolyser facility creates several jobs: at least one or two people would be needed to manage the small-scale electrolyser, while maintaining the commercial-scale version would require a team of at four to six people.

Figure 8 Overview of the methanol value chain and electrolyser planned in the North Sea Port



Source: ENGIE, CCU hub consortium

Methanol synthesis

- Methanol synthesis from CO2 and hydrogen is a well-known chemical process. However, synthesis of methanol in the industrial setting of CCU requires careful calibration and testing of the process to achieve optimal settings. Important factors are the purity of the CO2 (which is discussed above) and proper physical conditions set for the reaction, such as optimal temperature, pressure, catalyst, etc. However, the process is not different from the commercially used processes for producing methanol.
- Thus, no serious technical challenges are faced by the CCU-based methanol synthesis process. The commercial catalyser for the conventional methanol synthesis process can be used during CCU-based methanol synthesis from exhaust gases under dynamic operating conditions.
- There is a common agreement that CCU-based methanol production will **create new jobs** at the production and supporting facilities as well as adjacent service providers. The methanol plant in Iceland, for example, has established (around) 12 permanent jobs and had a positive local impact, as people from the declining fisheries and marine industries

could be re-trained and re-enter the job market. A facility of around 40 ktonne/year and 55 ktonne/year of CO_2 captured is estimated to generate 20-30 jobs (0.5 to 1 direct plus indirect jobs for every additional tonne/year of production capacity[21]. Meanwhile, Steel2Chemical project estimates 25 direct and 25 indirect jobs per 100 ktonne/year of CO_2 avoided.

Methanol application opportunities and challenges

The consultation on the CO_2-based methanol value chains focused largely on the opportunities in the **water transport market** as a fuel, as well as use of methanol **in production of biodiesel, methylamines** and in **combined heat and power (CHP) generation** at greenhouses as a cleaner and recycled carbon fuel.

In terms of water transport, there are two factors making this opportunity more promising in terms of the CCU hub development: (1) location of the future production facilities of methanol in the North Sea Port area, and (2) high concentration of inland water vessels (river boats, barges, river cruise ships, etc.) that refuel at the North Sea Port.

- The baseline is that many water transport companies are increasingly recognising the need to make their fleets and economic activities more environmentally friendly. However, a large majority of them have not started introducing sustainable practices. The main challenge is that the companies do not see a business case in 'greening' their operations and the current regulatory environment has not created sufficient incentives or pressure to start acting. Also, due to longer life spans of vessels currently in use, replacing them with newer, greener models is likely to take place only after they have been retired from active use.
- Within the discussion about transitioning to alternative and environmentally friendly fuel options, LNG dominates because it is a more mature technology, hydrogen is present in some pilots, while methanol is the least discussed option. However, its advantages are also being recognised in comparison to alternatives. Methanol is seen as advantageous on such criteria as environmental performance in LCA (lower emissions of SO_x, NO_x, particulate matters), cost of the storage, capital cost for ship conversion (lower than for LNG), new build dual tankers are only marginally more expensive than conventional fuel, widespread availability alleviates many infrastructure limitations on land and at sea.
- Incentives from the current regulation and polices for greening fleets, including transition to a new fuel, are minimal to non-existent among inland water transport companies. But the incentive are more prominent for the maritime shipping sector:
  - The current status in Belgium and the Netherlands is that sulphur emissions reduction has already been achieved in inland shipping, but not maritime transportation. In this respect, it was argued that the sulphur pollution regulation can create a case for methanol uptake in maritime shipping, rather than inland water transportation.
  - While the Renewable Energy Directive 2 has been translated at Belgian level, it is definite that a certain share of green fuel will be obligatory for all transport modes including marine. This can give added impetus to CCU-based methanol options.
  - CCU-based methanol production in the North Sea Port can be one of the flagships in Belgium's strategic efforts to tackle climate change – i.e. National Energy and Climate Plan – and in reaching objectives of the Effort Sharing Regulation. Such recognition provides additional stimulus for methanol uptake.
- A notable observation during the study is that methanol fuel has been gaining traction in the maritime sector (not inland shipping); seven methanol-fuelled ships have been

[21] Methanol Institute estimates for a study on the methanol production in the US

converted since the first example was transformed in 2017[22]. This uptake is faster than that observed with LNG.

- There are several pioneering initiatives driven by the willingness of selected companies to showcase new green solutions. They are isolated examples and often benefit from public funding and incentives promoted by ports (e.g. discounts for greener ships). For example, a Green Deal initiative in the Netherlands, involving public, private, research and financial organisations, will implement a number of measures to substantially reduce CO2 and other harmful emissions by the inland and marine shipping sectors. The targets for the inland shipping sector are 40% CO2 emissions reduction by 2030 and climate neutrality by 2050, and 70% reduction by 2050 in maritime shipping.[23]
- The commitments on reducing carbon emissions adopted by the International Maritime Organisation are aimed at encouraging maritime transport operators to lower their emissions and look for more cost-efficient solutions. Switching to methanol is one of such solutions.
- There is a notable difference between public and private water transport companies in terms of green ambition, strategies and the pursuit of cleaner technologies. Public companies have demonstrated more commitment to sustainability objectives, and been more active in putting forward pioneering initiatives and showcases. For example, Vloot has invested in electric boat and related infrastructure for its canal ferry services.

Regarding the application of the methanol in production of biodiesel and methylamines it was found that there are substantial feasible opportunities within in the North Sea Port:

- In the North Sea Port there are well established producers of biodiesel that are Cargill Bioro bidodiesel refinery[24] and Oleon-Bioediesel operating plant[25] that currently consume around 70 tons of methanol annually. These companies could be potential consumers of the CCU-based methanol.
- Further potentially large procurer of the CCU-based methanol is Eastman-Taminco. Located in Ghent it is the largest European producer of methylamines (mono-methylamine, di-methylamine, and tri-methylamine)[26]. With the existing production capacity its annual methanol demand is around 200 kilotons.
- In both value chains there are no technical barriers related to substitution of the traditional methanol with the CCU based methanol provided the quality is assured. No technical implications are envisaged. Price competitiveness is the only possible challenge that can be faced by the CCU-based methanol in this market.

Regarding the application of methanol in combined heat and power generation in greenhouses, there is little progress on the ground. The Proeftuincentrum voor de Sierteelt, East Flanders has raised a number of important discussion points in this field:

- CCU-based methanol use in CHP systems for greenhouses (i.e. CO2 exhaust repurposed to stimulate plant growth) has not been tested in practice. Greenhouse farms in East Flanders do, however, have experience using natural gas and other traditional fuelled CHP systems with CO2 absorption.

22 https://www.methanol.org/wp-content/uploads/2019/02/MI-Presentation-on-Methanol-as-a-Marine-Fuel.pdf

23 https://www.greendeals.nl/green-deals/green-deal-zeevaart-binnenvaart-en-havens

24 https://www.cargill.com/agriculture/bioro-biodiesel-refinery

25 http://www.fbbv.be/en/members/oleon-biodiesel

26 https://www.eastman.com/Company/Worldwide/our_sites/Pages/Ghent_Belgium_Taminco.aspx

- With more research and experimentation – adjusting burners and boilers, changing some logistics and storage infrastructure – converting these systems to methanol fuel is not expected to be technically challenging. Challenges related to the methanol properties in the engines can be addressed too including though testing activities and following technical recommendations offered in the domain. [27]
- It is not clear if the cost effectiveness of such a shift will make it an attractive business model for farmers or even for suppliers of methanol. It is most likely that CCU-based methanol will have a premium price which might be higher than traditional alternatives.
- A possible window of opportunity is that many greenhouse farms in Belgium anticipate new instruments being rolled out that may include public support to install CHP systems. Within this modernisation wave, there could be an opportunity to introduce methanol-fuelled CHP systems.

Economic and social impact:

- Existing in the North Sea Port biodiesel and methylamines producers can potentially be a substantial market for CCU-based methanol as they require large amounts of methanol in their production processes.
- There is a growing momentum for methanol in maritime industries due to climate issues and IOM commitments. This may create a wider market for traditional methanol, where 'green methanol' can also find customers.
- The premium price expected for CCU-based methanol can create challenges for its uptake. It is argued that the size of the premium cannot be too high to maintain business interest. Companies are less likely to go beyond 10-20% extra.
- In the water transportation domain, shipping companies' customers can play a decisive role. Their choice for greener services and readiness to pay a premium price can promote the business case for green methanol. While more prevalent than before, customers with 'green demands' are still in the minority and tend to be larger companies, such as Heineken. As yet, there is little to no regulatory pressure for products to reduce their overall environmental footprint .
- It was also stressed that producers' marketing strategy and actions can be an important factor in securing a bigger market for green methanol. There are various ways of helping to commercialise premium-priced green methanol. This can include blending it with traditional fuel to keep the cost down, and as an alternative input to manufacturing by bringing in 'green' features to the final product.
- A promising job generation potential is in the upper segments of the value chain associated with the methanol synthesis and electrolyser management. Between at the pilot and the commercial plants 25-24 and 100-180 permanent direct and indirect jobs can be created. Construction activities can also create 500-700 jobs over the 3-4 years
- On the downstream part of the value chain, job creation due to shift to CCU-based methanol has rather low potential. Substitution of inputs in biodiesel and in methylamines production does not require changes in the processes. Water vessels by switching to

[27] E.g. technical challenges of the methanol use in power generation are discussed by Murray and Furlonge (2009). Methanol has a significantly lower calorific value e.g. approximately half that of diesel. This is generally compensated for by a concomitant increase in the volumetric flow rate of methanol which can be achieved without deviation from usual operating conditions. Special nozzles can be used for high fuel distribution and low pressure drop. Methanol's lower lubricating properties can pose problems for standard fuel-delivery systems, e.g. in situations where the fuel comes into contact with other moving parts within the engine. This is suggested to be addressed by then the use of suitable lubricant additives, but this might affects combustion emissions. Alternatively, an appropriate pump (e.g. screw type) with effective coatings may be used.

methanol will not need any additional staff, but may require re-training. New methanol-fuel logistics and tanking facilities will be needed, which offer some opportunities for job-creation. Similarly, in the methanol-fuelled CHP system for greenhouses, employment generation is not promising. Current CHP system suppliers are likely to adopt the new technology using existing capacities. As noted above, logistics and tanking facilities might offer some opportunities for new jobs, but the number is not going to be large.

- Development of the CCU-based methanol value chain and products will require experimental activities. This will lead to knowledge-creation that will be accumulated locally with local stakeholders. This can potentially help these actors to capitalise on knowhow gained in other markets around the country or aboard.

3.4 CO2 mineralisation on construction materials

3.4.1 Technical description of the value chain

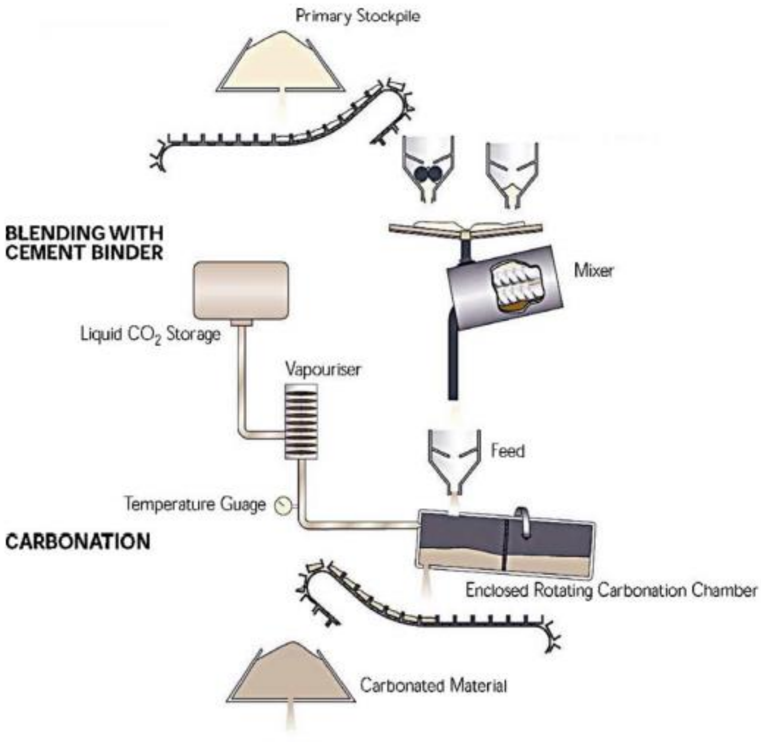
CO2 mineralisation of accelerated carbonation is a developing technology, which may have potential for the treatment of different wastes and contaminated soils and for the sequestration of CO2. Carbonation is the natural phenomenon in which calcium hydroxide reacts with carbon dioxide and is transformed into calcium carbonate. Calcium carbonate is found in the substrate all over the world and is an important natural resource for CO2 storage. It is better known as limestone and is widely used in the construction industry. Apart from CO2, a source of calcium oxide is also required, and in this case, this is slag. Slag is a by-product of steel production and it has for years been recycled to recover metal and valuable road metal. A new patented process is used to convert the fine residual product from the slag generated during production, into high-value construction materials by adding CO2. This new technique is done without adding expensive binders like cement – which is a cost-saving benefit. Such technology can be used in the production of floor tiles, roof tiles, clinkers, boarding stones, building blocks and briquettes.

This value chain has been included in this study due to its high viability: one of the most advanced technology providers is Orbix[28], a company based in Belgium which has been working on its so-called Carbstone technology for several years. By 2019, Orbix has managed to demonstrate and improve its technology and is now ready to bring it to the market.

Figure 6 illustrates a schematic of an accelerated carbonation process.

[28] https://www.orbix.be/en

Figure 6 Accelerated carbonation process



Source: Bertos et al., 2004.

The advantages of the Carbonation technology are the following:

- Production of high-value construction materials.
- Unique permanent storage of substantial quantities of CO2.
- Addition of cement can be avoided.
- Final stabilisation of alloy metals in slags; reuse of all fractions of the slag.

There are substantial efforts under way to produce construction materials via carbonation. Most are being undertaken by start-up companies and precommercial entities. Box 1 presents examples of such companies specialised in this new technology that have been emerging recently.

While these efforts are in the early stage, they highlight the potential for CO2 utilisation in the construction materials markets. However, the scalability and market viability of these approaches are affected by diverse factors, including (1) the purity and the availability of CO2, (2) the availability of low-cost alkaline reagents and/or facilities for their manufacture at scale, (3) the low-cost, commoditised nature of the existing analogous products, OPC and concrete, (4) restrictive building codes and standards wherein compliance is often a function of the material composition (e.g. OPC-based chemistries) rather than their engineering performance, and (5) the net amount of CO2 utilisation that can be achieved. [29]

[29] https://www.nap.edu/read/25232/chapter/5#51

Box 1 Emerging companies commercialising the carbonation of construction

- Carbstone technology from Orbix uses steel production waste as an input in the construction material manufacturing with application of carbonation process where CO2 is absorbed
- Solidia Technologies[30] is using carbonation processing which involves purified CO2, secured from industrial suppliers, at super ambient conditions.
- Carbon Upcycling UCLA[31] is using portlandite and industrial wastes as the primary reactants for carbonate mineralisation.
- CarbonCure[32] injects pure CO2 into ready-mix concrete formed during initial mixing. Their approach is currently being implemented across numerous ready-mix concrete plants in the United States.
- Carbon8 Systems[33] is using heterogeneous air pollution control (APC) residues as the alkaline reagent for the production of carbonate aggregates. The process involves contacting APC residues with pure CO2 supplied by industrial vendors. The approach has achieved commercial operations in United Kingdom based on its ability to encapsulate and isolate APC residues in a carbonate matrix.

3.4.2 CO2 mineralisation on construction materials – consultation findings[34]

CO2 mineralisation in construction materials has not been considered yet in the context of CCU initiatives at the North Sea Port. The technology, however, is available in Belgium and offered by Orbix. The technology is not commercialised yet, but it has been tested and demonstrated its good performance, as recognised by the international greentech community.

If commercialised, the potential social, economic and environmental benefits of the production plant can be significant. The advantage of the technology is in dual recycling opportunities: for the CO2 emissions and for the waste of steel industry.

From the technical implementation perspective, the technology requires the building and installation of facilities rather than incorporation into existing value chains of construction materials. Implementation of this value chain in the context of the North Sea Port would mean the construction of a new plant close to the steel plant and closely linked to by-product (slag) sources as well as CO2. Orbix will act as technology provider rather than engaging in the manufacturing process, therefore a manufacturer of construction materials would be needed to complete the value chain.

Overall challenges and opportunities:

- The CO2 mineralisation and carbonation is among the few CCU technologies recognised in the EU's emission trading scheme. This can be an important driver for technology application, as well as for the carbonated products. Whether this opportunity has already been exploited needs to be further investigated.

30 https://www.solidiatech.com/contact.html

31 https://www.co2concrete.com/contact/

32 https://www.carboncure.com/contact-us

33 http://c8s.co.uk/contact/

34 Interviewees: Representatives of Orbix and "Stepstone to a circular city" project manager

- There is a constant need for R&D, especially when opening a new plant, because depending on the material used, the process changes. See also a note on the standardisation and meeting the environmental quality requirements. The standardisation of the final product has been a technical challenge that can be resolved, but requires adjustments to the content and experimentation with the processing. This challenge is case specific, as the content of the slag from various industry units can vary. The possible presence of heavy metals makes the process of quality fine-tuning important before the product can gain approval.
- Another aspect here is to prove the environmental quality of the final product, to ensure it has a low footprint. There are no current norms for products containing CO_2, therefore there is nothing to compare it with (no reference), which renders the certification difficult.
- Changing a production plant to use the Carbstone technology is thus difficult, requiring new facilities where the CO_2 is very well controlled and mastered, which is complex and expensive.
- The building market is very conservative which renders the marketability of the product difficult.

Socio-economic impact:

- The CO_2 mineralisation technology developed by Orbix has strong potential to establish symbiotic linkages that are wider than other CCU technologies because it valorises the waste stream and offers cross-benefits to the steel and construction materials industries, as well as to consumers of the final products.
- In helps to create new jobs along several phases of the value chain, including management of the slag, carbonation, manufacturing of products, CO_2 and input material sourcing, as well as in support services like logistic, distribution, etc. The number of new jobs created will depend on the scale and production capacity of a new facility, and can range from 30 to 100 direct and indirect jobs, according to technology providers. Construction and installation of the new facility could create between 80 and 150 temporary jobs lasting a few months to a couple of years.
- There is a potential energy and resource saving impact: the technology decreases the amount of cement used, which is an energy- and resource-intensive material. With the substitution of cement, it helps to reduce energy consumption. More efficient and less time-consuming processes offer further energy saving.
- The economics of the Carbstone-based production is promising also thanks to possibilities offered through the emission trading market. Carbon emissions reduced can be converted into quotas that can be sold on the carbon market under the European Emission Trading Scheme or on existing international carbon market schemes.
- Being a Belgian technology, its commercialisation in Belgium generates a special impact by raising the country's visibility as a green technology innovator, as well as for the North Sea Port and its CCU hub.
- A production facility with this technology is likely to be constantly engaged in developing new types of products ranging from construction materials for buildings, to unique building blocks for industrial infrastructure, roads, pavements, bridges, and other public facilities. This means new research, innovation and experimentation that will help to strengthen the local knowledge and scientific base.

3.5 CO2 enrichment of plant growth in greenhouses

3.5.1 Technical description of value chain

The benefits of CO2 enrichment of plant growth and production within the greenhouse environment are well known. CO2 plays an essential role in photosynthesis, a chemical process that uses light as a source of energy to convert CO2 and water into sugars in green plants. Through a respiration process, these sugars are used for growth by the plant. The main aim of greenhouse owners is to increase dry-matter content and economically optimise crop yield. CO2 increases productivity through improved plant growth and vigour. Some ways in which productivity is increased by CO2 include earlier flowering, higher fruit yields, reduced bud abortion in roses, improved stem strength and flower size. The amount of CO2 in the outside air is approximately 350 parts per million. However, this is not sufficient for the plants concentrated in the greenhouses; the CO2 levels drop as all plants are using carbon dioxide for photosynthesis. By adding CO2 enrichment, it is possible to increase the photosynthesis potential of the crops, especially on sunny days.

There are several traditional methods that provide CO2 enrichment:

- The supply of liquid CO2.
- Combustion of fossil fuel using air heaters.
- Combustion of fuels with a central burner, in combination with a heat storage tank.

The most common method of CO2 enrichment for greenhouse application is the combustion of fossil fuel, where the cleanest option is natural gas. Using the waste CO2 from industrial sources is another solution that has been drawing more interest in recent years, especially in the Dutch agriculture sector.

Moreover, the technology is already present the North Sea Port area on the Dutch side in the Glastuinbouw Zeeuws-Vlaanderen zone. Through the WarmCo project, the Yara Sluiskil fertiliser plant is actively recycling both residual heat and residual CO2. Glastuinbouw Zeeuws Vlaanderen forms part of Biopark Terneuzen and is the most sustainable greenhouse horticulture zone in the Netherlands.

3.5.2 CO2 enrichment of plant growth in greenhouses – consultation findings[35]

East Flanders has about 360 greenhouse companies covering over 470 hectares. Many of these greenhouses have already been using CO2 for stimulating plant growth. However, according to interviewees, upgrading or introducing CO2 feeding systems is a priority as part of wider modernisation plans which include better energy and resource efficiency.

The Linde Group in the Netherlands has successfully commercialised industrial CO2 capture and use in greenhouse technology. The technology has been implemented under the project Organic CO2 Assimilation by Plants (OCAP) which is discussed in Case Study 7 presented in Appendix A. Although this value chain was ultimately deemed out of scope for the CCU value chains, some findings about it are presented below.

Overall opportunities and challenges:

- The technology is not new, but OCAP has perfected the implementation side (i.e. it is able to control productivity in greenhouses precisely, a key success factor). Overall, the company's business is growing very fast, with increasing numbers of agro-farms seeking to

[35] Interviewees with representatives of Linde Gas Benelux B.V. and Proeftuin Zwaagdijk

deploy OCAP technology and services. There is still a great potential in this part of Europe, including Belgium, where many greenhouses are still using old methods.

- Another innovative feature is that it is an example of industrial symbiosis: OCAP has managed to generate value for industries who have to remove their CO2 emissions and the agro-sector that is striving to boost productivity and improve its green credentials through a well-functioning CO2 enrichment solution.

Socio-economic impact:

- In terms of economic impact, the technology is beneficial for the entire sector. Harvests will be larger, and it prompts investment in bigger greenhouses. There appears to be little economic risk associated with investing in this technology.
- Application of CO2 enrichment in Belgian greenhouses can create new jobs; however, they will be mainly connected to secondary employment such as transport of CO2 including hauliers, CO2 compressions/liquification, IT development, etc.

3.6 Re-scoping of the CCU hub value chains

In the course of the study, many relevant stakeholders have been interviewed to better understand the types of value chains and help focus the study, as well as to gain insights from case studies piloted or commercialised in other countries. These interviews helped to reflect on the potential of each value chain in the context of the North Sea Port CCU hub's implementation and feasibility, including its economic and market viability. These discussions also helped to refine or realign the scoping of the CCU value chains targeted in this study.

Despite interesting results observed in some case studies, implementing a full value chain for them was difficult to justify economically. At the same time, additional opportunities were identified that could be very promising for the local economic actors and contribute to efforts dedicated to meeting climate goals.

In the final scoping of the value chains in the CCU hub, the following adjustments were thus introduced: the value chain on CO2 to greenhouses was found to be unviable in the context of East Flanders, as well as a wider Belgian context. Several constraints were identified including, for example, the cost of transporting CO2 could too expensive especially if the size of the customer pool is unknown (i.e. larger markets could justify CO2 being transferred through pipelines). Alternatives such as rail and road transportation just add to other environmental concerns. More importantly, many of the local greenhouse farms produce their own CO2 from CHP generation units. In the past decade, CHP technology has become more popular because it offers an efficient source of heat, electricity and CO2 feeds for stimulating plant growth in the greenhouses. Such a 3-in-1 solution leaves farmers little incentive to look for external sources of CO2.

Box 2: Combined heat and power generation for greenhouses

Combined heat and power or CHP is an efficient way of using natural gas or other fuels (e.g. diesel, mazut) in a greenhouse. CHP creates electricity, while heating up water. With CO2 as a by-product, these are three key ingredients for a greenhouse operation.

CHP is also known as cogeneration. As its name indicates, it is the process of simultaneously producing electrical energy and thermal energy in one system. Especially in greenhouse horticulture, the advantages of combined heat and power can be significant.

Greenhouse crops require a few basic ingredients: light, temperature, carbon dioxide, water and nutrients. This is needed for photosynthesis, which can be boosted by adding more of these ingredients to the greenhouse. Cogeneration takes care of three of these important elements required for photosynthesis.

Nevertheless, during discussions with stakeholders from the farming community, an opportunity was identified to replace traditional fuel used in greenhouse CHP units with CCU-based methanol. The advantages of methanol is that its combustion does not produce other emissions commonly associated with the use of diesel or mazut, and the transportation and storage of methanol is simpler than, for example, natural gas. In the long run, the use of CCU-based methanol will also allow local agro-companies to demonstrate their commitment to climate change mitigation and be ready for possible emission targets and compliances that can be imposed by states.

In the CCU-based polymers value chain, only the synthetic naphtha-based value chain had potential, according to the experts interviewed, while the CO2 to polyol value chain had little potential in the short- to medium-term due to the complex technological demands and established practices. The processes at Dow, for example, are fully built on naphtha-based production lines. It is therefore economically and technically easier to switch to synthetic naphtha-based CCU technology, rather than bring in and launch a new CO2 to polyol technology from scratch. Furthermore, it was stressed by the DOW representative that the polyol product market for the company is fractional in comparison to polyethylene and polypropylene markets. Market size is very important as it can predefine the carbon capture volumes and potential contribution to climate targets.

To sum up, the rescoped CCU value chains for CCU hubs will exclude the CO2 to greenhouses value chain, as well as CO2 to polyol options in the final analysis of the potential impact. In the analysis of the downstream part of the methanol value chain, it will include use of methanol as fuel in water transport, as well as in CHP generation for greenhouses.

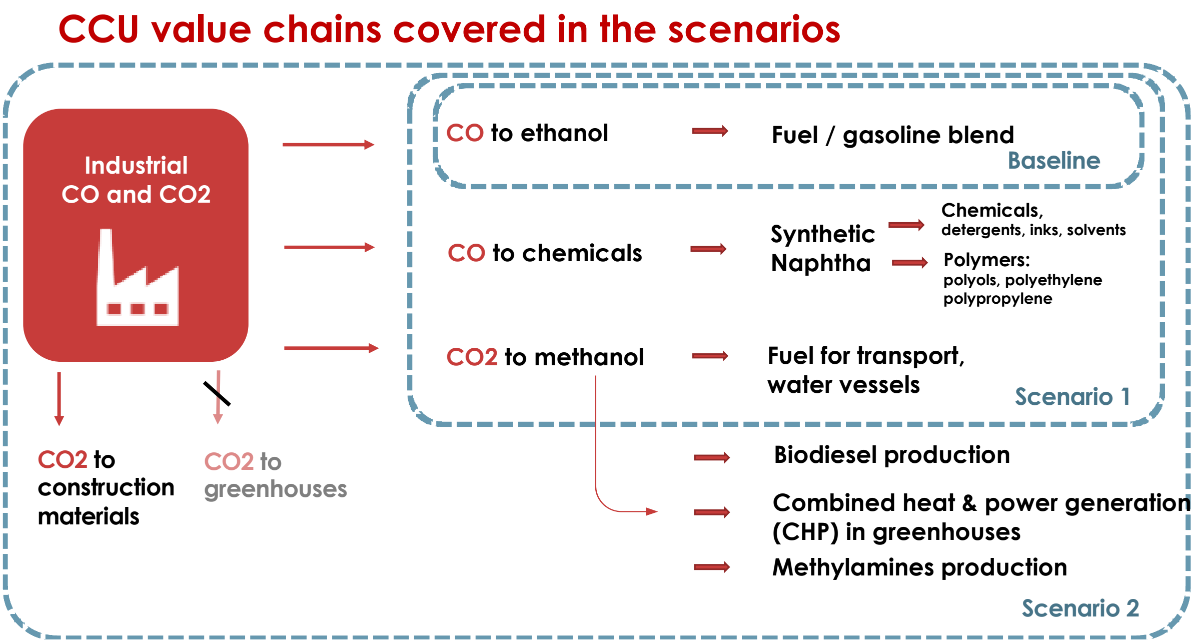
4 Scenario analysis

4.1 Selection and design of the scenarios

Three scenarios of CCU cluster development in the North Sea Port and beyond have been tested in this study. These included the baseline scenario where the current state of play will continue, while two other scenarios are based on the various parameters and permutations of new value chains and boundaries of the CCU hub's outreach. The geographical boundaries of the scenario stay within the North Sea zone that is shared between East Flanders of Belgium and Zeelandic Flanders in The Netherlands, due to proximity of some key players involved in the CCU hub on different sides of the border.

The figure below schematically shows the scoping of each scenario and which value chains in includes, while the figure**Error! Reference source not found.** below summarises the scenario profiles.

Figure 9 Scoping the value chains in the Scenarios for this study



In this study the following scenarios have been put forward:

The **baseline scenario** represents what would happen without additional activities, initiatives, policy or technical interventions. This means it includes the CO to ethanol value chain established with the launch of the commercial plant that deploying LanzaTech's waste gas CO fermentation into ethanol technology. The commercial-scale plant is being constructed by ArcelorMittal in the industrial zone of Ghent and the North Sea Port. It is the first installation of its kind on an industrial scale in Europe and, once complete, annual production of bioethanol is expected to reach 80 million litres a year.

Scenario 1 includes the value chains that are being piloted under R&I projects and planned under local initiatives. These are in addition to the CO fermentation into ethanol value chain covered in the baseline scenario. CO2 to methanol and CO to chemicals and polymers are prioritised in the CCU hub value chains, involving significant R&I and feasibility testing efforts. Dow and ArcelorMittal have been central in promoting R&I and piloting of CCU for production of *synthetic naphtha* from steel mill gas that is further used in the synthesis of ethylene, propylene and C4 hydrocarbons that further feed production of various *polymers* (plastic, rubber for use in industry, food packaging, and household goods), and *chemicals* (solvents, adhesives, inks, etc.). *Methanol* is another highly prioritised value chain in the CCU hub initiative as it is. Feasibility assessment is being done in cooperation with several economic, academic and public actors, including ArcelorMittal, local authorities, Ghent University, as well as energy producer ENGIE. To this end, the CCU hub consortium has been carrying out a technical assessment for installing an electrolyser fed by offshore wind energy for the production of hydrogen, which is an important part of the sustainable CCU-based methanol production. Estimated capacities in the methanol project are the following:

Demonstration project	Global/commercial scale project
• 63MW electrolyser: using about 440 GWh/y of (new) renewable electricity; producing about 8600 tonnes/y of green hydrogen • Locally 'produced' CO2: about 63,000 tonnes/y will be used • Producing green methanol: about 46,000 tonnes/y	• 300MW electrolyser: using 1800GWh/y of renewable electricity; producing 35,000 tonnes/y of green hydrogen • CO2 from steel industry: up to 25,7000 tonnes/y • Producing green methanol: about 187,000 tonnes/y

Source: North Sea Port CCU hub

This scenario also considers the downstream segment of the methanol value chain covering the use of methanol in water transportation, i.e. in marine and inland water shipping.

Thus, this scenario assumes that three value chains (CO to ethanol, CO to chemicals and polymers, and CO2 to methanol for transportation) will be functioning in the North Sea Port zone and thus forecasts the socio-economic impact of all of them.

Scenario 3 is the most inclusive in this study. In addition to the existing and pilot North Sea Port zone CCU value chains (covered in Scenario 2), it also includes CO2 mineralisation for construction materials, as well as more diversified uses of methanol, including as a water vessel fuel, input in biofuel and in the production of chemicals and fuel in CHP units for greenhouses in East Flanders.

CO2 mineralisation technology was selected for the scenario because it is available in the Belgian marked and offered by Orbix, a local technology provider. Furthermore, it is based on the use of waste slag from steel production, which ArcelorMittal can provide as needed. This represents an attractive industrial symbiosis option where, not only CO and CO2 are recycled, but it also sees waste being valorised (see more discussion on the technology in the Orbix case study).

As discussed in section 2, in the course of the analysis, the value chains for CO2 in greenhouses were ultimately excluded from the analysis due to the poor economic and technical feasibility of this approach in comparison to the growing interest and uptake of CHP, which provides heat and electricity but also CO2 for stimulating plant growth in the greenhouses. As a clean fuel, methanol is considered a highly attractive option in CHP generation, and combined with the low set-up/adjustment cost for generators, it is likely to be a promising market for CCU-based methanol to be produced in the CCU hub.

The use of methanol in biodiesel and chemicals has been considered because biodiesel production is already represented in the North Sea Port area by Cargil and Oleon, while the methylamines and resins manufacturing are represented by Eastman and Dynea-Unilin. The assumption in this scenario is that part of CCU methanol will substitute the traditional methanol supplies in these companies.

Thus, the outreach of scenario 3 includes four value chains (CO to ethanol, CO to chemicals and polymers, CO2 to construction materials and CO2 to methanol) with various uses as a fuel and as an input material. Together, these stand to deliver measurable socio-economic impacts.

The table below briefly summarises the profiles of the scenarios analysed in this study.

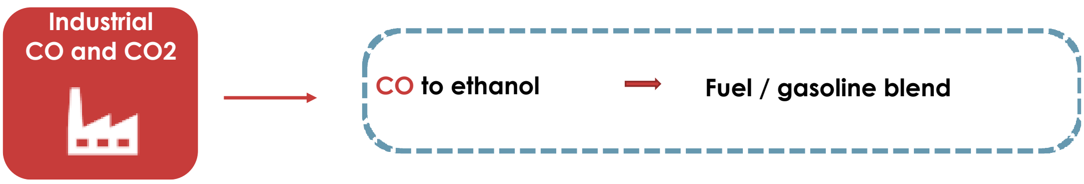
Table 3 Scenario profiles

Scenario	features	Details
Baseline scenario	No additional interventions – One value chain: *CO to ethanol	'No change' (counter factual) baseline scenario captures the continuation of current developments. This scenario includes autonomous developments of the ongoing project focused on CO to ethanol value chains. LanzaTech's commercial-scale facility is under construction with a planned launch in 2021. The impact scale will be linked to this value chain.
Scenario 1	CCU hub with three value chains: *CO to ethanol *CO2 to methanol for transport fuel *CO to chemicals and polymers	This scenario covers three value chains: CO to ethanol which is at a commercialisation stage; CO2 to methanol and CO to chemicals, value chains currently being explored and tested. The CO2 to methanol project is seeking investment while the CO to chemicals and polymers pilot has been launched and will test its small-scale facility with the aim of scaling it up at the premises of DOW and ArcelorMittal. Here, assumptions include the full-scale deployment of these technologies, that they will go beyond the pilot scale. Downstream of the methanol value chain is the water transport sector.
Scenario 2	CCU hub with five value chains: *CO to ethanol *CO2 to methanol for transport fuel *CO to chemicals and polymers *CO2 to construction materials *CO2 to methanol for - biodiesel production - Methylamines production. - CHP generation in greenhouses Note: Use of CO2 to greenhouses was excluded from the scenario due to non-viability	This scenario is the most inclusive and assumes the development of a diverse mix of CCU value chains under the CCU hub. In addition to value chains considered in scenario 2, it also considers additional value chains: (1) CO2 to construction materials, (2) CO2 to methanol for biodiesel production, (3) CO2 to methanol for the chemicals market mainly to methylamines synthesis (4) CO2 to methanol for heat and electricity generators in greenhouses. The value chain of CO2 in greenhouses as a stimulant for plant growth was not found to be a viable option in the region. Alternatively, greenhouses in East Flanders foresee good opportunities for using methanol as a clean fuel for their CHP generation units.

4.2 Assessment of impact under each scenario

Following the analytical framework presented in section 1.2.2 we have identified three impact categories namely economic, social and innovation impacts, as dimensions for the analysis. Case studies, interviews and literature have provided data, information, insights, as well as approximation on the impacts generated by each type of value chain. These finding have become a basis for feeding the analysis in scenarios.

4.2.1 Baseline scenario: No additional interventions and one CO to ethanol value chain



In the event of no further interventions or additional activities, the impact will fold around one value chain (CO to ethanol) that is being established in the North Sea Port industrial zone. As the commercial ethanol plant is still under construction, the impact has not been demonstrated. Thus, the analysis below is a forecast taking into consideration the experience of the existing ethanol plant in Shougang China and prevailing local economic and policy conditions. Findings and lessons from the ongoing Steelanol project[36] have also been taken into consideration.

4.2.1.1 Economic impact

As discussed above, this is the first installation of its kind on an industrial scale in Europe and it is still at the construction stage. Though the full economic impact is unclear, some temporary impacts are associated with the construction activities.

- ***Competitiveness***

With regards to competitiveness, technically it should depend on how cost-effective the ethanol produced though this technology is compared to traditional ethanol production. Today, the prices for ethanol range from €0.7 to €1.3 per litre in the EU fuel market[37]. The statistics show that the difference in price between countries is due to various taxes and subsidies for gasoline. Also, as a general rule, wealthier countries have higher prices while less prosperous countries and those that actually produce and export oil have significantly lower prices.

Observations from the Shougang project showed that the projected cost of production of new ethanol is competitive with the production of the lowest-cost bioethanol available today. This factor is likely to be significant in the Belgian case: considering the medium to higher range prices of bioethanol in the current market of western Europe, there is a likelihood that the cost of the new CO-based ethanol will be comparable or even advantageous. Thus, one can expect that the **commercial viability** of the ethanol to be produced in the new North Sea Port plant will be strong, therefore it is **highly likely to be competitive** in the established European market.

Furthermore, the positive image of the product could also contribute to better interest from potential consumers. The main market for the new ethanol is as a fuel. Prospective interest from the aviation sector is also a factor. Pilots of ethanol to alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK)[38] are promising, attracting interest from key players, such as Boeing, Virgin Atlantic, and Mitsui via the Steelanol project.

The **business model** of the new line will have to rely on the price competitiveness of the product. As presented in the case study, in Shougang the procurement of ethanol is assured by the state fuel company and this is the main driver of the stable business model for the ethanol plant. One cannot guarantee creation of similar conditions in Belgium. Therefore, the business model will have to be based on other factors including price and demand. Recognition of CCU fuel under the REDII could also reinforce the green fuel market.

This project is bringing **new value chains** in the region; however, the final product will be **entering the existing ethanol market** rather than creating a new one. With envisaged 80 million litres annual supply, it closely matches the demand in Belgium and can be disruptive in the

[36] http://www.steelanol.eu/en

[37] https://www.globalpetrolprices.com/ethanol_prices/

[38] https://www.lanzatech.com/2019/11/22/lanzatech-moves-forward-on-sustainable-aviation-scale-up-in-the-usa-and-japan/

market. Consumption of ethanol fuel in Belgium alone is around 105 million litres annually, and therefore the new ethanol will likely be supplied to a wider EU market. Considering the proximity, it can be supplied to The Netherlands market (with over 300 million litres/year consumption), Germany (1560 million litres/year consumption) and France (with over 750 million litre/year consumption).[39]

It is clear that the gross value added of the ethanol industry will be significantly increased within the regional economy. Alco Biofuel located in the North Sea Port area already produces 240 million litres per year of bioethanol. With the introduction of the CCU-based value chain, the **ethanol production will increase by 33%.** The estimated **value added to East Flanders' economy will be between 65 to €110 million a year** including taxes on the final price of the product. In total, **€150 million in investment** has been secured to launch the plant, including EU funding of €10 million for the Steelanol project, with the main investor being ArcelorMittal.

The Shougang project demonstrated that there was no relocation of new companies to the region. The construction of the ethanol plant in the North Sea Port has also shown a **reliance on the existing companies** in construction and temporary engagement of technology providers (e.g. LanzaTech, Primetal, Sulzer Chemtech, Emile Egger & Cie SA, Fluence Corporation). In the long run, it is likely that there will be increased capacity among distributors or exporters of transport fuel due to increased supply of ethanol, however the precise economic impact is not clear yet.

The Shougang experience also demonstrated increased interest in the new technology from public bodies in China. Significant economic possibilities for the country, as well as the strong intention of the government to promote energy independence, novel technologies, and showcase sustainability efforts has helped to **secure public investment** for existing as well as new projects. Developments within the ethanol plant in the North Sea Port zone were driven by industry, but support from the public funds plays an important role. Funding from the European Union for Steelanol was provided as a grant subsidy for building the facility and testing the technology. This was a significant factor in launching the unique value chain and making the region a pioneer (first in the EU and second globally) in CCU-based ethanol production.

There is a growing global interest in the technology, however **it is not clear** how this will create direct economic impact on the region and its economy. Here, one can envisage a positive benefit in terms of visibility (image building) for the region as a leader in CCU technologies, which can potentially attract investments for new CCU projects.

The discussion of **impact in terms of the energy and resource import independence of the region is less relevant** in the current context of the local ethanol market. The existing production capacities of ethanol fuel is already beyond the current consumption volumes, as discussed above. However, in the context of the European market, the additional ethanol synthesis capacities can contribute to overall European independence from imports. This is especially important because many EU member states are increasing their mandates for biofuels.[40] One possible advantage of CCU-based ethanol is that it might not be vulnerable to prices of traditional sources of sugar. At the same time, there are also concerns about expected

[39] https://www.indexmundi.com/energy/?product=ethanol&graph=consumption&display=rank we have recalculated barrels into litres here

[40] The EU's consumption of ethanol for use in vehicles has increased by 2.4% since 2010 as higher biofuel mandates to meet the bloc's 2020 target. https://www.icis.com/explore/resources/news/2019/01/11/10305307/outlook-19-europe-fuel-ethanol-uncertainty-still-a-feature-for-2019?intcmp=mega-menu-

European production capacity outstripping expected demand, which could prove a growing challenge to players in a market.[41]

- ***Wider economic benefits and costs***

The economic cost and benefits to downstream economic players might vary. As discussed above, due to significant additional volumes of ethanol entering the market, it is likely that there will be a need for higher capacity distributors or exporters of transport fuel. This will result in **additional revenues** for these companies, but it is also likely to require additional investment infrastructure, transportation, etc. On the other hand, the gasoline distribution companies that blend new ethanol into motor fuel do not need to introduce any new processes or technologies. In the Shougang case, for gasoline distribution the price and quality of CCU-based ethanol has been the same as the traditional alternative, no changes have been introduced in their process.

Following the discussion on cost-competitiveness above, it is safe to assume that the cost and therefore the price of the CCU-based ethanol will not be higher than traditional ethanol. Therefore, **no financial impact** on the final consumers is envisaged, **nor is there an extra cost for the procurers** of the new ethanol who blend it with gasoline.

The Shougang project stakeholders have indicated that **no negative economic externalities,** such us creating additional economic cost or burden on other parties or the population, are envisaged in coming years. It is also safe to have similar expectations for the new plant in the North Sea Port.

4.2.1.2 Social impact

- ***Employment creation***

Opening a new industrial plant will lead to the creation of skilled jobs associated with a range of activities. This includes engineering, technical, monitoring, logistics and other positions needed to keep the technological process running. While these positions are long term, there are also temporary posts associated with the construction and installation activities.

According to estimates by ArcelorMittal and the Steelanol project, the new CCU-based ethanol plant will **create up to 500 construction jobs** over a period of two years and **20 to 30 new permanent direct jobs** linked to running the plant. It is also likely that there will be a **few indirect jobs created** (e.g. at the companies blending, distributing or exporting transport fuel due to significant increases in supplies of ethanol from the same industrial zone).

According to information from the Shougang project, over 120 permanent or long-term positions needed to operate the main facility and for supporting services have been created in China. In addition, nearly 1000 temporary jobs have been created during the construction stage. This is an interesting observation as the capacity of the facility in China is just slightly higher than the one in Belgium. Higher labour costs in Belgium[42] may prompt more mechanisation of many processes alongside measures to boost efficiency and keep costs down.

41 Ibid

42 http://www.worldsalaries.org/engineer.shtml

There were **no job losses** associated with the Shougang experience; the technology does not disrupt the existing technological structures of the steel mill or eliminate any elements. The same is envisaged for the plant in the North Sea Port zone.

- ***Linkages and partnerships***

The initiation, construction and launch of the ethanol plant has been associated with a number of new partnerships across different industries. This is not surprising because CCU projects are an example of industrial symbiosis that is a form of brokering to bring companies together in innovative collaborations, finding ways to use the waste from one process or partner as raw materials for another[43]. The **new ethanol plant project assumes cross-industrial links** between ArcelorMittal (a carbon-emitting steel company), LanzaTech (a gas fermentation technology provider), Primetals (an engineering specialist), Sulzer (a distillation equipment supplier), Egger (a specialist pump maker), Fluence Corporation (offering wastewater treatment and waste-to-energy systems), and E4Tech (performing LCA on the produced fuels). Several key players in the transport sector (Boeing, Virgin Atlantic, Mitsui) have expressed their strong interest in and support for the Steelanol project.

Beyond that, the Carbon2Value project initiative[44], focusing on CO and CO2 separating technology experimentation, links up ArcelorMittal and LazaTech, and also involves the East Flanders Development Agency (POM) and the University of Lille.

All in all, the projects focusing on such innovative technology testing and demonstration rely on a wider partnership for the best technical environment, as well as in implementing soft analysis around the project.

- ***Strengthening the local knowledge base***

Another dimension of social impact that can be important for the region is strengthening the local knowledge base. Observations in the Shougang project showed the pilot plant activities have generated a substantial impact in terms of building research capabilities and the scientific base in the region. Shougang plant's internal research team has collaborated with a local university to adapt the new technology and engaged them in experimental work. The research and translation of research and experimental results from lab to pilot facilities has provided valuable knowhow and capabilities both for the company and for the university researchers.

In the case of the ethanol project in the North Sea Port, there is also potential for knowledge-related benefits. The presence of a strong research and innovation cluster in biotechnology in East Flanders can explain the high attention being given to the pioneering syngas fermentation technology, and assures **learning- and knowledge spill-overs** from the demonstration project. Learning benefits are likely to reach the R&D communities of Ghent Bio-Economy Valley, Bio Base Europe Pilot plant, and the Capture initiative[45] including scientists from Ghent University, as well as VITO and the University of Antwerp.

In the case of Shougang, a number of high-class research staff and engineers have been drawn to the research and pilot project team. They have been critical in adapting the new technology and implementing it at pilot scale. There is evidence of brain gain, which contributes to strengthening the local knowledge base which can benefit the local economy. Similarly, in the North Sea Port case, foreign technology and expertise has been introduced

43 https://fissacproject.eu/en/what-is-industrial-symbiosis/

44 https://www.carbon2value.be/en/

45 https://capture-resources.be

during the construction stage thanks to the involvement of LanzaTech and other technology providers (Primetal, Sulzer Chemtech, Emile Egger & Cie SA, Fluence Corporation). However, **it is too early to say if the plant will attract highly skilled professionals from outside** the region and country in the long run, or whether the local pool of professionals will be sufficient to maintain the facility.

- ***Visibility and image***

Initiating the ethanol plant has **benefited the region's image as a leader in CCU**. The uniqueness of the technology and the fact that it is the first commercial-scale example in Europe (second globally) has contributed to the region's international visibility. As discussed above, the importance of image, and especially the formalisation of the overall CCU hub initiative is likely to strengthen the interest and confidence of new investors and other technology providers to come to the region.

4.2.1.3 Innovation impact

- ***Technical and technological advancement***

The launch of the ethanol plant in the North Sea Port area has been associated with extensive experimental work and activities that required additional research and innovation efforts. It is common that a new technology when brought to the market, or commercialised, needs a series of adjustments. The ethanol project is no exception, requiring **significant effort to adjust improve and implement the technology** at various segments of the value chain.

The EU-funded (H2020) Steelanol project's main objective was to demonstrate the cost-effective production and valorisation of sustainable bioethanol. It started with some testing of the compatibility of the LanzaTech gas fermentation process with the steel mill waste gas from ArcelorMittal's steel plant. A mobile fermentation unit (gas testing station) was installed for a number of weeks. Two rounds of live testing generated promising results and represented an important step for the project, showing that the LanzaTech process could be integrated within ArcelorMittal's steel mill.

Under the Carbon2Value project funded by the INTERREG2SeasMersZeeen programme, a set of research activities have focused on demonstrating a cost-efficient solution for separating CO2 and CO from steel-waste gas from the blast furnace. Trials have been run with a new pilot installation at the company premises of ArcelorMittal Ghent, which separates CO2 and CO from gases produced during the steelmaking process. This is a good example of work that resulted in technological advancement of the processes, which is important for CCU-based ethanol production, as well as for other CCU value chains.

Fluence Corporation, a waste to energy technology provider, provides another example of technical advances via its specially designed wastewater and waste-to-energy system for use in the steel industry. The company was able to achieve the desired effluent qualities using advanced anaerobic digestion technology. By adding waste-to-energy treatment to the system, the biogas produced can be used to power the Steelanol plant and thus increase overall efficiency in the process.

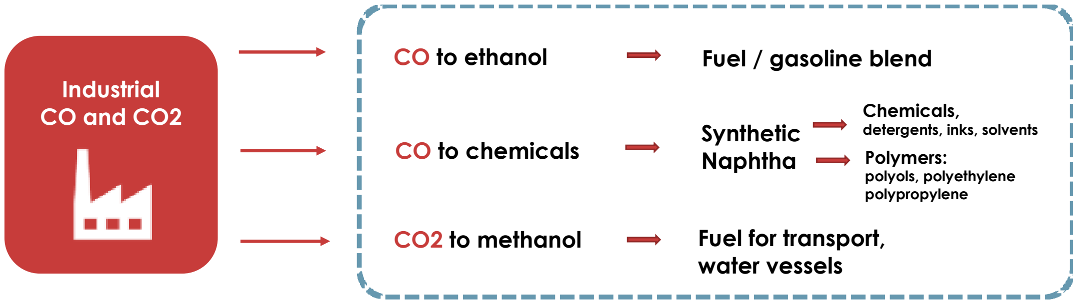
While LanzaTech is already known as a technology pioneer, the project has also allowed local partners to become **leaders in deploying this technology** in Europe and among the leaders in this field globally.

This is a clear case of **technology transfer** (using a new foreign technology) and the first commercial implementation of the technology on the continent. It did not result in the filing of new patents, as the focus was on demonstration rather than invention per se.

- ***Capabilities of local companies***

The experience with the ethanol plant launch has been, above all, a significant learning, capability and expertise-building exercise for ArcelorMittal, the host and main driver of the project. In construction of the ethanol plant, local contractors have been involved. The construction process itself has not generated any specific impact on local companies in terms of increasing local technological capabilities, etc. The construction followed the provided specifications and plans, and have not included any non-standards or sophisticated technologies or processes. The technology providers discussed above are all from outside Belgium (US, Switzerland, etc.). Thus, the **no significant direct impact on the capabilities of the local companies** at the construction stage has been observed. In the long run, at the operational stage also no specific impact is envisaged, as there is no need for specific changes or R&D efforts.

4.2.2 Scenario 1: CCU hub with three value chains: ethanol, methanol for fuel and polymers



This scenario includes the value chains that are being piloted under R&I projects and planned through local initiatives. In addition to the CO to ethanol value chain covered above in the baseline scenario, CO to chemicals and polymers and CO2 to methanol value chains are analysed here. The last two have been prioritised in the CCU hub value chains and are currently attracting significant R&I and feasibility testing efforts. This scenario also considers the use of methanol in water transportation and analyses associated impacts.

This scenario assumes the cumulative impact of all value chains considered here, which means its impact will be greater than in the baseline, where only one value chain is considered.

In the analysis of this scenario the important sources of information were representatives of key stakeholders in the targeted value chains of the CCU hub, such as Dow, ENGIE, Ghent University, other research and thematic experts, and the methanol and polymer downstream segment (e.g. water shipping companies and polymer product manufacturers in ongoing projects who were interviewed during the study, see section 3.2.2 and 3.2.3).

Furthermore, observations, lessons and insights on impacts from the following case studies have been used:

Case studies	*Value chain covered*
Shougang LanzaTech fuel ethanol plant (China)	**CO to ethanol fuel**
CO2-based polyol production at Covestro (Germany/Belgium)	**CO2 to polymers**
Technical photosynthesis of butanol and hexanol in Rheticus project (Germany)	**CO and CO2 to chemicals**
George Olah Renewable methanol plant (Iceland)	**CO2 to methanol**
CO2-based chemical production at Thyssenkrupp (Germany)	**CO2 to methanol and other chemicals**

In addition, information and insights from the research and pilot projects Carbon4Pur[46], Rheticus and Steel2Chemicals, have fed the analysis below.

4.2.2.1 Economic impact

- ***Competitiveness***

While the competitiveness of the CO to ethanol value chain is likely to be strong, as discussed in the baseline scenario, there is **less confidence in the price competitiveness of the CCU-based methanol, chemicals and polymer products**. Consulted stakeholders generally agree about the likelihood of higher prices for these new products compared to traditional fossil-based alternatives. This can create challenges for wider uptake of the products. In the CCU-based methanol case, water transport is said to be the biggest potential market. Stakeholders from water transport companies argued that the premium price cannot be too high for their businesses to remain viable. The companies in this sector are less likely to pay above 10-20% extra. A shift to methanol fuel in water transport can also be predicated on other factors: for example, the sustainability strategies of companies where voluntary commitments are more common among larger scale companies and publicly owned companies. In the case of polyol and chemicals, due to a wider variety of products containing CCU-based input materials (chemical and polyol), other factors than the price can play a role in their market competitiveness. This can include better or special qualities that are not offered by the traditional alternatives, green conscious consumers, guaranteed (public) procurement, etc.

For example, case studies on commercialised products (Covestro's polyol and George Olah's methanol) have demonstrated that their products could successfully enter the market with a premium price. In the case of Covestro, polyol was used to make mattresses and it resulted in a superior product which could also be promoted as sustainable (produced from recycled CO2). This was key point in the successful business despite the premium price. George Olah's methanol is procured by several companies in Europe that are prepared to pay a premium price due to the 'green' nature of the product.

Specialty chemicals developed by Evonik from CO2 are said to be competitive in the present market where the traditional alternatives also have rather high prices. However, Dow experts envisage a higher production cost of the CCU-based polymers and chemicals.

It is likely that the green image and labelling of products will be increasingly important in securing a business case and business models for CCU-based chemicals, polymers and fuels. However, each CCU product case will be impacted by different factors. While ethanol and methanol are both transport fuels, today they have very different market conditions. The ethanol market is well established, and blending is encouraged by regulations. The first application of methanol in transport, namely water transport, was demonstrated in 2017. It has only been followed by seven other cases in marine shipping. These experiences were positive however, the wider market uptake would still require specific measures. Recognition of CCU fuel under the REDII is one such measure.

It was also mentioned that better opportunities for methanol are evident in maritime shipping because of the pressure to cut sulphur emissions, while inland shipping companies have already reduced such emissions by using cleaner fuel. The CCU hub, by being located in the port area, has opportunities for securing a strong market for methanol, but this would require special strategic actions to gain commitments from potential consumers. There is no market for

[46] https://www.carbon4pur.eu

methanol fuel and it has to be created to secure the commercial viability of the methanol value chain.

In this scenario, the value added to the regional economy of the new value chains will differ.

As discussed in the baseline scenario, value added to the local economy of introducing an **ethanol plant** can be between **€65 and €100 million a year**. Introduction of a new **pilot methanol facility** can generate €**11 to12 million a year**. Expanding it to the **commercial scale facility** can generate €**45 to 50 million a year of** value added to the local economy.[47]

In the CCU-based **chemicals and polymers value chain case, no significant addition to revenue flows** in the local economy are envisaged. This is because the existing production lines of chemicals and polymers at Dow will get a new feed of CCU-based synthetic naphtha instead of the traditional naphtha. But overall output volumes are not envisaged to change, thus no additional products will be generated.

Table 4 Value added to the local economy – new revenue streams generation under scenario 1

Value chain	New VS existing production line	New production capacities envisaged per year	Value added to local economy (annual revenue) envisaged in million euros
CO to ethanol	New production line	80 million litres	65-110
CO2 to methanol	New production line	187,000 tonnes (full scale) 46,000 tonnes (pilot scale)	45-50 11-12
CO to chemicals and polymers	'Greening' of the existing value chain	No additional production volume	None (or insignificant)

The analysed case studies and the ethanol plant already constructed offer **no evidence of new companies relocating to the region** thanks to new value chains and projects. Most of the case studies present non-commercialised technologies which can explain this observation. In the George Olah case, which is a pilot plant, its small scale did not incentivise potential downstream players to settle in the vicinity of the plant. It is challenging to predict whether such a trend will remain once new larger scale commercial facilities get launched in the future. For the fuel-based value chain, it is likely that there will be increased capacity among distributors or exporters of fuel in the long run, however the scale of economic impact is not yet clear.

All of the projects analysed in this scenario can testify to a **high interest from investors** in their technology or products. Furthermore, public funding has been provided to most of the initiatives. The CCU-related initiatives in the North Sea Port zone have been primarily pushed by industry, namely ArcelorMittal and Dow as part of their effort to comply with emission-reduction targets. However, support from public funds has played an important role and will continue to do so in the future evolvement of the hub.

As discussed in the baseline scenario, in the current market setting for the ethanol value chain, the need to import energy and resources (import independence) is less relevant to the region because the AlcoBiofuel plant located at the North Sea Port already produces more ethanol

[47] Global methanol pricing data https://www.methanol.org/methanol-price-supply-demand/

than is consumed in Belgium. When it comes to impact from CCU-based methanol and chemicals value chains, several stakeholders acknowledged the positive contribution of these value chains. To make this possible, there should be a commitment to further 'greening' the marine, road and aviation transport. **CCU-based methanol would be especially relevant in cutting the imports of fossil-based fuel** for vessels using the North Sea Port. Similarly, Dow could decrease its use of traditional naphtha and substitute it with the synthetic variety in its production of CCU-based greener chemicals and polymers

- ***Wider economic benefits and costs***

In this scenario, the economic benefits generated on the downstream segments of the value chain could be significant. The baseline scenario has envisaged additional revenues for distributors or exporters of transport fuel. This can also be true for methanol fuel. Introducing green methanol and ethanol would mean additional cost (e.g. for adjusting infrastructure, logistics, etc.)

Economic benefits for the shipping companies are not as obvious, while the cost will include having to adjust engines to methanol fuel, as well as higher fuel cost. However, some savings could potentially come from reduced SOx and NOx emissions that represent the bulk of the environmental cost burden on shipping companies. Stricter carbon emission limitations and therefore costs might also be avoided due to the switch to greener fuel. Recognition of CCU-based fuel under the regulations on greenhouse gas emissions in the shipping industry will be a precondition for that.

Downstream companies of the chemicals and polymers value chains are not likely to have costs related to any adjustments or retrofitting needed to CCU-based materials. However, premium prices for the materials demands some strategic action by final manufacturers. As it has been shown in the Covestro case study on CO2-based polyol, it is the higher performance quality of the polyol and the 'green image' of the final product that has been key to the success of the product, despite the higher price for new materials and the final product.

4.2.2.2 Social impact

- ***Employment creation***

Opening ethanol and methanol production plants will lead to the creation of skilled jobs associated with a range of activities, including engineering, technical, monitoring, logistics and other positions needed to keep the technological process running. In the methanol value chain, an electrolyser facility located at the ENGIE site will also create technical positions. In the chemicals and polymers value chains, supplementary jobs are envisaged in the processes associated with synthetic naphtha production, separation of CO and CO2, and the syngas channelling and conversion. In addition, the construction phase will create jobs for construction professionals, equipment-makers, consultants and infrastructure suppliers, as well as installers and engineers for testing and adjusting.

The table below summarises the estimated potential job-creation in each value chain under scenario 1.

Figure 10 Estimates on the potential new employment creation under scenario 1

Value chain		Permanent jobs	Temporary jobs
CO2 to methanol	**New methanol plant:** • **Pilot – 46 ktonnes/year** • **Commercial scale – 187 ktonnes/year**	• At pilot plant: 25-45 jobs • At commercial plant: 100-180 jobs (direct and indirect jobs)	• Construction and installation ~500-700 jobs (over 3-4 years)

Value chain		Permanent jobs	Temporary jobs
	Electrolyser (ENGIE) • **Pilot – 63 MW** • **Commercial – 300MW**	• Pilot – 1-2 jobs • Commercial scale – 4-6 people	
	Downstream value chain: use of methanol fuel in water shipping	• No new jobs in vessels, but retraining of existing stuff • No new jobs in fuelling facilities due to switch to methanol	• Jobs in ship engine modification
CO to Ethanol	**New ethanol plant**	• 20 - 30 jobs at the facility (direct jobs)	• Construction ~500 jobs (over 3 years)
	Downstream value chain: fuel distribution	• 3-10 jobs at fuel distribution companies (indirect jobs)	• Likely none
CO to chemicals and polymer	**Synthetic naphtha production facility**	• 50 -100 new jobs (direct and indirect jobs)	• Installation ~150-250 new jobs (over 2-3 years)
	Syngas conversion		
	CO and CO2 separation		
	Chemical and polymer production	• No new jobs, but greening the existing jobs at Dow	N/a
	Downstream value chain: use of polymers and chemicals in manufacturing of various goods	• Existing production processes barely impacted	N/a

The Methanol Institute estimates that 0.5 to 1 job is created per kilo tonne/year of production capacity.[48] This includes direct jobs at the production facility and indirect jobs, such as in logistics and external support services downstream. These coefficients have been used to estimate the number of permanent jobs that could be envisaged with the launch of the methanol production facility under the CCU hub. The pilot plants will create between 25 and 45 new jobs, while the large-scale facility, with annual capacity of 187 ktonnes, will require between 100 and 180 people to be employed. In addition, the maintenance of the electrolyser feeding hydrogen to the methanol synthesis will also create 4-6 additional jobs at ENGIE. Construction and installation phases can create 500-700 temporary positions.

Job-creation due to the shift to methanol-based fuel is not very promising in the water transport sector. Vessels will not need additional crew, but may need to retrain existing staff. The current fuelling facilities need little to no adjustment in converting from traditional fuel to methanol, according to the experts. The North Sea Port stakeholders envisage a few additional fuelling facilities for methanol which lead to a few temporary jobs. However, refurbishment of the vessel engines to use methanol would require engineers and technicians, thus creating temporary jobs.

In the ethanol value chain, as presented in baseline scenario (according to the Steelanol project assessment) 20-30 permanent jobs are to be created directly at the facility and in connection to steel processes. In addition, around 500 temporary jobs will be created during

[48] Estimates from Goerge Olah methanol plant are slightly higher – 12 permanent jobs for a pilot plant of 4000 tonnes/year capacity, which gives 3 jobs per 1 kilo tonne/year. This can be explained by the small size of the plant. With larger scale facilities economies of scale are normally observed.

the construction and installation phase. A few jobs are likely to be created at the companies blending, distributing or exporting transport fuel due to a significant (~33%) increase in the supply of ethanol.

The Steel2Chemical project has estimated that in the CCU-based chemical and polymer production per 100 tonnes of CO2 avoided annually, 25 direct and 25 indirect jobs will be created. Dow representatives estimate an additional 50 to 100 jobs will be created at its steelmaking facility thanks to the CCU connection. These jobs will be associated with operations such as CO and C2 separation, production of synthetic naphtha, syngas conversion, etc. There are also many temporary positions that can be associated with the construction and installation activities.

Furthermore, it is also safe to envisage that there will be **no existing job losses** as a result of new production lines in each of the value chains because the technologies in each of the three value chains do not disrupt the existing structures of the steel mill, nor eliminate any elements. The same is envisaged in the plant in the North Sea Port.

- ***Linkages and partnerships***

The ongoing projects around establishing all three value chains have been associated with extensive collaboration across different industries and organisations from other countries. Local steelmaker ArcelorMittal is a central node in these partnerships and the main driver of the CCU-focused R&D, experimentation and piloting. Other key local industrial players here are chemical industry leader Dow and energy producer ENGIE. Initiatives aimed at promoting the three CCU value chains also employed the services of a number of local and international players, including technology providers, suppliers of equipment and solutions, public authorities, researchers as well as the potential consumers.

Box 3: Stakeholders that engaged in partnership under projects addressing specific value chains

CO to ethanol	CO to chemicals and polymers	CO2 to methanol
Steel mill plant – Arcelor Mittal	Steel mill plant – Arcelor Mittal	Steel mill plant – Arcelor Mittal
LanzaTech – ethanol fermentation technology provider	Dow – chemical company	ENGIE energy company
Primetal technologies	Ghent University	Ghent University
E4Tech	Institute for Sustainable Process Technology (ISPT)	City of Ghent
North Sea Port	North Sea Port	North Sea Port
POM Oost Vlaanderen	TNO.ECN	POM Oost Vlaanderen
University of Lille	University of Lille	Bio Base Europe Pilot Plant
	Tata Steel	Capture

These initiatives were brought together through several funded R&D and piloting projects, namely Steelanol[49], Carbon2Value[50], and Steel2Chemicals[51], and constitute the CCU hub regional initiative.

In addition, as part of the technical implementation of facilities, other companies have provided specific services or equipment (e.g. in ethanol plant's construction Sulzer distillation equipment supplier, Egger pumps supplier, Fluence Corporation wastewater treatment and waste-to-energy systems supplier were involved). Boeing, Virgin Atlantic, Mitsui have expressed interest as well.

- ***Strengthening the local knowledge base***

Case study analysis has demonstrated that CCU technologies and initiatives can help to build the local knowledge base, strengthen research teams at the companies and local research organisations, contribute to frontier expertise, and foster research collaboration with foreign partners. This is also because the initiatives have been largely R&D oriented, thus focused on creating new knowledge and innovative results. Piloting and demonstration activities, such as in the George Olah methanol plant and Covestro pilot facility for polyol production, have helped to build practical knowledge and new product- and market-related knowledge.

In the context of the North Sea Port's fostering of CCU, all initiatives around the three value chains have until this point also been focused on research, experimentation, testing and piloting. This has surely resulted in new knowledge, in some cases, in unique research results and strengthened expertise of those involved, including industry and academia. As already mentioned in the baseline scenario, the presence of the strong research and innovation cluster in biotechnology, as well as a strong overall chemical research community in the region (as well as in the whole of Flanders) can stimulate learning and knowledge spill-overs from the demonstration project(s), in particular through scientists involved in the Capture initiative at Ghent University[52], VITO and University of Antwerp, and the R&D community at the Ghent Bio-Economy Valley, and Bio Base Europe Pilot plant.

In most of the studied cases, high-level research staff and engineers have been attracted to the initiatives for research, piloting, and commercialisation, which represents a brain gain for the local economy. In the ethanol case, it has brought the unique technology and expertise of LanzaTech and other technology providers to the NSP. R&D projects focused on CCU have brought expertise from France (Lille University) and The Netherlands (TNO.ECN) that complemented the expertise of local partners.

In the long run**, it is uncertain** if the commercial-scale implementation **will attract highly skilled professionals** from outside the region and country, or whether the local pool of professionals will be sufficient to maintain the facility.

- ***Visibility and image***

All ongoing CCU initiatives have helped to build a positive image for the region as a leader in CCU. This can be helpful in attracting new investment and new CCU technology leaders to the region.

49 http://www.steelanol.eu/en

50 https://www.carbon2value.be/en/

51 https://ispt.eu/news/steel2chemicals-paving-the-road-for-reducing-millions-of-tons-of-co2-emission/

52 https://capture-resources.be

4.2.2.3 Innovation impact

- ***Technical and technological advancement***

All case studies reported an accumulation of technical expertise among actors directly involved in the projects due to the CCU experience. R&I, demonstration and testing activities led to valuable lessons that will be helpful in setting and managing the commercial-scale facilities.

There is an agreement that all R&D, piloting and the commercial plant establishment work under the methanol initiative, Steelanol, Carbon2Value, Steel2Chemicals projects and other relevant initiatives in the region have contributed to the advancement of the CCU technologies. For example, the ethanol project has undertaken significant work on adjusting, improving and implementing outside (foreign) technology at various segments of the CO to ethanol value chain. Other projects have helped to design efficient CO and CO2 separation technologies that are essential for securing the quality of the inputs to and outputs from CCU processes. The Dow synthetic naphtha example is a case in point.

The ethanol project has put the region on the map as a European and global pioneer in the deployment of CCU-based ethanol production technology. As already mentioned in the baseline scenario, it is a clear transfer of foreign technology case. In other case studies, the technology has been developed locally.

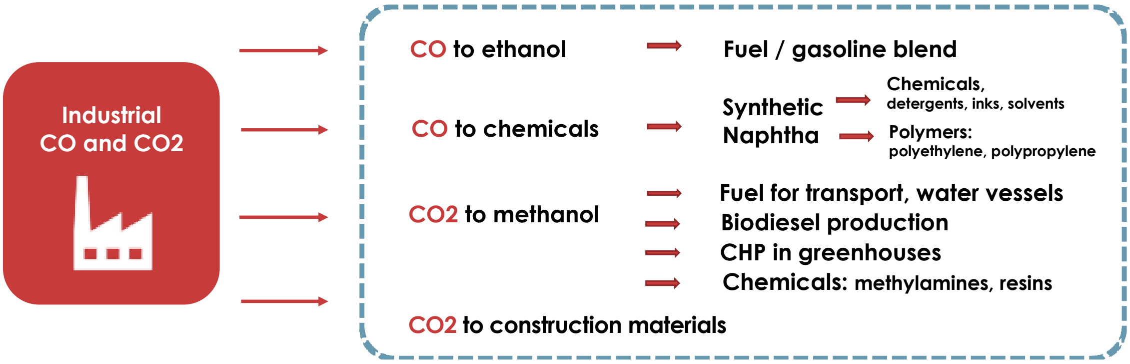
All case studies reported work on patents for their inventions, which resulted from their long-term R&D activities on CCU solutions.

- ***Capabilities of local companies***

It is desirable that the innovative projects and technology implementation also impact local companies on upstream or downstream value chains to upgrade their capabilities. However, in the analysed case studies not much has been reported on the impact on local entrepreneurship development (e.g. in downstream value chains, emergence of research spin-offs or wider innovation spill-over to other companies in the regional industrial clusters). This might be due to the fact that many of the technologies are still in development, testing, etc. With further rollout of the CCU technologies, more active development of the entrepreneurial ecosystem might emerge.

With the assumption that the technological and learning spill-over effect is more likely in the larger-scale commercial projects, the experience of the ethanol plant launch has been studied, with local contractor involvement observed in its construction. This involvement, in itself, has not generated any specific impact on local companies in terms of increasing local technological capabilities, etc. The construction followed the specifications and plans, and did not warrant many non-standard or complex technologies or processes. The technology providers discussed above come from outside Belgium (US, Switzerland, etc), thus no significant direct impact on the capabilities of the local companies at the construction stage has been observed.

4.2.3 *Scenario 2: CCU hub with all value chains*



This scenario includes all value chains discussed in the previous scenarios, as well as the additional CCU opportunities that are currently not being discussed in relation to the CCU hub initiative. These are the carbonation of construction materials value chain, as well as an alternative downstream use for methanol in biodiesel production, the combined heat and power (CHP) generation for greenhouses, and the production of methylamine and resins for the chemicals market.

This scenario assumes the cumulative impact of all value chains considered here, which means its impact will be higher than in the baseline and in Scenario 1 analysed above.

All interview consultations have fed the analysis in this scenario. Observations, lessons and insights on impacts from the following case studies have been used:

Case studies	*Value chain covered*
Shougang LanzaTech fuel ethanol plant (China)	**CO to ethanol fuel**
CO2-based polyol production at Covestro (Germany/Belgium)	**CO2 to polymers**
Technical photosynthesis of butanol and hexanol in the Rheticus project (Germany)	**CO and CO2 to chemicals**
George Olah Renewable methanol plant (Iceland)	**CO2 to methanol**
CO2-based chemical production at Thyssenkrupp (Germany)	**CO2 to methanol and other chemicals**
CO2 mineralisation in construction materials Orbix (Belgium)	**CO2 mineralisation**

4.2.3.1 Economic impact

- ***Competitiveness***

The above scenario analyses have shown that the competitiveness of CCU-based products differs; e.g. ethanol has shown to be competitive in the current market, while CCU-based methanol, chemicals and polymers are still subject to higher production costs which pushes the price up. Case studies have also shown that special arrangements for procurement and promoting the product's green image, as well as advantageous product qualities could address the premium price issue and improve the business case for the product.

In the CCU-based construction materials case, Orbix's Carbstone offers a solid business case. It applies carbon mineralisation technology using waste slag and CO2 emissions from the steel industry. Recognition of Carbstone construction materials within the emissions trading market as a carbon sink or so-called 'CO2 negative' product would add significant weight to this business case.

Carbstone has been going through R&I and testing with efforts focused on launching the pilot production facilities in Belgium, and eventually bringing the product to market. According to the technology providers, the product will have better qualities than the traditional alternative. The StapSteen project[53] implemented in the city of Ghent has also tested and validated Carbstone pavement blocks. The technology has won several international awards and there is growing interest from industry and investors.

With the Belgian construction sector seeing over 30% growth since 2010 and the outlook for this market generally positive[54], manufacturing CCU-integrated materials such as Carbstone at the North Sea Port could be economically promising. With the launch of building materials like floor tiles, building blocks, pavers, bricks, briquettes etc, as well as the CO2 binding filler and granulates[55], **the value added to the local economy could be between tens to hundreds of millions of euro per year.**

Another set of opportunities discussed in this scenario is the use of CCU-based methanol beyond that envisaged in Scenario 1. These include:

- Use in production of biodiesel
- Use as an input to synthesise methylamines
- Use in the combined heat and power (CHP) generation in greenhouse systems

Biodiesel and methylamines are already being produced in the North Sea Port zone. The Cargill Bioro biodiesel refinery[56] produces 250,000 tonnes/year and the Oleon-Bioediesel plant[57] refines 100,000 tonnes/year. Eastman-Taminco is the largest European producer of methylamines (mono-methylamine, di-methylamine, and tri-methylamine) with capacity of around 150,000 tonnes/year[58].

To produce 10 tonnes of biodiesel roughly 2 tonnes of methanol is required. Cargil Bioro and Oleon-Biodiesel would thus need around 50,000 and 20,000 tonnes/year of methanol respectively. For the methylamines production at Eastman-Taminko approximately 200,000 tonnes/year of methanol would be required[59]. These companies are promising markets capable of absorbing all envisaged volumes of CCU-based methanol (187,000 tonnes/year from full-scale plant and 46,000 tonnes/year from the pilot plant).

The application of methanol in CHP generation for greenhouses has not been tested. However, some positive experience on use of methanol in electricity and power generation has been successfully demonstrated[60]. The scale of the methanol-based CHP in greenhouse horticulture in the region[61] depends on many factors, including cost efficiency, regulatory pressure to control other air pollutants, and the willingness of farmers to adjust to a new fuel. According to

53 https://vlaanderen-circulair.be/nl/doeners-in-vlaanderen/detail/stapsteen-naar-een-circulaire-stad

54 The European Construction Observatory: https://ec.europa.eu/growth/sectors/construction/observatory_en

55 See products variety https://www.orbix.be/nl/materialen/carbinoxr

56 https://www.cargill.com/agriculture/bioro-biodiesel-refinery

57 http://www.fbbv.be/en/members/oleon-biodiesel

58 https://www.fsma.be/sites/default/files/public/prospectus/2010/2010-%281085%29-EN-EMS20091307-A02-B01-C01-NP-CD19_01.pdf (see page 78)

59 Based on Mansouri et al. (2012) estimates of mass balance

60 See https://www.methanol.org/power-generation/

61 *Greenhouse horticulture in Belgium is mainly focused in Flanders, which has about 1,930 hectares spread out over 1,514 companies (food and floriculture). Greenhouses are found all over Flanders, with a notable concentration in Antwerp (847 hectares) and in East and West Flanders (426 and 471 hectares respectively). East Flanders has about 360 greenhouse companies.*

the regional Proefcentrum voor de Sierteelt, the majority of greenhouses in Flanders use CO2 to boost plant growth. Some greenhouses get the CO2 gas delivered, others take it from their own heating system. The latest best practice for greenhouses in Flanders is through CHPs that provide heat, electricity and CO2 for plant stimulation – an energy efficient option which is favoured by public subsidies, making investment in CHP attractive[62]. As carbon and other emissions regulations tighten, shifting from traditional fuel (diesel, natural gas) to CCU-based methanol could be a climate-neutral solution for the sector.

As discussed in Scenario 1, price may be an issue for potential buyers of CCU-based methanol. However, the detailed analysis of the business model, potential savings in delivery cost, and other factors may yet prove the economic feasibility of this application.

Integration of CCU-based methanol in biodiesel and methylamine production, as well as the adoption of methanol-based CHP in greenhouses in the region is not expected to add a great deal to revenues, thus **the net value added to the economy will be insignificant**. However, it can contribute to the goal of making the region more independent in terms of **materials and energy** (i.e. substituting imports for locally recycled products). It can also help in diversification and therefore strengthening of the CCU-based methanol market.

- ***Wider economic benefits and costs***

The greatest **economic benefits** generated on the downstream segments of the value chain in this scenario are likely to come from additional opportunities generated in downstream chains.

In the construction materials case, companies using novel CCU-based materials could benefit from their better performance and durability, which generates savings in the long run (e.g. in public infrastructure like roads, pavements, bridges), while helping to permanently lock down carbon emissions. Downstream companies in construction value chains are not likely to incur any major adjustment costs moving to CCU-based construction materials. Comparable pricing for these materials also means no additional costs for end-users.

The economic impact on consumers of the biodiesel and methylamines value chain is not likely to be prominent, as producers of these products will likely absorb any cost fluctuations internally and follow the traditional market price when selling their product.

As for greenhouses, there will be a cost related to switching to the new fuel and new CHP systems. However, subsidies currently available for greenhouses make installing new methanol or dual fuel CHP systems a promising option.

4.2.3.2 Social impact

- ***Employment creation***

While the discussion and estimates for employment creation under Scenario 2 are valid for this scenario, the additional estimates are added for value chains covered in the analysis. Table 5 below presents estimates for all value chains considered for is scenario.

Use of CCU-based methanol in biodiesel and methylamines production will not assume any technical changes in production processes, therefore **no additional jobs** will be created.

Similarly, in greenhouse farms, the shift to methanol fuel in CHP systems **will not create additional jobs**, nor would installation of new CHPs require dedicated full-time technicians. On the side of the CHP technology providers, one does not expect new employment, but rather an upgrade

[62] https://www.freshplaza.com/article/2149576/belgian-greenhouse-horticulture-constantly-developing/

of technicians' skills along with adjustments to systems so they can operate on methanol. One can envisage some additional work for greenhouses that have already installed CHP (converting them to dual fuel so they can use methanol). These, however, **will create short-term jobs only**.

In the CO2 mineralisation case, the scenario envisages a new facility for construction materials close to the steel production plant and use of steel slag in the production of these materials. There are no specifications on possible capacities of the new facility, but the available streams of secondary materials at ArcelorMittal's industrial site are sufficient for any sized facility. Depending on the scale of a new facility, the **number of new direct and indirect jobs to be created there can range from 30 up to 100**. This includes jobs directly within the facility (carbonation, manufacturing), but also at the logistics work (sourcing and channelling input materials and CO2, as well as transporting the final product). Construction and installation of the new facility will create **between 80 and 150 temporary jobs** lasting from a few months to a couple of years. On the users side no new jobs are envisaged.

As with Scenario 1, **no existing job losses are envisaged** as a result any new value chain launch. The new technologies will not disrupt the existing technological structures of the steel mill, thus not affecting any segment of the existing chain.

Table 5 Estimates of potential new employment creation under Scenario 2 (additional value chains added in coloured cells)

Value chain		Permanent jobs	Temporary jobs
CO2 to methanol	**New methanol plant:** • **Pilot – 46 ktonnes/year** • **Commercial scale – 187 ktonnes/year**	• At pilot plant – 25-45 jobs • At commercial plant: 100-180 jobs (direct and indirect jobs)	• Construction and installation ~500-700 jobs (over 3-4 years)
	Electrolyser (ENGIE) • **Pilot – 63 MW** • **Commercial – 300MW**	• Pilot – 1-2 jobs • Commercial scale – 4-6 people	
	Downstream value chain 1: use of methanol fuel in water shipping	• No new jobs in vessels, but retraining of existing stuff • No new jobs in fuelling facilities due to switch to methanol	• Jobs in ship engine modification
	Downstream value chain 2: use of methanol in biodiesel production	• No new jobs, but greening of the existing jobs at Cargil Bioro and Oleon-Biodiesel	• N/a
	Downstream value chain 3: use of methanol in methylamines production	• No new jobs, but greening existing jobs at Eastman-Taminco	• N/a
	Downstream value chain : use of methanol fuel in CHP in greenhouses	• No new jobs in greenhouses • retraining of the existing CHP suppliers	• Possibly limited number of jobs in the existing CHP system modification towards dual fuel
CO to Ethanol	**New ethanol plant**	• 20-30 jobs at the facility (direct jobs)	• Construction ~ 500 jobs (over 3 years)
	Downstream value chain: fuel distribution	• 3-10 jobs at fuel distribution companies (indirect jobs)	• Likely none
	Synthetic Naphtha production facility	• 50-100 new jobs (direct and indirect jobs)	

Value chain		Permanent jobs	Temporary jobs
CO to chemicals and polymer	**Syngas conversion**		• Installation ~150-250 new jobs (over 2-3 years)
	CO and CO2 separation		
	Chemical and polymer production	• No new jobs, but greening the exiting jobs at Dow	N/a
	Downstream value chain: use of polymers and chemicals in manufacturing of various goods	• existing production processes hardly influenced	N/a
CO2 mineralisation in construction materials	**New plant for production of carbonated construction materials**	• 30-100 new jobs depending on the scale of the new facility (direct and indirect jobs)	• Construction and installation ~80-150 temporary jobs (over 1-2 years)
	Downstream value chain: construction industry	• Jobs in the construction industry not influenced by the substitution of the materials	N/a

- ***Linkages and partnerships***

Scenario 1 showed that ethanol, methanol and chemicals and polymers value chains have been associated with extensive collaboration across different industries and organisations from other countries (see **Error! Reference source not found.** in the Scenario 1 section). Collaboration is the core principle of flagship projects receiving European and national funding (Steelanol, Carbon2Value, Steel2Chemicals). Indeed, the CCU hub initiative has been uniting many actors and ongoing exploration, research and piloting projects. In addition, there are a number of service and technology providers who have been involved in the installation of new facilities.

When it comes to the additional value chains considered in Scenario 2, one can envisage **new linkages and partnership to be created** while planning, testing and implementing the projects.

The launch of the CO2 mineralisation-based construction materials manufacturing will require close collaboration between at least three parties: steel mill plant, construction materials producer, and a technology provider such as Orbix. Construction, installation, logistics and other types of service and technology providers will be needed during. Experts at Orbix also noted that research and testing activities focusing on the end products' quality, health and environmental safety performance will also be important. The StapSteen project is an example of collaboration of this nature, uniting a university, city authority, research institution and private company. It is likely that the roll out of the CO2 mineralisation value chain in the CCU hub will spur other product development projects leading to the further collaboration of key players with academia and possibly with other actors.

Installation of methanol-fuelled CHP systems at local greenhouses will require several dimensions of collaborative activities. It will have to start with research and experimentation with the methanol as a fuel for the CHP for greenhouses, which could involve such actors as the research station Proeftuin Zwaagdijk[63], greenhouse farms, CHP technology providers, CCU-based methanol producers, and possibly other research partners.

[63] https://www.proeftuinzwaagdijk.nl

Commercial linkages will be established between CCU methanol producers and biodiesel manufacturers Cargil Bioro and Oleon-Biodiesel, as well as with the methylamine producer Eastman-Taminco.

- ***Strengthening the local knowledge base***

As the analysis suggests, Scenario 1 is likely to result in local knowledge base building and spill-overs to a wider research community across the region and country following the development of the new CCU value chains of methanol, ethanol, and chemicals in the North Sea Port area.

Research and testing activities in the CO2 mineralisation of construction materials will be likely to **contribute to the pool of knowledge about this technology, new materials, and optimisation** of the process. As discussed above, it is likely that the rolling out of this value chain will be associated with experimental projects focusing on the development of new construction materials. It is common that such projects involve academic researchers which further contributes to science.

While promoting methanol-fuelled CHP in greenhouses and CO2-mineralisation-based construction materials production, new knowledge will be generated through **experimentation, research and testing activities**, as discussed above. The application of methanol in CHP generation is still rare and testing this in greenhouse conditions and in combination with CO2-aided plant growth will likely be a first experimental research project of this type. The evidenced and lessons from this project would be useful to boost greenhouse horticulture and reduce its carbon footprint.

As discussed in Scenario1, **one cannot guarantee that the CCU rollout will result in massive brain gain** (i.e. attracting highly skilled professionals from outside the region and country). The analysed cases studies and ongoing piloting CCU activities in the North Sea Port zone have not demonstrated this impact strongly. Introducing methanol-fuelled CHP in greenhouses and CO2-carbonisation value chains are not that promising in this regard. The region is likely to offer a **sufficient pool of local professionals** for commercialisation and long-term maintenance of various CCU value chains.

- ***Visibility and image***

It has been noted that all ongoing CCU initiatives have been contributing to the North Sea Port area and East Flanders' **visibility and image as a leader in CCU** promotion. Further rollout of the CCU hub will be helpful in attracting new investment and new CCU technology leaders to the region.

4.2.3.3 Innovation impact

- ***Technical and technological advancement***

Scenario 1 showed that all R&D, piloting and commercialisation activities with CCU technologies in the North Sea Port area have been contributing to the advancement of CCU technologies. All case studies reported the accumulation of strong technical expertise due to experience with the CCU projects by actors directly involved in these projects. A transfer of foreign technology is being demonstrated by a CCU-based ethanol plant constructed in the port area, while in the chemicals and polymers case, local technology development is being observed. Many R&I activities (thanks to long-term research projects) also resulted in patents and innovation.

As for the CO2 mineralisation case, although Orbix technology has been tested and demonstrated its viability, it has not yet achieved commercialisation. Through the R&D and testing activities the technology has been brought to TRL 8, where the prototype system has been successfully tested. As discussed above, rolling out this value chain is highly likely **to spur**

development of a wider set of construction-based CCU which would be suitable for application in many more areas of the economy.

Another important note is that the Orbix technology has been developed in Belgium and it is recognised as one of the best in a group of similar technologies. Promotion of this technology and support in its commercialisation would mean strengthening the technological leadership of the country in this specific area.

In the methanol fuelled CHP case, it is highly likely to be **a pioneering project,** bringing in several sustainable solutions together (CHP, CCU fuel, CO2 enrichment by plant), and applying it in the greenhouse horticulture context.

- ***Capabilities of local companies***

The case studies and experience with the CCU value chains piloted in the North Sea Port area **have not massively impacted local entrepreneurship** (e.g. in downstream value chains, emergence of research spin-offs or wider innovation spill-over to other companies in regional industrial clusters). It remains rather targeted and confined in terms of outreach developments in this area.

Nevertheless, some stakeholders consulted in this study entertain the **possibility that further CCU technology rollout might result in the emergence of an entrepreneurial ecosystem around the North Sea Port zone**. More systematic and scaled up development of the CCU hub, diversification of CCU value chains, including CO2 mineralisation in construction materials, new applications in the greenhouse horticulture sector, as well as other new value chains might well foster entrepreneurship and start-ups in this technological area.

It was also mentioned that putting the CCU initiatives within wider programmes on industrial symbiosis development might help to achieve better results in building a stronger entrepreneurship ecosystem in the region.

4.3 Comparative summary of scenarios

The summary of impacts envisaged under each scenario is presented in Table 6 below.

The scale of the impact in each scenario would differ due to the technological scope and number of value chains covered. Each value chain considered in this study comes with a certain value in increasing social and economic benefits. It is clear that the value chains with products not currently represented in the regional economy can bring the largest value added, as there will be benefits created on upstream and downstream segments. Namely, methanol is likely to be the most impactful value chain, but at the same time most complex in terms of technical implementation. Products that already have their market (ethanol, chemicals/polymers, construction materials, biodiesel, methylamines) will face fewer challenges, but some would still need to overcome competition from traditional alternatives which are cheaper in some cases. Combining these value chains can yield a cumulative impact and determine how complex and viable each scenario is likely to be.

The analysis clearly demonstrates that the **positive socio-economic impact of the last scenario is the highest**. However, the **cost and complexity of this scenario is also the highest**.

Table 6 Comparison of impact scale across scenarios

	Baseline One value chain	Scenario 1 Three value chains	Scenario 2 Four value chains and extra downstream options
Economic impact			
Competitiveness	+	+++	++++
• Competitive/commercially viable new value chain	*Highly competitive*	*Medium to high*	*Medium to high*
• Value added to local economy	*65-110 mln eur/year*	*110-160 mln eur/year*	*150-250 mln eur/year*
• Arrival of new companies to the regions	*Low*	*Low*	*Low*
• Increased interest from investors, new/envisaged investment flows	*Medium*	*Medium to high*	*Medium to high*
• Higher energy and resource independence	*Low*	*High*	*High*
Wider economic benefits (+) and costs (-)	++/0	++/-	+++/-
• New revenues, profits, savings for consumers and other companies	*Medium*	*Medium to High*	*High*
• Extra cost for consumers, negative economic externalities	*None*	*Medium*	*Medium*
Social impact			
Employment	++	++++	+++++
• New jobs created	*~ 23-40 permanent jobs* *~500 temporary jobs*	*~180-325 permanent jobs* *~1150-1250 temporary jobs*	*~210-425 permanent jobs* *~1200-1600 temporary jobs*
• Old jobs lost	*None*	*None*	*None*
Linkages/partnership	++	++++	+++++
• New partnerships created within and across industries	*in 1 VC* *(up to 8 partners)*	*In 3 VC* *(~20-25 partners)*	*In 4 VC* *(~up to 40 partners)*
Fostering local knowledge base	+++	++++	+++++
• New knowledge, better expertise	*1 VC, no diverse downstream*	*3 VC related expertise*	*4 VC – related expertise + wider downstream options*
• Knowledge spillovers	*Medium to high*	*High*	*High to very high*
• Brain gain in the region	*None or limited*	*None or limited*	*None or limited*
Image and visibility of the region	++++	+++++	+++++
• Positive impact/ Recognition of leadership	*Medium to high*	*High*	*High*
Innovation impact			
Technological advancement	+++	+++++	+++++
• Improvement of technology and process	*In 1 VC and associated technologies*	*In 3 VC and associated technologies including shared ones*	*In 4 VC, wider downstream options, and associated technologies including shared ones*
• Technological leadership	*Medium*	*High*	*High*

	Baseline **One value chain**	**Scenario 1** **Three value chains**	**Scenario 2** **Four value chains and extra downstream options**
• TRL progression	*In 1 CV* *TRL 8-9*	*In 3 VC* *TRL between 4 and 9*	*In 4 VC* *TRL between 4 and 9*
• Technology transfer	*Yes*	*Only in 1 VC, rest local technology development*	*Only in 1 VC, rest local technology development*
Capabilities of local companies	***0***	**++**	**+++**
• Innovation, new services by local companies	*None*	*Likely yes*	*Highly likely yes*
• Creation of start-ups, spinoffs	*No impact*	*Likely yes*	*Likely yes*
Feasibility			
Cost	*150 mln eur*	*300 – 400 mln eur*	*400-500 mln eur*
Complexity and technical challenges	*Resolved*	*Attracting CO2 to methanol technology owner* *Secure renewable energy supply*	*Attracting CO2 to methanol technology owner* *Secure renewable energy supply* *Engaging construction material manufacturer*

A more concise overview of the comparative analysis based on the table above is presented in Table 7 below.

Table 7 Summary of impact comparison across scenarios

	Baseline	**Scenario 1**	**Scenario 2**
Economic impact			
Competitiveness	**+**	**+++**	**++++**
Wider economic benefits (+) and costs (-)	**++/0**	**++/-**	**+++/-**
Social impact			
Employment	**++**	**++++**	**+++++**
Linkages/partnership	**++**	**++++**	**+++++**
Fostering local knowledge base	**+++**	**++++**	**+++++**
Image and visibility of the region	**++++**	**+++++**	**+++++**
Innovation impact			
Technological advancement	**+++**	**+++++**	**+++++**
Capabilities of local companies	**0**	**++**	**+++**
Feasibility			
Cost	**150 mln eur**	**300 – 400 mln eur**	**400-500 mln eur**
Complexity and technical challenges	+++	++++	+++++

5 Conclusions and recommendations

Promotion of large-scale industrial initiatives requires solid justification from environmental, economic and social development points of view. The CCU hub initiative that is being launched in the industrial zone of the North Sea Port is one of the most ambitious carbon capture and utilisation initiatives in Europe. Today, when economic prosperity has to be assured in conjunction with social and environmental sustainability, the big challenge is in making the right decision on actions and investment. In the context of the North Sea Port, as well as East Flanders development, this means that the CCU hub is expected to help sustain the local economy, create new jobs, foster economic and innovation linkages, while helping the local industries to reduce their carbon, as well as broader environmental footprints.

The present study has tried to analyse how much the planned ideas and piloted projects would be able fulfil the expectations put upon the CCU hub initiative. The study is forward looking and based on lessons of other CCU projects in EU and globally. Considering that the CCU practice is still new and in many cases technologies and value chains are in the R&D and piloting stage the evidenced of actual impacts and lessons from the real practice examples are still scarce. This study largely relied on the consultation with the stakeholders engaged in the CCU projects in the EU and beyond and their analysis and assessments of the impact that can be generated.

5.1 Key take aways

In the **economic impact** dimension, the key observations and conclusions are the following:

- Estimates and economic forecasts in this study have demonstrated that implementation of the value chains of CCU-based methanol, ethanol, chemicals/polymers and construction materials can result in *€150-250 million annual value added to the local economy*.
- *The competitiveness* of most of the CCU-based products under current conditions is likely to be challenged by higher production cost and therefore the higher market price. The premium price challenge is especially highly relevant for the methanol, chemicals, polymer cases. However, some business cases are secured by creating protected markets such as in China where state guarantees procurement of all CCU-based ethanol produced in the LanzaTech plant, or with special clients who are ready to pay a premium price, such as methanol from CRI George Olah bought by gasoline and biodiesel companies in the UK, Netherlands, Sweden and Iceland, in the example where CO2-based polyol was purchased by a mattress manufacturer, Recticel.
- Current examples of projects are still small and *struggle to secure resources or energy independence* from a region or country. But this should change for the better with upscaling and larger scale production. For instance, at Dow the deployment of the CCU technologies and production of synthetic naphtha from the local steel blast furnace gases would be able to offer a significant decrease in dependency on naphtha supplies from oil refineries. Similarly, switching from traditional fuel to methanol by ships hosted by the North Sea Port would be able to decrease reliance on fossil fuel. For biodiesel producers (Cargill Bioro and Oleon-Bioediesel) and methylamines producer (Eastman-Taminco), up to 80-90% of methanol supply can be replaced by the CCU based methanol,
- There are very few commercial-scale examples of CCU. The CCU initiatives currently implemented in different parts of the world are mostly smaller in scale (i.e. R&I, pilot or demonstration projects). The small scale of these initiatives has not allowed the *emergence of new business ecosystems*. However, it is believed that larger-scale commercial production is very likely to generate impact in downstream parts of value chains where

other companies will start using CCU-based materials/chemicals in their production lines, or introduce new products.

- There is an increasing *interest from private investors* in CCU-based product-oriented businesses. Most of the companies that brought the technology into the market began as start-ups and managed to attract significant investments (e.g. LanzaTech is one of the fast-growing cleantech companies, as well as CRI, and Orbix,). Regions piloting such businesses can also benefit from private investment (venture capital, etc.) if they can show an interesting and convincing business idea.

In the **social impact** dimension, the following is found:

- Estimates in this study have demonstrated that launching all viable value chains (CCU-based ethanol, methanol, chemicals/polymers, construction materials) considered in this study will result in *200 to 425 new permanent jobs* at the industrial facilities, related services, upstream and downstream segments, as well as *1200 to 1600 temporary jobs* related to construction and installation. At the same time, there is evidence that no jobs would be lost and some jobs will even be 'greened over'.
- *Fostering cross-industry linkages* is at the core of the CCU. At the minimum, bilateral links are established between CO or CO2 sources (e.g. steel company) and a partner converting the CO and CO2 into new materials (e.g. chemical company). More complex networks are being established in methanol production where, for example, a renewable energy supplier enters the network; meanwhile the local biodiesel and chemical companies, greenhouse farms or water shipping companies can enter as consumers of the CCU based methanol; and in carbonated concrete production, construction companies enter the network. Other types of companies could be specific technology providers, logistic companies, gas pipeline owners, various service providers, water and waste companies, fuel distributors, export companies, etc.
- *The image and visibility* of the region and the North Sea Port is among the other positive impacts of hosting CCU projects. In light of the increased ambitions in climate change policies this is an important element in overall regional and national efforts towards reaching the climate targets.

Technological and innovation impact is another dimension of socio-economic impacts:

- *Technological advancement* is often reflected in the technological leadership status obtained by a region, or a company, or a CCU cluster. Many CCU projects are pilots or experimentations which allowed their technologies to progress in TRL scale. New patents are filed under many CCU initiatives. Technology transfer is another impact that has been observed in some projects (e.g. LanzaTech bringing CO to ethanol technology).
- *Fostering knowledge* in the region is seen in all CCU projects. Many of them stem from innovative initiatives that helped to strengthen the knowledge base in the region and even attract highly qualified experts. Involving local knowledge organisations has been seen in many projects where they are engaged in experimental or monitoring work.
- *Innovation spill-overs,* such as the increased capabilities of other companies, are not always observed but can be potentially expected of the companies represented in the downstream value chain when they start adapting to new input materials and retrofitting their equipment. It was noted that often, with the regulation push towards more sustainable processes, investment is done also in overall modernisation and enlargement of facilities.

5.2 Policy recommendations

This study has demonstrated that the environmental, economic and social benefits of the CCU technology deployments could be promising for the local economy, while their wider diffusion can offer solid input towards addressing global climate change imperatives. This study, however, also showed that there are a number of obstacles that prevent the CCU initiatives from easily and quickly penetrating the current industrial and economic systems. Addressing these obstacles would need favourable framework and market conditions that can be created by carefully designed policy measures and incentives.

With the proliferation of the circular economy in the EU there are growing calls for carbon removal via re-use and storage in products[64]. Yet, CCU is still not well understood and embraced by a wider policy and economic community and often not regarded as a promising approach for GHG reduction. There are several challenges that prevent the CCU technologies to gain wider diffusion in the market:

- Economic barriers related to the cost of CCU technologies and products.
- Technological challenges requiring further improvements, testing, piloting, research and innovation.
- Ambiguity and lack of understanding of CCU technologies' environmental performance.
- Policy barriers that are mainly due to uneven playing fields, lack of favourable framework conditions and limited political support.

These obstacles are interlinked and to great extent reinforce each other, which means resolving them would require a **comprehensive approach**. Addressing these obstacles would need favourable framework and market conditions that can be created by carefully designed policy measures and incentives. A major policy signal has to come from the EU regulatory landscape where international regulatory framework also needs to be contextualised. National and regional policies are also important in setting local and national ambitions and strategies and driving the local actions.

Below are policy recommendations addressing challenges faced by CCU technologies in the EU. They have been generated based on consultation with stakeholders, lessons from the analysed case studies, as well as suggested in the analytical reports on CCU reviewed in this study.

5.2.1 Recommendations addressing economic challenges

Economic challenges are faced by many new technologies arriving on the market, and especially for green technologies as often the environmental sustainability mission does not immediately translate into commercial viability. Economic obstacles faced by CCU projects are related to (i) high price of the product and (ii) high investment cost of CCU projects.

(i) Price competitiveness of the CCU products

Today, the majority of CCU products produced with captured CO/CO2 are more expensive than traditional chemical synthesis routes so it is difficult to compete with conventional products. As shown in the analysis in this study, price competitiveness remains an issue for all types of CCU products, except for the CCU-based ethanol price that is expected to be comparable to the traditional ethanol production, including the ones produces for biofuel purposes. The current low prices for fossil resources acts as an obstacle to the competitiveness

64 COM(2020) 98 final, A new Circular Economy Action Plan: For a cleaner and more competitive Europe, Brussels, published on 11 March 2020

of CO_2-based products. High price might also block demand for CCU products, although the study has shown that there are customers ready to pay premium prices for greener products or features of the products (e.g. manufactures of mattresses from CCU polyol, selected water transporters), but those are in a minority. A rise in prices for fossil resources and/or increased availability of renewable energy at the lowest cost possible could support the implementation of such technologies. Without creating favourable framework conditions, regulatory support, boosting or securing market interest, it will not be possible for CCU products to continue competing with cheap fossil-based alternatives.

Recommendations:

- Promote public procurement instruments for CCU-based products/services, e.g. public transport and shipping services can specify recycled carbon-based fuels in their green procurement products; construction of public buildings or infrastructure can specify procurement of carbonation-based construction materials.
- Promote other schemes that will boost demand for CCU products and fuels, e.g. setting specifications for fuel blends, carbonation-based construction materials, recognition under the local green product labelling, etc.
- Set examples to follow, e.g. public transport companies (train, water shipping) can shift to CCU-based fuel use which would create a secured market for the CCU fuel and help in further rolling out to a wider market.
- Recognise that CO_2 must have a price that induces emitters to re-use it as a resource, wherever fossil replacement technologies are becoming available. Develop mechanisms that effectively lead to a progressive increase of the price of CO_2 emissions.

(ii) High investments cost

The analysis in this study shows that under the current market and policy framework conditions CCU technologies are not profitable yet. To launch any CCU technology, large investment is needed. Furthermore, many CCU technologies and support processes such as segregation of various gases existing in the flue gas mix, need more research and testing in order to reach better efficiency. Thus, direct financial support to the research, innovation, development, demonstration, pilot and commercial projects will still be needed.

Recommendations:

- Ensure diverse EU funding schemes for upscaling and commercial projects in CCU and related technologies such as green hydrogen. Today, many CCU technologies have been developed in labs; they need incentives and direct support to move to the market.
- Dedicate special support instruments for industrial symbiosis projects. It can be a purely public funding or co-funding of the new facilities, or a combination of public and private financial instruments with favourable financing conditions.

5.2.2 *Recommendations addressing technological challenges*

The analysis in this study has demonstrated that most of the CCU value chains have not yet reached full commercialisation. Furthermore, there is rising number of promising innovations suggested by scientists and entrepreneurs, for example growing bacterial protein from waste CO_2[65], boosting algae farming with industrial CO_2[66], CO_2-based speciality chemicals[67], and numerous other examples[68]. Maturing these technologies will be key to scaling them up: making them more efficient; ensuring end-products are high quality and safe; reducing their dependence on high energy and resource inputs; and developing efficient and less costly gas separation, hydrogen production and other auxiliary technologies. Looking toward the future, in addition to continuing work on these technologies, research and innovation should be pursued for new routes to valorise industrial flue gases.

Recommendations:

- Encourage carbon-intensive industries that have little room to manoeuvre in cutting their carbon emissions, to invest, introduce and integrate carbon-recycling technologies that can also generate additional value in their local economies.
- The EU should sustain its leadership in CCU technologies by continuously supporting technology development, commercialisation, upscaling as well as R&I in novel carbon-recycling possibilities. Technological barriers that exist now can find solutions via R&I and testing efforts. All these are needed to de-risk the required CCU development trajectories, to explore alternative processes and find economic and environmental optimisations at different scales and with different process setups.

5.2.3 *Recommendations on ensuring the environmental performance of CCU*

The environmental performance of CCU technologies remains the most complex and debated issue. This is because such performance could be unique to each CCU project and depend on a combination of many factors. These factors include (i) the availability of renewable energy as a guarantee of the climate mitigation potential of CCU products that require energy for production processes, as well as (ii) lack of comprehensive LCA assessment methodology for CCU.

(i) Availability of renewable energy

The key parameter for CCU product sustainability is its climate mitigation potential which, ideally, should be higher than for conventional products. It depends on the substitution of similar products on the market made from fossil- or bio-based feedstocks; otherwise CCU products would simply create a rebound effect with more material use and CO_2 emissions. Use of renewable energy is core in defining the climate mitigation potential of all CCU products as the production process is energy intensive, and in many cases CCU chemicals and fuels are defined as power-to-X, which means they store renewable energy which would otherwise be curtailed. In the methanol production case, powering hydrogen electrolysis with wind- or solar-

65 NovoNutrients, novonutrients.com

66 https://www.treedom.net/en/blog/post/carbon-dioxide-is-becoming-fish-food-1876

67 https://corporate.evonik.com/en/technical-photosynthesis-25100.html

68 https://carbon.xprize.org/prizes/carbon

based electricity could help to mitigate the irregularities in production and use energy that is otherwise not consumed.

From the economic perspective, the CCU product while offering the climate mitigation potential, should also be competitive with conventional alternatives. This is mostly not the case as the analysis in this study shows. The *cost of renewable energy* is one of the major factors adding to production costs and reducing the demand for – and competitiveness of – CCU products against conventional products. Thus, access to affordable renewable energy sources is key a determinant for the commercial success of CCU product.

Recommendations:

- Policy and investment support are highly recommended in expanding renewable energy production, scaling up existing capacities and launching new renewable energy production capacities, which for CCU projects can be off-grid installations, however overall greening of the electricity grid should be the ultimate aim.
- Addressing the cost of the renewable energy to encourage its competitiveness against fossil-based energy should be a priority policy objective. Wider deployment is one of the ways to cut production costs and prices (which has been seen with the wind energy deployment). Redistributing fossil fuel subsidies[1] to support renewable energy development, as well as using carbon tax revenues for investment in clean energy production facilities, could also be part of the policy support package.

(ii) Lack of a commonly recognised, comprehensive LCA assessment

Poor understanding of the environmental benefits and associated footprints – and of the economic returns that CCU projects can generate – are barriers to their eventual development and acceptance. There could be multiple approaches for assessing environmental benefits and impacts using various sets of parameters.

The most commonly used parameter in the CCU context is greenhouse gases emissions (GHG) savings, CO2 being the most prominent. To date, there are still no reliable estimates for the total actual implementable saving of GHG emissions via CCU technologies, due to the fact that the usable emissions described do not correspond with the actual saved emissions: the emissions savings can vary greatly, depending on the employed technology (i.e. can be smaller or larger than the amount of used CO2 emissions, depending, in particular, on the energy to be spent during the process and the emissions associated with that). It is even possible that an increase in emissions will occur. Therefore, a full individual life cycle assessment is necessary to identify the environmental effects of each technology application[69].

Other parameters used in the environmental impact assessment of CCU products can include air and water pollution, energy efficiency, material efficiency, impact on ecosystems, water and land footprints, etc. These impacts, however, are scarcely addressed in CCU related LCA. Furthermore, benchmarking against the environmental footprint of alternative products is not well addressed. For example, there is an emerging debate about offering CCU fuels an even playing field with biofuel because biomass production puts more pressure on the environment

[69] EC 2019, Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects by Ramboll, the Institute for Advanced Sustainability Studies, CESR (Centre for Environmental Systems Research at the University of Kassel, CE Delft, and IOM Law, January, 2019

due to vast land use and impacts on ecosystems, whereas fuel from CO_2 recycling requires no land[70]. Therefore, the need for a comprehensive assessment is increasingly stressed.

Recommendations:

- Development of a comprehensive LCA guideline for assessing the environmental impact of CCU projects, as well as common recognition of methodologies across Europe and possibly internationally need to be facilitated on an EU level. For CCU, it is necessary to calculate the CO_2 avoided rather than the CO_2 used in the process. The methodology should focus not only on climate mitigation and GHG reduction, but also cover other impacts related to ecosystems, water, land use, air, energy, materials and waste.
- LCA results should become a basis for fair recognition of CCU technologies in the European Emissions Trading Scheme, in as much as they lead to a net reduction of CO_2 emissions over the whole life cycle. LCA should also become a basis for demand-boosting instruments for CCU products (e.g. procurement, product certificates and labels, minimum fuel blending quotas, etc.).

5.2.4 Recommendations addressing regulatory gap

The analysis presented in the studies, as well as challenges discussed above conclude that there is no proper framework conditions that will help CCU technologies reach wider acceptance and become commercially viable. While the rhetoric of carbon recycling are generally positive in the policy discourse on circular economy, industrial symbiosis, as well as opportunities under the Renewable Energy Directive II (REDII), there are no regulatory provisions that ensure competitiveness. CCU technologies need support through a regulatory framework and a long-term policy that will systematically address the economic, technological, and environmental performance or recognition of related barriers .

CCU is not part of the ETS market, and this holds back the development of CCU technologies as industries wanting to decrease GHG emissions by using a CCU solution would not be eligible. From the discussion above, it is clear that part of the reason for omitting or excluding CCU in ETS is the lack of guidance on LCA. Another issue is that there is no mechanism for setting the price of CO_2 (carbon market, tax, etc.).

70 CORESYM 2019, CarbOn-monoxide RE-use through industrial SYMbiosis between steel and chemical industries, report prepared by Metabolic under Coresym project

Recommendations:

- Develop a regulatory framework that incentivises both the permanent sequestration of CO2 into, for example, polymers or construction materials by the mineralisation as well as temporary sequestration in CCU fuels. The regulatory setting should assure comprehensive LCA methodology for CCU as a precursor for other regulatory measures (addressed below), and securing an even playing field with bio-based and traditional products.
- Ensure that CCU is ultimately recognised under the EU Emissions Trading Scheme in order to allow a breakthrough for CCU technologies. Namely, along with the carbon storage via mineralisation, the accrediting of GHG emissions avoided and/or carbon negative emissions should be considered under the EU-ETS.
- A smart carbon-pricing system should be introduced to push CCU projects into profitable areas. Carbon taxation should be applied with a warrantee of an international level playing field – within Europe and with border-tax adjustments between the EU and the rest of the world.[1] Carbon taxation should also be sensitive to various types CCU products: e.g. carbon tax for CCU fuel could be paid by the CO2 producer, while if it is a CCU product with a longer lifetime (e.g. polymers, construction material) the carbon tax would be paid by the product user. At the same time, benchmarking against footprints of currently used (e.g. fossil-and bio-based) products should be considered in calculating carbon tax.
- Ensure full implementation of the revised Renewable Energy Directive (RED II), which includes mandatory targets for CO2-based fuels, via rapid and fair adoption of the required Delegated Acts[1]. At the same time, encourage members states and regions to consider concrete strategies and plans on deployment of CCU technologies in achieving the 2030 and 2050 climate targets and the new EU Green Deal goals.
- Ensure that standardisation bodies (CEN and national bodies) work hand in hand with industry in developing required standards for the new CCU industry (e.g. standards for the quality of captured CO2). Align policy and regulatory development around industrial symbiosis and CCU, such as on standards development, reporting, indicators, and for promoting CCU by building favourable framework conditions for industrial symbiosis.

Appendix A Case studies

A.1. Case study 1 – Shougang LanzaTech Fuel Ethanol Plant in China

Case	Shougang LanzaTech Fuel Ethanol Plant in China
Project	CO to Fuel ethanol production plant
Country/Location	International, the plant of this case study interest is located in China
Company(ies)	LanzaTech
Value chain/products	Fuel ethanol
Industrial sector	Steel and iron
Market readiness level	Commercial plant

A.1.1. Background

LanzaTech is a bioprocessing platform which provides an economically robust route to carbon capture and re-use enabling the monetisation of local gas sources with moderate capital investment, giving off-grid communities access to clean energy. LanzaTech produces fuel ethanol from renewable, non-food resources, including industrial fuel gases and other waste gases, such as those produced from the gasification of municipal solid waste and waste biomass, and it also develops bio-catalytic toolkits for gas fermentation. The ethanol it produces can be used as a low-carbon fuel and can be converted downstream to jet fuel, diesel and household products.

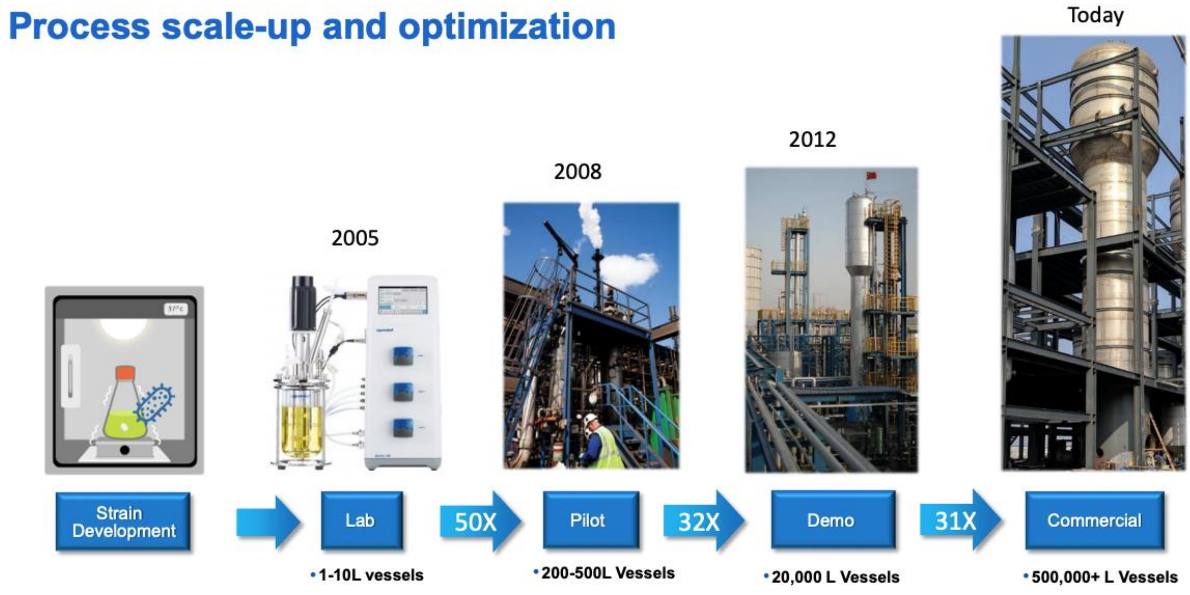
LanzaTech was founded in 2005 and is based in Skokie, Illinois. R&D facility and laboratories opened in New Zeeland, Auckland in 2005 and are now located in Illinois, USA, with a pilot facility in Georgia, USA, and additional offices in China and India. In 2008, LanzaTech began with a pilot plant in New Zealand, where it produced both ethanol and 2,3-butanediol.[71]

Figure 11 LanzaTech projects

Source: Lanzatech

[71] https://www.lanzatech.com

Figure 12 Scaling-up of the LanzaTech technology over the years



Source: Lanzatech

In 2005, LanzaTech's cofounder and chief scientific officer set out to identify acetogens that could grow on steel mill gas residues and produce useful products. He identified a promising microbe that had been isolated from rabbit gut and brought it to LanzaTech's laboratories in New Zealand. After an extended period of accelerated natural selection, during which the microbes were repeatedly grown and those that produced the highest levels of ethanol were isolated, a strain was identified that produced sufficient ethanol to be economically sound while still being robust enough to grow on industrial gases. The resulting microbe is not a GMO, rather a natural strain selected to perform optimally with steel mill residues[72].

Over the years, LanzaTech has been scaling up its CO and CO2 facilities and invested significant effort in optimising the process. The company has been developing commercial plants at the sites of industrial facilities in several countries but at the time of writing there is only one project that has been launched and functioning commercially. That project in China is the most interesting for the present study due to the fact that it is the only facility that is bringing its product to market.

LanzaTech, Tangmin (Wellington) and China's Shougang Group have launched an ethanol plant in China's Hebei province named Beijing Shougang LanzaTech New Energy Science & Technology Co. As a joint venture between carbon recycler, LanzaTech, Shougang Group, a leading Chinese iron and steel producer, and its New Zealand partner TangMing, the first commercial facility converting industrial emissions to ethanol.

The plant, located at the Jingtang Steel Mill in Caofeidian, deploys LanzaTech's technology which relies on anaerobic bacteria to ferment waste emissions of the steel mill. It has a production capacity of 46,000 tonnes of ethanol per year and has been operational since early May 2018. The ethanol produced meets the ASTM International D4806 standard for blending with gasoline to be used in automotive engines and the Chinese standard for denatured fuel ethanol.

[72] http://www.arpae-summit.com/paperclip/exhibitor_docs/14AE/LanzaTech_Inc._131.pdf

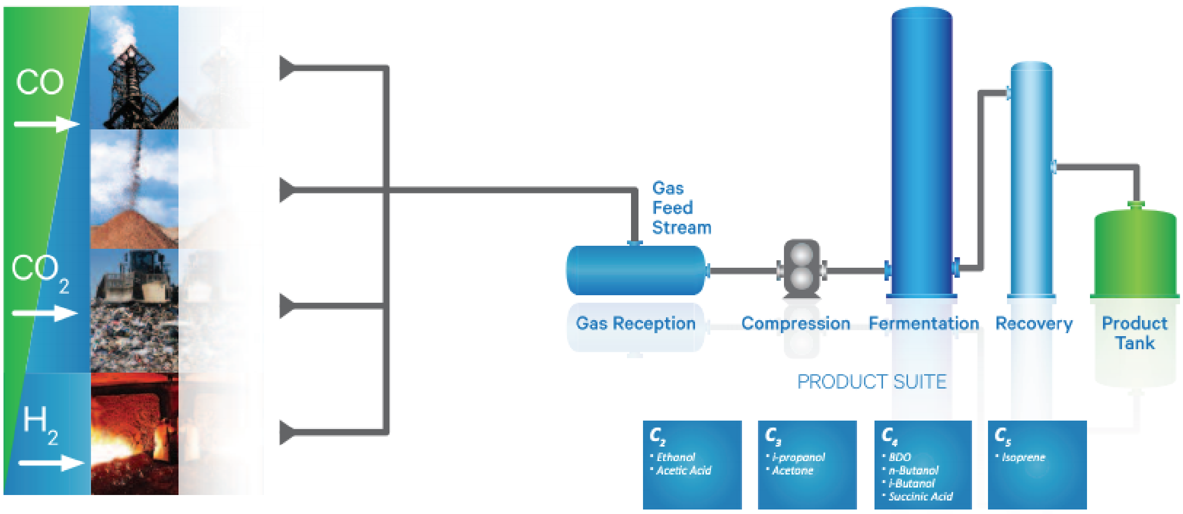
Prior to launching the full-scale industrial facility, LanzaTech and Shougang experimented with the technology at a demonstration plant for six years. This required a lot of manpower, material and financial resources, and Shougang Group has maintained support throughout. There have been many challenges in translating the results of the lab-based research into the pilot facility scale, upscaling from small-volume laboratory fermenters to seven-metre-diameter fermentation reactors. Linking each industrial process was a novel and very challenging process, but the pilot project eventually managed to address these challenges. Lessons from the pilot plant have been instrumental in the commercial scale plant. It has to be noted that the rapid post-pilot upscaling to the commercial plant and resulting construction of the facilities helped to expedite the launch.

By 2025, Shougang facility expects its ethanol fuel capacity to reach 94,000 tonnes, reducing annual carbon dioxide emissions by 900,000 tonnes and nitrogen oxides by 5,450 tonnes. As the first project in the country, as well as globally, it has raised a lot of interest from other locations in China; discussions are ongoing about various projects in different stages of development.

A.1.2. Value chain

In the steel industry, carbon is used primarily as a chemical reactant to reduce iron oxide to metallic iron. The resulting steel-mill waste gases are unavoidable residues of industrial production. The residual gases produced through this reaction represent the biodegradable fraction of industrial waste and are an inevitable consequence of the chemistry of steelmaking. When gas fermentation is deployed in the steel mill, instead of sending a residual gas stream to a flare or power generation unit, it is cooled, cleaned and injected into a fermentation vessel containing proprietary microbes and liquid media. The microbes grow and increase their biomass by consuming CO/CO2/H2. As a by-product of this growth, they make ethanol and chemicals that are recovered from the fermentation broth, similar to the way that yeast makes ethanol or other products. The fermentation products (ethanol) are separated from the fermentation media and purified for sale as a fuel-grade gasoline component and as chemical intermediates.

Figure 13 LanzaTech CCU value chain at steel-mill



Source: LanzaTech

While both CO/CO2 and H2 are utilised in the LanzaTech process, its proprietary microbes are also able to consume hydrogen-free CO-only gas streams, due to the operation of a highly efficient biological water-gas-shift reaction occurring within the microbe. This reaction allows the bacteria to compensate for any deficiency in H2 in the input gas stream by catalysing the release of hydrogen from water using the energy in CO. The low temperature and low-pressure gas fermentation route benefits from tolerance to a wide variety of impurities and pollutants, eliminating the need for extensive gas clean-up or conditioning. The microbes used in the gas fermentation process convert carbon to ethanol at very high selectivity compared to the conventional chemical synthesis routes. The result is higher overall fuel and thermal efficiency.

A.1.3. Socio-economic obstacles and opportunities faced by the project

- China has been promoting circular economy policies for several years. Thus, sustainable technologies that allow the circulation of waste by converting them into resources have been and still are of high interest to the government. There is considerable support for green and alternative energy technologies. Furthermore, in China, expanding the channels for raw materials for fuel ethanol is one of the energy industry's objectives as part of its industrial development strategy. CCU-based ethanol technology is a natural fit within the strategy. Furthermore, the industrial potential in China is vast:

  > *"China's steel output is about 800 million tonnes, using half of the steelmaking tail gas resources every year one can produce 5 million tonnes of fuel ethanol, rich in raw materials, easy to use and low in collection cost…" (*Dr Chao Wei, Assistant General Manager at Shougang Langze Technology *73)*

  Thus LanzaTech technology, has received significant interest and has been largely motivated by these policy developments in China.
- Furthermore, an important economic driver for the Shougang project has been government financial support. In its initial construction stage, it received funding from the local government in terms of green findings and investments.
- The business case for the produced bioethanol is also secured by a state scheme that ensures the procurement of the full amount of ethanol produced which is further used in gasoline blends. The price for the ethanol is also regulated by the government, which helps to create stable turnover and predictable income streams.
- Technical issues that needed special attention were addressed during the pilot phase. The pilot plan allowed for experimentation and adjustment of the technology and processes before the commercial plan was initiated.

A.1.4. Social and economic impact observed

A.1.4.1 Economic impacts

Competitiveness

New business lines/models/product portfolio	A new and unique value chain of steel mill gases-based ethanol production has been set up by this project. The business model applied here is firmly based on the secured sales through the state procurement scheme.
Formation of new markets and value chains in the region	The commercial plan involves a new value chain in the regional economy. The new product has entered the existing ethanol fuel market without facing fierce competition.

73 Dr Chao Wei, Assistant General Manager of Shougang LanzaTech New Energy Technology in its interview to a Chinese newspaper, featured in the article 'Shougang Langze will be the world's number one in the next month' , by the reporter Pan Fuda.

Relocation of companies to the region	No new companies have been relocated to the region besides opening the joint venture where LanzaTech is a partner.
Increased interest from investors, new/envisaged investment flows	Still to check about private investor interest in China and globally. There is a lot of interest from the Chinese state which is likely to invest in new CCU facilities. (Overall, LanzaTech technology is highly ranked in the international business and investors ratings in the area of cleantech and bioeconomy.)
Higher energy and resource independence (from import)	The new alternative source of cleaner fuel is a small but important step towards energy independence. While the impact is not significant, it sets an example that has managed to draw interest from other regions in China, their governments and industries.

Economic benefits and costs

New value chain related revenues, profits, gross value added created (for various companies)	While the return on big investment in CCU facility will still take time to recoup, the new value chain has been delivering revenues to the producers. No specific economic impact has been reported on companies in the downstream part of the value chain, namely on the gasoline distribution company that blends new ethanol into the motor fuel. For them, price and quality of CCU-based ethanol is the same as the traditional alternative, no changes were needed in their process.
Economic/resource savings achieved (if any)	The projected cost of production is competitive with the lowest-cost bioethanol available today. There are no premium price-related issues that are often seen with green products. This means there is no impact on the expenses for the consumer of the ethanol. Nor is there any extra cost for the procurer of the ethanol who further blends it with gasoline.
Costs and negative externalities experienced and envisaged	No negative externalities are envisaged in coming years.

A.1.4.2 Technological and innovation impacts

Technical and technological advancement

New, improved, technical expertise	This project was a real technological breakthrough for LanzaTech and Shougang LanzaTech New Energy Technology Experience with the pilot plant generating strong expertise and experimental and scientific knowledge about various processes within the CCU-based ethanol production process.
Technological leadership	LanzaTech is already a global technological leader in the fermentation-based CCU technologies. The Shougang project is the first commercial plant, which basically labelled Shougang as an industry leader in this type of CCU technology.
TRL progression	The transition from pilot plant to the commercial production prompted very high levels of TRL.

Transfer of more advanced technology into the local region	This is a clear case of transfer of CCU technology which is a foreign technology to China. Plus, this was the first commercial implementation of the technology.
Intellectual property/new patents filed	The technology used in the Shougang project is currently unique in the world. LanzaTech has received over 600 patents world-wide.

Capabilities of local companies

Opening of new supporting services (logistics, ICT, infrastructure setting and management)	Local contractors were involved in construction. This has not in itself generated any specific impact in terms of increased technological capabilities, etc. The construction followed the specification and plans with no non-standard or overly sophisticated technologies or processes.
Innovative service provision of local companies	No significant impact in terms of new service levels or lessons for other local companies have been observed. (Need to check this again)
Creation of start-ups, spin-offs	Except for the joint venture between LanzaTech and Shugang Group, no other entrepreneurial start-ups have been seen.

A.1.4.3 Social impacts

Employment

New jobs in new value chains	The CCU plants at Shougang created over 120 permanent or long-term job positions to operate the main facility, as well as in maintaining supporting services.
New jobs in supporting services, logistics, ICT, infrastructure setting and management	Nearly 1000 job positions (temporary jobs) have been created during the construction stage. There are also no job losses: the technology does not disrupt the existing technological structures of the steel mill and does not undermine or replace jobs related to them.

Fostering knowledge in the region

Strengthen knowledge base in local research organisations and businesses	In building the research capabilities and scientific base, the pilot plant activities had an extensive impact. Shougang's internal research team collaborated with local university teams to adapt the new technology and experimentation processes. The research and translation of experimental results from lab to pilot facilities provided knowhow and capacity building both for the company and for the university researchers.
Brain gain in the region through the project	A number of high-class research staff and engineers have been drawn to the Shougang research and pilot project team. They were core in adapting the LanzaTech technology and implementing it at pilot scale.
Partnership with universities and PPPs	As noted above Shougang's internal research team collaborated with the local university during the research and pilot stages.

Linkages and partnerships

New partnerships created within industry, across different industries	By definition, a project like this involves cross-industrial links: the steel industry working with the biotechnology sector and supported by ICT and other process services.
International partnerships created	This CCU project is an international project with LanzaTech originating from New Zealand and currently an international company, and the Chinese metallurgical company Shougang Group.
Visibility and image	
Improved visibility for companies' brands	The project resonated because it is a global first to take this unique CCU technology to market. This project positioned Shougang as a pioneer in the sustainability efforts among steel and iron producers.
Market potential	
Price competitiveness of the product	As discussed above, the production cost of the CCU-based ethanol is comparable or lower than traditional bioethanol cost, making it competitive on the bioethanol market. In the Chinese case, the processes for fuel are controlled by the state, which makes price competitiveness less relevant. But all in all this system allows the CCU ethanol producer to make a business case.
Marketing strategy available	No special marketing strategy was needed. The state procurement agreement commits state oil companies to buying all ethanol produced at Shougang.
Customers established	The final customers are gasoline consumers. It is not known if they are informed about the source and content of their gasoline, or indeed if they would have any preference. The 10% ethanol blend in gasoline is a standard in China so it is unlikely that CCU ethanol-based blends need any specific labelling. In the middle stages of the value chain, the consumers are the state oil companies bound by standardised pricing and regulated procurement policies. Incentives and consumer choice play a marginal or minimal role in this process.

A.1.5. Lessons

Lessons	
Economic aspects	The project's economic success is in its stable business model that is secured through the guaranteed procurement of the product by state companies. The role of public procurement as an instrument for supporting sustainable innovation can be significant.
Technological and innovation aspect	Bold and active industrial commitments to new technologies are associated with risks, but can also quickly bring them to the forefront of the industrial community. CCU-based bioethanol technology has been increasingly showing its viability in commercial application, which is good news to industries looking for solid technological solutions to cut their carbon emissions.

	Further application of this technology can spur improvements in the products and market diversification.
Social aspects	CCU-based bioethanol production facilities create stable, long-term jobs both directly at the facility and indirectly through the service facilities. There are also no job losses.
General lessons	A shared vision between the companies and the government is important in promoting such initiatives. Guarantees offered by the state via public procurement agreements, as well as targets on fuel blends can create a strong supporting framework for the CCU-based bioethanol projects.

A.2. Case study 2 – George Olah Renewable Methanol Plant

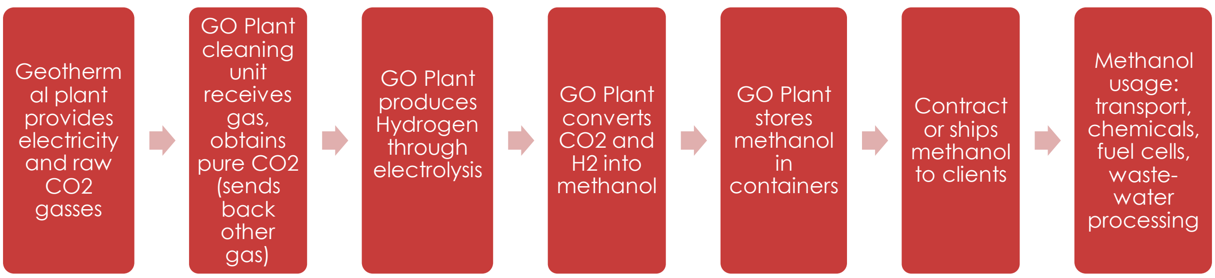
Case	**George Olah Renewable Methanol Plant**
Country/Location	Svartsengi, Iceland
Company(ies)	Carbon Recycling International (CRI)
Value chain/products	Methanol
Industrial sector	Energy
Market readiness level	Commercialised on a pilot scale

A.2.1. Background

George Olah Renewable Methanol Plant (GO Plant) is the first production facility producing methanol (also labelled 'Vulcanol') from CO2 emissions emanating from geothermal sources. It is a pioneering facility that aimed to demonstrate that this technology works at full industrial scale. The key milestones of the project, which started in 2006, include the launch of the pilot plant and lab with production capacity of 0,001 t/day in 2007, equity raised in 2009-2010, launch of Vulcanol production as an industrial demonstration with a capacity of 4 t/day in 2012, and launch of the second demonstration plant with a capacity of 12 t/day or 4k t/year in 2015.

It is important to stress that the GO Plant is still a demonstration plant for the technologies and is regarded as Carbon Recycling International's main 'lab'. While it is in operation and supplies methanol to the market, production is not yet profitable. It helps CRI to "sell the idea" in view of other projects (e.g. there are plans to build 300 tonne/day plants in China and Europe).

A.2.2. Value chain(s)



The GO Plant operates in close symbiosis with the nearby geothermal Svartsengi Power Station, which provides CO_2 (up to 10% of its CO_2 emissions) and electricity. The CO_2 is sent to the GO Plant, mixed with other non-condensed gases. The GO Plant is not a carbon capture plant per se and focuses instead on the cleaning and processing of CO_2. Once CO_2 has been purified, it is mixed with locally produced H_2 to produce methanol, which is then filled in containers. The shipping of methanol to clients is subcontracted to an external company. GO Plant delivers methanol to a variety of clients and uses: gasoline in the UK and the Netherlands, production of biodiesel in Sweden, fuel cells (e.g. for hydrogen cars) in Denmark, waste-water processing, and chemical manufacturing.

A.2.3. Socio-economic opportunities and obstacles faced by the project

Opportunities and support factors that have been driving the technology development:

- The current market for methanol is 4 tonnes per day; the potential for upscaling the CCU to methanol production is a key driver.
- Participation in research projects co-funded by Horizon 2020 helped to test and further develop the technology.
- Private investment was key in demonstrating the technology. The GO Plan is 100% equity funded (first round by Icelandic investors and later rounds by investors from the US, Canada and China). As CRI was the first to build such a plant using these technologies, it was challenging to raise equity, especially during the financial crisis and breakdown of Iceland's banking system. Some promised investments did not materialise.
- Reliance on the local technical knowledge was not a driver per se but it did support the work and did not create obstacles. CRI had its own expertise and had a network of contractors to both build and commission the plant. They also hired a few local employees who transitioned from other industries (ship, fishing). Most of them were already familiar with machinery (e.g. compressors) and how to maintain similar installations. Some retraining was needed, for example on how to use computer monitors to operate the plant, and for maintenance on components that were similar to piston-based engines but used for a different purpose. There was also equipment, such as electrolysers, columns, and other tools that workers were not familiar with so they received training.

Obstacles challenging the development of the technology and/or project:

- While there is an interest in the technology, the policy debate as framed by the EU has been challenging. The ongoing build-up of the policy framework through the Renewable Energy Directive (RED) has been a challenge more than an opportunity, as it created uncertainties for Vulcanol in the emerging market. The recognised methodology for LCA does not fully recognise benefits like a fossil or biofuel substitution. Developments beyond 2021 are also uncertain.
- When using an electrolytic process, such as the GO Plant technology, for the methanol to be accepted as 'green' (i.e. carbon footprint neutral) it has to be within a national electricity system that is based on 100% renewable energy sources. There are only two countries that qualify for 100% renewable energy in the national grid: Norway and Iceland. The guarantee of renewable energy origin can be ensured by arranging a contract with, for example, wind energy park developers for a specific number of years at a certain price, but it is a potentially time-consuming negotiation that well-established companies (e.g. Ikea, Lego) seem best positioned to navigate. At the moment these options are not open to developers interested in GO Plant type of project.

A.2.4. Social and economic impact observed

A.2.4.1 Economic impacts

Competitiveness

New business lines/models/product portfolio	Vulcanol is the commercial name of the green methanol that has been developed and put on the market. However, the volumes of it are rather limited because it is produced in the GO Plant. This plant is the demonstration plant of CRI, which is ten times smaller than the envisaged commercial plant. By building it, they have demonstrated that the technology was commercially viable, even though the plant itself is not. The idea is to then make it easier to find investors and build larger plants which would be profitable. It has also helped CRI to develop the right process and technical skills to build this kind of installation, and to assemble a network of reliable contractors, etc.
Formation of new markets and value chains in the region	The GO Plant is now selling the product, but in reality the purpose is to sell CRI's expertise: the demonstration plant has created the market itself (since it did not exist before), which they plan to extend it to other countries, even beyond Europe. They benefit from a first-mover advantage and boosted the company's international profile.
Opening of new businesses and value chains in the region	The project has also demonstrated that there is a market for green methanol; it is possible to find customers. *"The GO Plant will continue to be mostly our developing platform, something we can show. It helps us to set up projects with a larger capacity, and therefore more profitable."* (CRI)
Relocation of companies to the regions	This did not seem to have taken place within the GO Plant installation.
Increased interest from investors, new/envisaged investment flows	There is increasing interest from investors also due to demonstration facilities. CRI has been invited to set up CCU-based methanol production facilities in several countries.
Higher energy and resource independence (from import)	Being a small-scale facility, the contribution of the plant to energy and resource independence is insignificant. But by showcasing the technical, and commercial viability of the new technology and product, it creates a case for larger scale production facilities that can eventually make an impact.

Economic benefits and costs

New value chain related revenues, profits, gross value added created (for various companies)	Experience with the demonstration plant showed that the technology of methanol production is commercially viable. Being a demonstration facility, it did not result in great revenues and profits, but instead proved that there are customers and market for the green methanol and launching the new larger scale facilities will thus be justified.
Economic/resource savings achieved (if any)	The demonstration plant had no intention or objective to achieve economic or resource savings, although it might have been possible.
Costs and negative externalities experienced and envisaged in coming years	Any unexpected costs or losses can be coming from the potential uncertainties in the policy.

A.2.4.2 Technological and innovation impacts

Technical and technological advancement

New, improved, technical expertise	The GO Plant is the global pioneer demonstration plant of CCU and electrolysis-based methanol technology, as well as the first demonstration of Vulcanol, a geothermal CO2 to methanol production technology. Its biggest contribution was to bring the technology to the last TRL level where it demonstrates how it can operate under real-life conditions. R&I activities and experience with the GO Plant has also helped CRI to develop the right processes and technological development knowhow. "*Building the GO plant has really helped us with the tech we have. We have been able to fill a number of patents based on the things that we discovered at the GO plant, this is also where we are testing our new reactor design, which we just implemented in the German plant project. So it is a very important plant for us in terms of process and technological development*. " (CRI)
Technological leadership	GO Plant is the global pioneer demonstration plant of CCU and electrolysis-based methanol technology, as well as the first demonstration of the Vulcanol geothermal CO2 to methanol production technology.
TRL progression	Its biggest contribution was to bring the technology to the last TRL level where it demonstrates how it can operate under a real-life conditions. Besides building the plant, CRI has also demonstrated that the technology was commercially viable, even though the plant itself is not. The idea was to demonstrate the technology to make it easier to find investors and build larger plants which would be profitable.
Transfer of more advanced technology into the local region	No international technology transfer has taken place under this project, but it has fostered and developed a new frontier technology.
Intellectual property/new patents filed	Thanks to R&I and development activities at the demonstration plant several patents have been filed by CRI.

Capabilities of local companies

Innovative service provision of local companies	As mentioned above, Go Plant employed a number of support services; for logistics (and shipping), and for building and operating the plant. However, the services offered by these companies did not require innovative approaches.
Opening of new supporting services (logistics, ICT,	No new support service has emerged as a result of the project.

infrastructure setting and management)	
Creation of start-ups, spin-offs	No local spin-offs or start-ups.

A.2.4.3 Social impacts

Employment

New jobs in new value chains *New jobs in supporting services, logistics, ICT, infrastructure setting and management*	CRI had its own expertise and a network of contractors to both build and commission the plant. They also hired a few local employees who transitioned from other industries (ship, fishing). Most of them were already familiar with machinery (e.g. compressors) and how to maintain similar installations. However, some retraining was needed in certain process and for some specific equipment. The GO plant employed people working in related industries who wanted to change jobs, eventually to get positions that are closer from their home and family. The plant itself is run by a team of 2-3 operators working in shifts. Considering a five-shift system, the estimate of the job-creation is 12 direct FTE. (A larger plant would employ about 25 people for direct operations, but the increase in jobs is not proportionate to the growth in scale.) GO Plant is in charge of its own management, counting about five employees. Thus, the number of direct current jobs is 12+5 (in a larger plant this number could be: 25+10). Some indirect employment for support services include: maintenance jobs; and logistics (delivering the containers to ships and shipping the product abroad). These roles would be partially internalised in a bigger plant, which would also allow the handling of much larger tanks. In addition, during development a team of people from CRI were involved, including process and mechanical engineers, CAT specialists, as well as business developers.

Fostering knowledge in the region

Strengthen knowledge base in local research organisations and businesses	The impact on the region was not the focus of the project. The local business community involvement was represented by local contractors, such as logistics and shipping groups, builders and some operating staff at the plant. The project did not generate a notable impact on the local entrepreneurship ecosystem, no eco-cluster, spin-off or regional initiative has emerged as a result. The impact was limited to gaining some experience for the local contractors in project building and installing Vulcanol facilities. Apart from the technological advancements this was not a ground-breaking job for the local contractors.
Brain gain in the region through the project	CRI itself is based in Iceland and it has international specialists hired in the local office.
Relocation of companies due to higher attractiveness	This has not been observed.

Partnership with universities and PPPs	The plant is there to demonstrate the technology and promote it abroad, and it has enabled CRI to conclude new research partnerships, notably in Europe (especially H2020 projects). In Iceland, CRI specialists worked with the Icelandic Innovation Centre, where they applied for projects with local university researchers. They also worked with the Icelandic Research Foundation.
Linkages and partnerships	
New partnerships created within industry, across different industries	The demonstration plant has linkages with the local energy company which is also a provider of CO2 from geothermal sources.
International partnerships created	No international partnerships have been pursued within the demonstration plant project. But, there are international customers of the methanol.
Company visibility and image	
Improved visibility for companies' brands	As the first zero-footprint methanol production plant globally, it generated additional visibility for CRI and the country as a pioneer in this technology and potentially as a new strategic location for a large-scale commercial plant for producing Vulcanol.
Market potential	
Price competitiveness of the product	The price for Vulcanol is higher than for traditional methanol. Current customers accept the premium due to its 'green' nature. Overall, CRI specialists do not see price competitiveness as a big challenge for their product as there is confidence in demand for the green methanol even with the premium price.
Marketing strategy available	The marketing strategy has been developed alongside the launch of the green methanol. Within this strategy the commercial name Vulcanol was created which aims to show the unique feature of methanol that originate from CO2 emissions coming from geothermal sources.
Customers established	The demonstration plant has limited production volumes, but has well-established customers; fuel and chemical companies in the UK, Netherlands, Denmark and Sweden using methanol for blending with gasoline and in chemical polymer production.

A.2.5. Lessons

	Lessons
Economic aspects	• Since the commercialisation activities are still to come, it is too early to see any direct economic impact and value added, both for the company and for the regional economy.
Technological and innovation aspect	• Strategically focused R&I and demonstration projects like this can help a region to gain technological leadership.

	• Involvement of a wider network of scientific and industry actors ensures better adoption of the technologies, establishing synergetic links and achieving better results. • Government assistance can be instrumental in ensuring the presence of green energy suppliers with sufficient capacity for CCU-based production/processes to be carbon neutral.
Social aspects	• In terms of employment, further development of the CCU industry could remobilise a certain number laid-off workers (but not all, as plants are small scale). To be sustainable, companies will have to be more local, adapted to the local environment, and better able to re-use effluent/waste and the renewable energy that is available.
General lessons	• A shared vision between the companies and government is important in promoting such initiatives. Adjusted to the local circumstances, PPP is possibly the most workable model for CCU initiatives in the existing climate policy framework, which does not offer suitable conditions for CCU technologies.

A.3. Case study 3 – Carbon2Chem: CO2-based chemical production at Thyssenkrupp

Case	Carbon2Chem project
Country/Location	Germany, Duisburg
Company(ies)	Thyssenkrupp
Value chain/products	Methanol, ammonia, polymers
Industrial sector	Steel, chemicals, (also focus on cement and waste incinerators)
Market readiness level	Precommercial

A.3.1. Background

Thyssenkrupp is a German multinational conglomerate focused on industrial engineering and steel production. The company is based in Duisburg and Essen and divided into 670 subsidiaries worldwide. It is one of the world's largest steel producers, ranked seventh worldwide. The company is the result of the 1999 merger of Thyssen AG and Krupp, and now has its operational headquarters in Essen. In addition to steel production, Thyssenkrupp's products range from machines and industrial services to high-speed trains, elevators and shipbuilding. Chemical, steel and electricity industries employ more than half a million people in Germany.

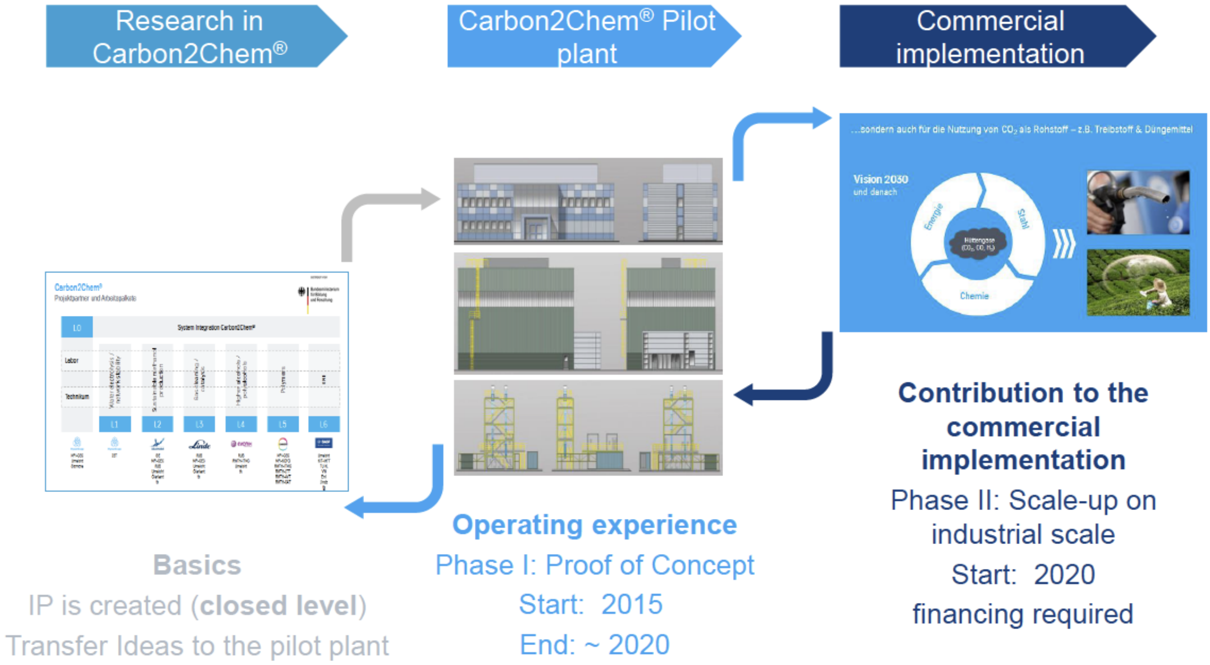
The company has ventured into CCU through its steelmaking facilities. In 2018, Thyssenkrupp started producing sustainable methanol from metallurgical gases, and now also ammonia at the Duisburg pilot plant – Carbon2Chem project. The project started in 2016 with 18 partners from industry and academia[74]. The initial phase has taken four years and includes R&I activities and the eventual launch of the pilot plant.

The aim of Carbon2Chem is to use gases from steelmaking as raw material for chemical products including the CO2, CO and nitrogen contained in them. Surplus electricity from renewable energies will be used as an energy source for the electrolysis of hydrogen needed to synthesise methanol.

The German Federal Ministry for Education and Research (BMBF) is funding the project with more than €60 million. The partners involved intend to invest more than €100 million by 2025. They have earmarked about €1 billion for commercial realisation that will start in 2020.

[74] Other partners in Carbon2Chem project are AkzoNobel, BASF, Clariant, Covestro, Evonik, Fraunhofer-Institut für Solare Energiesysteme (ISE), Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnik (UMSICHT), Karlsruher Institut für Technologie (KIT), Linde, Max-Planck-Institut für Chemische Energiekonversion, Max-Planck-Institut für Kohlenforschung, RWTH Aachen, Ruhr-Universität Bochum (RUB), Siemens, Technische Universität Kaiserslautern, Volkswagen, Zentrum für Brennstoffzellentechnik (ZBT)

Figure 14 Carbon2Chem project phases



Source: Carbon2Chem project

Current state of play: The technical centre is built adjacent to the Thyssenkrupp Steel Europe site in Duisburg on an area of 3700m2 and it was opened November 2016. By August 2017, the topping-out had been accomplished and in March 2018, the demonstration (pilot) plants were put into operation. A hall for water electrolysis, pipeline bridge, gas purification plant, laboratory building (520m2) as well as a workshop building, control room and social rooms were all built.

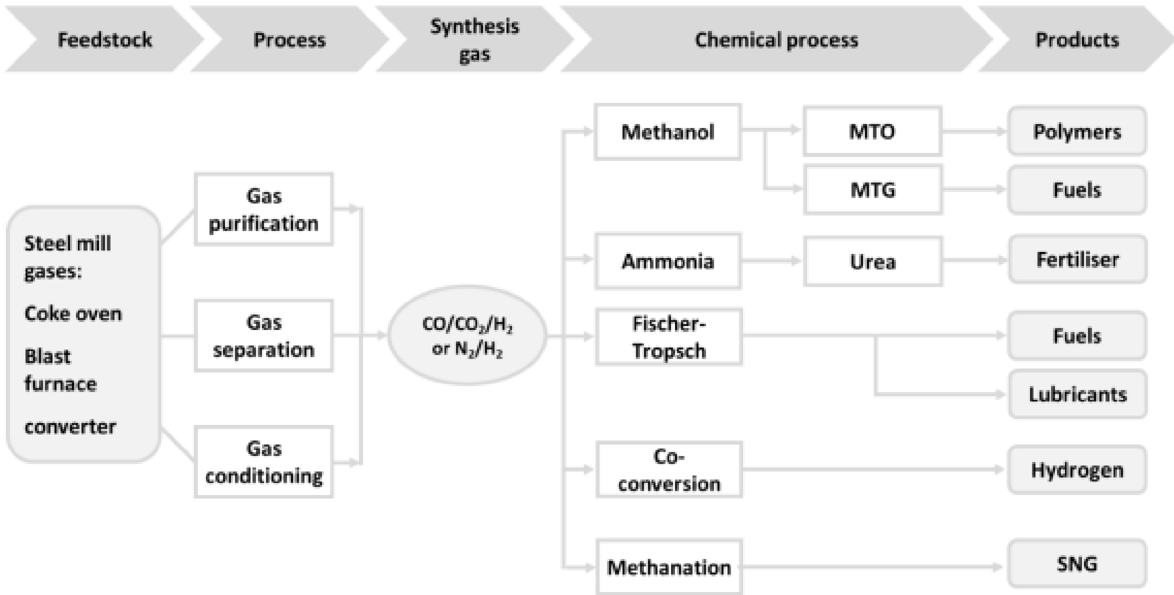
The commercial implementation phase will start in 2023 and focus on constructing and launching a large-scale CCU facility.

A.3.2. Value chain

The CCU process introduced at the pilot plant is based on renewable energy-based electrolysis and production of methanol, ammonia, and other chemicals. The figure below illustrates the value chain based on integrated CCU processes.

Among other things, steel mill gas contains hydrogen and nitrogen and also large amounts of carbon in the form of carbon monoxide, carbon dioxide and methane (44% N2, 23% CO, 21% CO2, 10% H2 and 2% CH4). Carbon, hydrogen and nitrogen form the basis of numerous chemical products. Nitrogen and hydrogen can be used to make ammonia. In turn, ammonia can be used to make mineral fertiliser. Carbon (i.e. carbon monoxide and carbon dioxide) and hydrogen are base materials for methanol. Methanol – one of the most widely produced organic chemicals – can be used to power cars and aircraft or to synthesis other chemicals and polymers.

Figure 15 Value chain at Carbon2Chem



Source: CarbonNext project report, available at http://carbonnext.eu/Deliverables/_/D2.2%20Industrial%20symbiosis.pdf

A.3.3. Socio-economic obstacles and opportunities faced by the project

- It is important to note that the facilities set up for CCU are part of a demonstration project to test the technologies and production processes, proving their technical feasibility before the production process is upscaled at the commercial facility. Technical challenges faced by the project are part of any demonstration project, and the overall purpose is to address these challenges and fine-tune the technology, process and parameters.
- The current pilot plant's production scale is small, but the project managers are confident that upscaling will not face technical issues as the pilot project is using a process that is not different from commercially proven processes for synthesising methanol and ammonia. The catalyst applied in this process is a conventional technology that has been applied in large-scale facilities carrying out traditional methanol synthesis.
- Access to renewable energy sources is a high-order challenge, to achieve carbon neutrality during production (electrolysis). The large-scale CCU facility needs a large supplier of 100% renewable energy. A separate renewable energy generation facility (e.g. wind park) will not be enough, according to the project manager. Securing a renewable supplier is a key focus of the company at this stage of the project.
- Political support is an important driving factor for the project. Increasing recognition of the importance of CCU development and research, the need for symbiotic relationships between industries to meet circular and low-carbon economy commitments, and receiving political and financial support for these activities from government have all factored into the project's success achieved so far.
- Involving a wide network of partners from many industries and scientific organisations was also critical for the project, because various technological aspects need specialist attention, while development of connections between industries would not work without a dialogue among these industries.
- Another issue is how climate change mitigation policy often singles out industries. It misses the holistic and systemic assessment of emissions that acknowledge interrelationships among various industries, their collective actions to avoid/prevent emissions, how they use land, and the results that can be achieved through CCU.

A.3.4. Social and economic impact observed

Since the CCU technologies employed within the Carbon2Chem initiative have been demonstrated and not yet commercialised, the observed impact is linked to the R&I, testing and demonstration activities. The wider impact is something that is expected with the launch of the commercial-scale CCU facilities.

A.3.4.1 Economic impacts

Competitiveness

New business lines/models/ product portfolio	No impact observed yet, as the product and technologies are still at the demonstration stage. Overall, the project is creating a basis for new products with a 'greener value' that will be competing with traditional and less sustainable alternatives. As presented above, several products have been developed within the Carbon2Chem programme. Project partners from the steel and chemical sectors have a solid business model in mind, while ensuring its functionality from the technical perspective. They have an economic incentive centred around a synergetic and mutually beneficial relationship. To be economically viable, the project needs to move to the next level and enter the market with its product(s). The partners are optimistic about this and they observe the increasing demand for products with a lower environmental footprint. While acceptance of premium prices for greener products has its limits, they believe there will be demand and that targeted marketing will help to promote such products.
Formation of new markets and value chains in the region	New market and value chains have not been established yet. As discussed above, the project is laying the ground for a new value chain and products, but the market for these is expected to be formed only after the launch of a full-scale production facility. The project managers are optimistic.
Opening of new businesses and value chains in the region	This impact is not observed yet, as the product and technologies are still at demonstration stage.
Relocation of companies to the regions	This impact is not observed.
Increased interest from investors, new/envisaged investment flows	The project itself (R&I and demonstration) has drawn investment from public sources that matched the investment of the company. The next phase, the launch of a production facility, requires €1 billion investment. (Check if external investors were attracted to this.)
Higher energy and resource independence (from import)	This has not been observed; the launch of the facility should be able to contribute significantly to a supply of methanol on the local scale.

Economic benefits and negative externalities

New value chain related revenues,	This impact is not observed yet, as the product and technologies are still at demonstration stage.

profits, gross value added created (for various companies)	
Economic/resource savings achieved (if any)	This impact is not observed yet.
Costs and negative externalities experienced and envisaged in coming years	The demonstration project has not generated negative economic externalities. The impact of envisaged full-scale production facility is not yet known.

A.3.4.2 Technological and innovation impacts

Technical and technological advancement

New, improved, technical expertise	The Carbon2Chem project has added to all partners' technical knowledge and experience with the technology. As a demonstration project the purpose is to gain additional knowledge about the performance of products and technologies under various conditions and parameters, in order to use this knowledge in a large-scale facility. The project has attracted leading researchers/experts, and research and testing activities have contributed to the technical expertise of all contributing partners.
Technological leadership	The project and technology developed can be regarded as 'benchmark CCU technology', as one of the most advanced projects of this scale. Project partners are now regarded as leading technology providers in the emerging CCU area. "*Carbon2Chem project is a benchmark for CCU technology and it had a big impact on the technological progress in this area. Implementation of the world-scale plant needs time, but there is a great interest and we are in discussion with potential customers all over the world, and invited to conferences…*" (Carbon2Chem team)
TRL progression	The R&I activities have helped to bring their technology to TRL 6 based on the establishment of a demonstration plant, with plans to reach TRL 7 upon pre-commercialisation.
Transfer of more advanced technology into the local region	The development and testing of the advanced technology, rather than transfer per se, has taken place within this project. The new technology is seen as a benchmark technology in CCU in the international context.
Intellectual property/new patents filed	R&D activities related to Carbon2Chem have resulted in around 50 new patents.

Capabilities of local companies

Innovative service provision of local companies	Since the project was only focused on R&I and demonstration activities, no wider impact on local companies beyond the project partners have been observed.

Opening of new supporting services (logistics, ICT, infrastructure setting and management)	One of the important prerequisites for the full-scale CCU facility to be launched is a secure a large supply of clean/renewable electricity. This is one of the biggest challenges facing the planned facility. This is an opportunity for a major renewable supplier to step in'
Creation of start-ups, spin-offs	Within the given phase of the project that focused on R&I and demonstration, no new start-ups have been formed. But with the establishment of the large-scale CCU facility, functioning value chain and new products, there are possibilities for new business models to emerge (e.g. clean fuel-based transportation on land and water etc.).

A.3.4.3 Social impacts

Employment

New jobs in new value chains	Jobs have been created in the R&I and demonstration plant, but these are not a major outcome or contributor to the local economy (they are not long-term jobs). In the commercial facility a number of jobs will be created but this will depend on its scale.
New jobs in supporting services, logistics, ICT, infrastructure setting and management	No insights or estimates available at this stage. But in the full-scale facility a number of jobs could be created through support facilities, e.g. energy supply (possible new renewable energy installations), etc.

Fostering knowledge in the region

Strengthen knowledge base in local research organisations and businesses	The project involved a number of research organisation as well as research units of the companies. The project has attracted leading researchers/experts. North Rein Westphalia is known for its strong research community and capacity. But at the same time, as discussed above, project activities also contributed to the technical expertise of the partners. Other businesses may have also benefited from an innovation dividend through their overall involvement in the complex industrial symbiosis system being established. (Check how many non-key local companies got involved in the innovation activities.)
Brain gain in the region through the project	As noted above, the project has attracted leading researchers/experts in the given area, and the region is already known for its advanced R&I base. It was noted that the national and regional governments recognise the impact of the project on the R&I community, especially on the regional level.
Relocation of companies due to higher attractiveness	This has not been observed, as the project involved locally established companies/facilities. Future developments in this respect are still to be seen at the commercialisation phase.
Partnership with universities and PPPs	The project itself was based on a partnership between companies, including known chemical companies, leading national research and technology organisations, and universities.

Linkages and partnerships

New partnerships created within industry, across different industries	The CCU facility is at its core an industrial symbiosis among several industries: steel, cement, CO/CO2 suppliers, chemical and energy suppliers involved in processing and converting the emissions.
International partnerships created	The partners involved in the project were all from Germany. New international partnership could be formed in the future, as interest in the new technology is emerging from industrial players from other European and non-European countries.

Company visibility, image (positive and negative externalities)

Green washing and damage/improved visibility for companies' brands	The overall impression is that the project has contributed to the positive image of the industrial companies, namely Thyssenkrupp and Akzonobel. Both are rather large players in their sector. Carbon emissions-reduction initiatives form an important part of their company strategies, and implementing pioneering technology in CCU serves those goals. Gaining recognition as a 'benchmark CCU project' also offers positive additional value.

Market potential

Price competitiveness of the product	While the new products (CCU-based methanol and ammonia) have not on the market yet, it is expected that the cost of these products will be more than traditional fossil-based alternatives. Despite this, the partners are confident that the product will be in demand. Market expectations according to the project managers are summed up in the following: There is a clear realisation that these products are not for mass market, but for the "frontrunners", i.e. companies making an effort to reduce their footprint by looking into more sustainable alternatives that they are ready to pay a premium for. The final cost of the premium will be translated to the final consumers and their motivation to pay a higher price for the product or services is the key factor in the overall business model for such products. The project believes demand for greener products and services will continue to grow over time, along with the market's readiness to pay a premium price for them.
Marketing strategy available	There is no marketing strategy **for the products** yet as full-scale production is still to be established.. Another market that the project is looking into is the **CCU technologies market**. Thyssenkrup relies on B2B relations with major industries that are interested in CCU technologies as well. In this setting, Carbon2Value and Thyssenkrup can envisage entering the market as a CCU technology provider/seller.
Customers established	Specific customers for the products are on the radar, but it is too early to talk about supply agreements. As for the CCU technologies, there are talks with several potential 'customers' for the installation of a methanol plant, CCU facilities, technologies, and customisation of the processes. All these technologies that have been demonstrated at Carbon2Chem are attracting the interest of industries facing pressure to reduce carbon emissions.

A.3.5. Lessons

	Lessons
Economic aspects	• Since the commercialisation activities are still to come, it is too early to see any direct economic impact and value added, both for the companies involved and the regional/local economy.
Technological and innovation aspect	• Strategically focused R&I and demonstration project can help a region to build technological leadership. • Involvement of a wider network of scientific and industry actors ensures better adoption of the technologies, establishing synergetic links and achieving better results. • Governmental assistance can be instrumental in ensuring the presence of green energy suppliers in sufficient capacity for CCU-based production process to be carbon neutral.
Social aspects	• While the R&I and demonstration activities help to bring in high-skilled human capital into the region, it cannot guarantee long-term jobs. Long-term job-creation potential will coincide with the successful commercial plant.
General lessons	• A shared vision between the companies and the government is important in promoting such initiatives. Adjusted to the local circumstances, PPP is the possibly the most workable model for CCU initiatives in the existing climate policy framework which does not offer suitable conditions for CCU technologies.

A.4. Case study 4 – CO2-based polyol production at Covestro

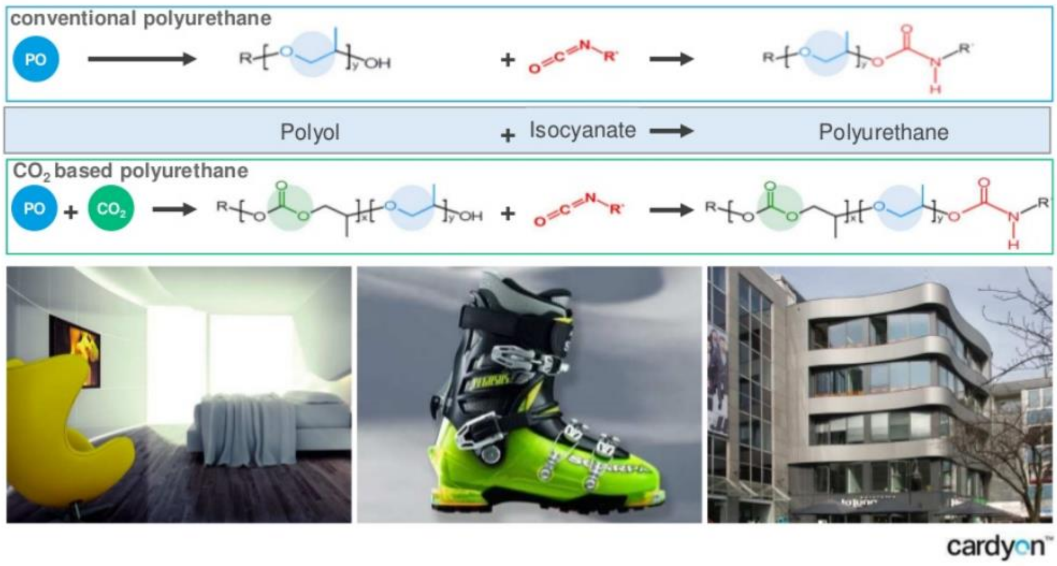
Case	CO2-based polyol production at Covestro
Project	Cardyon
Country / Location	Belgium
Company(ies)	Covestro
Value chain/products	Polyurethane production
Industrial sector	Chemicals
Market readiness level	Commercialised

A.4.1. Background

Covestro AG is a German company which produces specialty chemicals for heat insulation foams and transparent polycarbonate plastics. It is a Bayer spin-off formed in the autumn of 2015 and was formerly called Bayer MaterialScience, Bayer's materials science division.

Research about CO2 as a building block for polymers, namely polyurethanes started over 40 years ago and many researches have focused on finding the right catalyst for this process. The initial goal of this development was to develop a high-quality flexible foam material. With growing concern over climate change and carbon emissions, this process has acquired an additional value as an innovative CCU process.

Figure 16 Converntional and CO2 based polyurethane synthesis



Source: Covestro

It is important to mention that the extensive R&D and experimentation activities related to the new CO2-based polyols were developed at the so-called CAT Catalyst Centre, which is a collaborative effort between RWTH Aachen University and Covestro funded by these two partners[75]. Their initiative, called 'Dream Production', focused largely on developing the

[75] http://www.catalyticcenter.rwth-aachen.de/our-projects/dream-production.html

industrial production process CO-based polyols. The work included testing various catalysts, finding the optimum CO2-content that offers a balance between polymer chain flexibility and economy, other testing and experimentation research and LCA.

After continuous experimentation since 2009, the research team developed an innovative polyol called Cardyon, with a CO2-content of 20%, which makes up for the flexible polyurethane foam of mattresses. With the cooperation of the manufacturer/partner Recticel, the first CO2-based mattresses arrived on the market at the end of 2016. This added to Recticel's list of sustainable products recognised also for their technical performance.

Covestro has been operating its own production plant for the innovative polyols, which started in 2016 and is located in Dormagen. For this new process using CO2 technology, they work with a 25-metric-tonne chemical reactor and systems for processing the CO2-based polyol. The plant has a capacity of 5000 metric tonnes. The CO2 used is a waste stream from a neighbouring chemical facility. Although operating as a production facility, the plant in Dormagen was originally built as a pilot facility, thus its capacity is rather small.

Besides the cooperation between Covestro and Recticel in producing flexible CO2-based foams, another project is running to develop a rigid CO2-based foam. This project is called Carbon4Pur and is an EU Horizon 2020 project funded under the SPIRE programme. Carbon4Pur focuses on turning industrial waste gases (mixed CO/CO2 streams) into intermediates for polyurethane plastics in rigid foams/building insulation and coatings. Covestro is leading this project as coordinator and Recticel is a partner. ArcelorMittal provides the CO2 for the project.

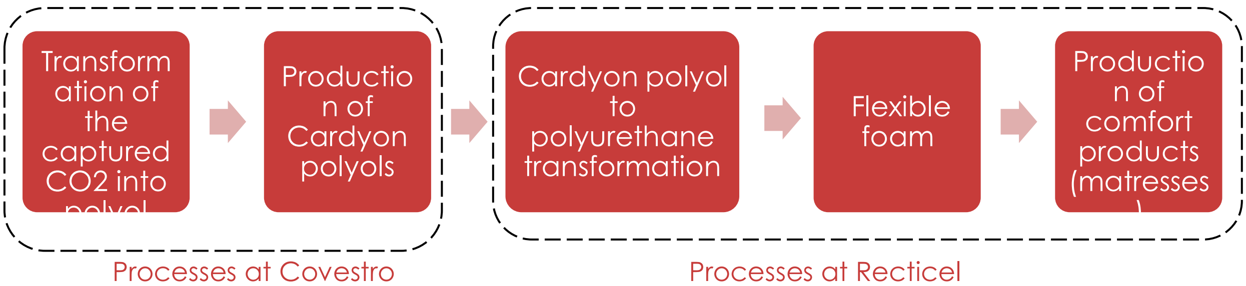
Covestro is now working on new application areas for its CO2-based technology: the manufacture of synthetic fibres using CO2 which can be used as a component in sports equipment.

With a current global polyols market of about 6.7 Mt/a, some 0.12 Mt/a of CO2 is estimated to be needed for polymer applications if the European polyol market continues to grow at the expected rates.

A.4.2. Value chain(s)

Covestro captures the CO2 from its chemical facility and transforms it using the right catalyst which is essential to make the chemical reaction with the CO2 possible. It results in a polyol called Cardyon: a raw material partially made of CO2 that becomes soft foam. Recticel then receives the Cardyon polyol and proceeds to the polyurethane transformation resulting in flexible foam and uses it in products such as mattresses.

Figure 17 Cradyon polyol based product value chain



Source: Covestro

A.4.3. Socio-economic opportunities and obstacles faced by the project

Opportunities and support factors that have been driving the technology development:

- Covestro was initially driven by a goal to develop a better-performing polymer, and binding CO2 molecules in the polymer structure was a promising technical solution which also offered environmental benefits – as concerns over climate change grew, this became a winning feature of the product.
- Recticel's decision to use new CO2-based materials in their product was motivated by the company's interest in developing a sustainable product portfolio, as explained in its Sustainability Strategy:

  > *"By developing the new Geltex® foam with CO2 polyol, we support the introduction of new sustainable technologies into our bedding products. At the same time, the new Geltex®mattresses are more durable with longer lifespans."* (CSR report of Recticel, 2017)

Obstacles challenging the development of the technology and/or project:

- The biggest technological challenge in creating new CO2-based polyols was to develop the catalyst. A lot of R&D was required to find the right catalyst as the formulation changes for every new application.
- Overall, any development of a new chemical product like polyol requires intensive R&D efforts and time. For example, in the current R&D project focusing on new types of polymers, bringing the product to the market is expected to take around 10 years. In Carbon4Pure, Covestro faced the challenge of a very energy intensive process which required lot of R&D to improve it.
- Covestro is for the moment working with artificial gas mixtures (not with industrial gases) due to security reasons. Indeed, working with industrial gases on lab scale is too dangerous and not possible. This represents a challenge, as working with industrial gases means the company has to clean and purify the gas first, and to have a demonstration plant next to the industrial source. Conditioning of the gas then takes place before to proceeding to the polyol production area.

On the Recticel side, there are no big technical challenges, but more related to upscaling. The company is open to increasing production based on CCU-based materials. However, as a pilot facility, Covestro has a volume limitation of 5000 tonnes/year, which in turn limits Recticel in its production.

A.4.4. Social and economic impact observed

A.4.4.1 Economic impacts

Competitiveness

New business lines/models/product portfolio	The cooperation between Covestro and Recticel resulted in a new product, special matrasses that can be labelled 'green products'. The product also has superior technical performance, justifying its premium price.
Formation of new markets and value chains in the region	A market for green intermediary input material, i.e. polyol that is used for manufacturing a consumer product. The market for this product is currently small.
Opening of new businesses and value chains in the region	The project did lead to a new business, but rather it extended the product portfolio of an existing company, Recticel.
Relocation of companies to the regions	No changes observed in this aspect

Increased interest from investors, new/envisaged investment flows	Not applicable. Production is small scale for now.
Higher energy and resource independence (from import)	No impact generated in this respect.

Economic benefits and costs

New value chain related revenues, profits, gross value added created (for various companies)	Based on the current small-scale plant, no significant profits have been achieved at Covestro or Recticel. The objectives of the pilot were more focused on testing the new technology and new products based on new polyols, validating the manufacturing and commercialisation opportunities, and testing the market acceptance of the final products. All these have been successful and increased the partners' confidence in upscaling this value chain.
Economic/resource savings achieved (if any)	No, this was not a core element of the pilot.
Costs and negative externalities experienced and envisaged in coming years	(To be discussed with the companies, focus on a future full-scale industrial facility.)

A.4.4.2 Technological and innovation impacts

Technical and technological advancement

New, improved, technical expertise	R&D efforts at Covestro have for many years allowed them to build expertise in advanced polyol synthesis with CO2 integration. "*Developing the cardyon® polyols based on our CO2 technology has been very demanding from a scientific point of view – we have gained tremendous insight on how the process works and how to improve it. And it has been great fun, as through our research network we made unexpected and profound discoveries previously unknown to us.*" (Dr Christoph Gürtler, Head of Catalysis Research/Covestro)
Technological leadership	Development of a new platform technology with potential impact for the plastics industry in total. Providing CO2-based plastic components with the same or better performance than conventional products.
TRL progression	In the years from the initial idea to precommercial pilot plant, the progression of TRL went from zero to almost the top level 8.
Transfer of more advanced technology into the local region	The in-house development and testing of the technology, rather than transferring it from somewhere else, has taken place through Covestro's long-lasting activities with CO2-based polyol R&D
Intellectual property/new patents filed	Covestro has filed over 40 patents in the field of CO2-based polyol research, and is today one of the global leaders in R&D in this area, as well as a technology leader in practical application.

Capabilities of local companies

Innovative service provision of local companies	No impact on other local companies has been observed.
Opening of new supporting services)	No impact on other local companies has been observed.
Creation of start-ups, spin-offs	No start-ups or spin-offs have been launched. Creation of CAT Catalytic Centre is a type of new R&D centre that has been created by Covestro and RWTH Aachen University, which is not a start-up or spin-off per se, but an organisation working on CO2-based innovations and products.

A.4.4.3 Social impacts

Employment

New jobs in new value chains	Although not a significant number, it has created indirect jobs and has had an indirect effect of creating new dynamics; new people are in the labs including a dedicated safety, new marketing team, new tech farm, etc. The same effects are predicted for the Carbon4Pur project; however, no concrete numbers or estimates are yet available. Moreover, beside potential job-creation, it will safeguard many jobs. With the extensive R&D work, several additional jobs can be associated with the CO2-based polyol development, including the team working at CAT CatalyticCentre[76]. At Recticel, there were no new jobs created, as changes or upgrades of the manufacturing process related to the new material were not large scale (due to limited supply of Cardyon). Nevertheless, staff had to be trained to work with the new material. Thus, existing jobs have been 'greened', rather than new jobs created.
New jobs in supporting services, logistics, ICT, etc.	N/a

Fostering knowledge in the Region

Strengthen knowledge base in local research organizations and businesses	R&D activities focused of CO2-based polyol at CAT Catalytic Centre (the collaboration with RWTH Aachen University) have culminated in specialist expertise which is globally recognised in this area.
Brain gain in the region through the project	R&D and pilot-related activities required strong scientific expertise, thus renowned scientists and engineers have been invited.
Relocation of companies	This has not been observed

76 https://www.covestro.de/en/sites/dormagen

Partnership with universities and PPPs

CAT Catalytic Centre is a collaboration between RWTH Aachen University and Covestro.

Linkages and partnerships

New partnerships created within industry, across different industries

A prominent example here is the long-term R&I partership between Covestro and RWTH Aachen University, formalised by the establishment of the CAT Catalytic Centre.

Another strong example is the partnership with Recticel that was established while the development and testing of the new CO2-based polyol was taking place, and an industrial partner was needed to develop the new material into consumer goods.

International partnerships created

Recticel is a Belgian company and Covestro is based in Germany, so this qualifies as an international partnership, though not an extensive one.

Company visibility and image

Visibility for companies' brands

The CO2-based polyol project has contributed a lot to the visibility of Covestro and Recticel and to their image as sustainability oriented companies.

This project is presented as a showcase example of innovation for circular economy and low-carbon economy. It has won several sustainability and innovation prizes.

Market potential

Price competitiveness of the product

The market price of the CO2-based polyol and products coming out of it is higher than traditional alternatives. But there is proven demand. Recticel is confident in the growing market potential for the mattresses based on the new polyol. Two winning features here are: **it is a green product with superior quality**.

Marketing strategy available

Recticel's Dream production' strategy includes marketing campaign and objectives. It generated good visibility for the innovation on different levels (for industry, researchers, society) and also plays with terminology associated with the dreaming/sleeping on comfortable mattresses!

Recticel also promotes their CO2-based polyol products (matresses) in traditional marketing formats.

Customers established	Recticel is a long-term partner and customer that procures the Cardyon polyol and develops the final product. Upscaling production will likely increase the number of such customers.

A.4.5. Lessons

	Lessons
Economic aspects	• There is firm evidence that the market for the new product is promising. Recticel is open to larger volumes of CO2-based polyol supply. However, an important factor in the success of the product is the superior quality that comes in combination with the sustainability features. This mean just making the product green might not be enough to achieve a successful product.
Technological and innovation aspect	• Industrial players are ready to take leadership in sustainable product development and cooperate with universities. This in turn boosts the knowledge base in the region and attracts highly qualified experts, further strengthening the local knowledge economy and increasing the competitiveness of the region in the long run. Such partnerships can benefit greatly from public support too.
Social aspects	• Strong social impact is generated through R&D and piloting activities. However, no durable impact on employment should be envisaged with commercial production facilities.
General lessons	• Companies can invest in and promote carbon-neutral products without direct support of government (funding). What is important is to create and maintain favourable framework conditions, as well clear and stable policy objectives for the long-term future.

A.5. Case study 5 – Technical photosynthesis of butanol and hexanol in Rheticus project of Evonik and Siemens

Case	Rheticus project for chemicals
Country/Location	Marl, Germany
Company(ies)	Evonik and Siemens
Value chain/products	Specialty chemicals, methanol
Industrial sector	Chemicals
Market readiness level	Research lab

A.5.1. Background

Launched in November 2017, the Rheticus joint research project is sponsored by the Federal Ministry of Education and Research and is linked to the Kopernicus Initiative which is supporting energy transition in Germany. The aim of Rheticus is to transform CO2 into specialty chemicals by combining electrolysis and fermentation processes.

Rheticus is done in collaboration between Evonik and Siemens. Siemens provides expertise in electrolysis technology used for converting the CO2 and water into hydrogen and CO (using electricity from renewable energy sources). Evonik's expertise is in the fermentation process; using metabolic processes and bacteria to transform gases containing CO into products.

The ultimate objective of the project is to demonstrate that artificial photosynthesis is feasible. Other benefits supposed to be the sustainable production of chemicals, energy storage, responding to energy fluctuations and grid stabilisation.

The project is still in research phase and the launch of the first test plant is planned for 2021 at the Evonik facility in Marl, Germany.[77]

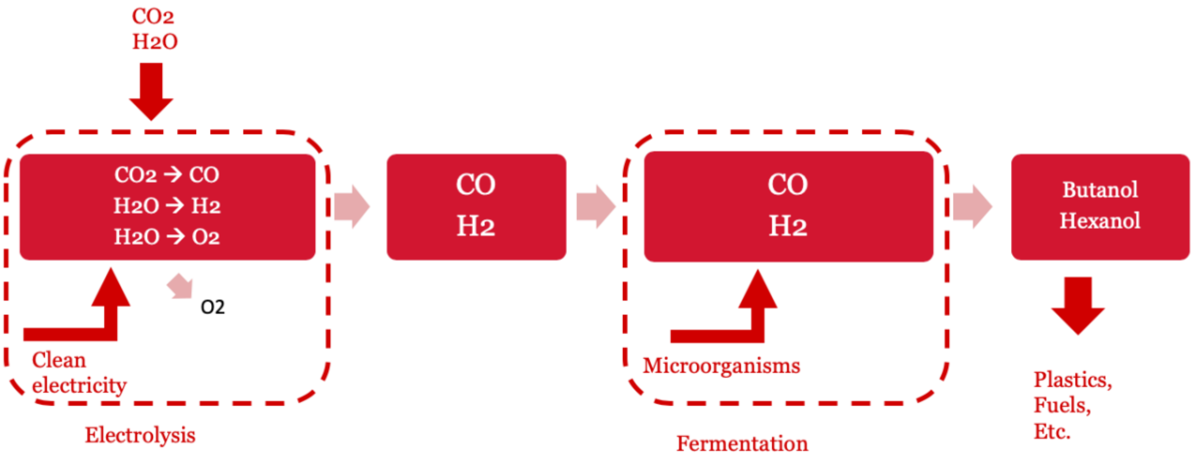
A.5.2. Value chain(s)

The technical photosynthesis established by Siemens and Evonik in the Rheticus project requires two main steps; the electrolysis and the fermentation.

During the electrolysis, Siemens converts CO2 and water, with the help of a green energy source, to CO and hydrogen. The two elements are then passed on to Evonik for fermentation. During this phase, the resulting secretion from the electrolysis, CO and hydrogen, is used and combined with bacteria which allows microorganisms to convert (through special metabolic processes) the CO contained in the synthesised gases resulting from the electrolysis. This results in specialty chemicals, such as hexanol and butanol, which are then used to produce plastics and nitrous supplements for fuels.

77 https://corporate.evonik.com/en/pages/article.aspx?articleId=25100

Figure 18 Value chain of technical photosynthesis established by Siemens and Evonik



A.5.3. Socio-economic opportunities and obstacles faced by the project

Opportunities and support factors that have been driving the technology development:

- Evonik and Siemens were driven by the goal of combining technology to prove that artificial photosynthesis was feasible. The focus was to help convert and store renewable electrical energy efficiently. The benefits were, however, proven to be multiple; the Rheticus technology is able to contribute to the reduction of CO2 emissions in the atmosphere, since it uses CO2 as raw material. Moreover, it means chemicals can be produced in a much more sustainable way.
- Support from the Kopernicus Inititative (which focuses on the energy transition in Germany) is one of the biggest drivers of the project. It will receive €2.8 million in funding from Germany's Federal Ministry of Education and Research (BMBF).[78]
- Another driver appears to be the CO2 tax in Germany, which makes a strong business case for Rheticus as it is now easier to convince companies to get involved in the project.
- The plant will be easy to adapt to different production requirements. It is modular and flexible regarding the location, the raw material sources and products manufactured. This adaptive characteristic makes the technology very attractive for the specialty chemicals industry.

Obstacles challenging the development of the technology and/or project:

- The energy source used for the electrolysis needs to be green and renewable, however it is really challenging to secure clean energy sources. A sufficient supply of clean energy is required, which means that the renewable energy sector has to grow to be able to respond to the demands of the project. Moreover, national plans and strategies to move to a greener energy system are still under construction in Germany which makes it difficult to go forward.
- The main obstacle is linked to the scientific development of the technology and to scale-up. The pilot plant has proven successful, however some elements linked to scientific barriers could go wrong when scaling up. These elements cannot be predicted in advance, but they will have to be dealt with. The present scientific barriers are related to time and to proving the feasibility of the technology.

[78] https://corporate.evonik.com/en/pages/article.aspx?articleId=25100

- Building a plant is never easy; it requires the right location and getting permission to set up there, which depends on the national regulation.

Business plan: The project applies a 'profit-planet-people' concept in its strategy development.

A.5.4. Social and economic impact observed

A.5.4.1 Economic impacts

Competitiveness

New business lines/models/product portfolio	Many products can be produced from butanol and hexanol: chemicals, household chemicals, feed, fuel, polymers, etc. Evonik is now looking at two different business models: the first approach is to use the technology to produce specialty chemicals for Evonik products. The second approach would be to sell the module to companies willing to convert CO2. This approach depends on the chemicals they would want to produce, and for that the technology would need to be adapted. The plant would be then controlled from the outside, as a remotely control digital process, but it still requires local people to run the process. People would need to be trained.
Formation of new markets and value chains in the region	This impact is addressed in Evonik's 'profit-planet-people' strategy. The impact of the project is positive, which is why the Ministry is supporting it. There are only a few projects using CO2 to produce commercial products. The Rheticus project is one of the first stepping out of the laboratory. The next step is to launch a commercial plant. Strong government support has been observed because the project is located in a coal mining region that needs to switch its industrial focus.
Opening of new businesses and value chains in the region	With the commercial plant, the production is predicted to deliver 20-30 metric tonnes of butanol/hexanol/product per year.
Reallocation of companies to the regions	The project is looking for companies interested in joining a joint venture (e.g. a customer for chemical products, a polymer based company/producer, etc.).
Increased interest from investors, new/envisaged investment flows	Many investors from all over the world are approaching Evonik's team either to invest in the technology or to buy it. Discussions are happening about the conditions, models, etc.
Higher energy and resource independence (from import)	No information

Economic benefits and costs

New value chain related revenues, profits, gross value added created (for various companies)	This impact has not been observed yet. However, such positive impacts are expected if the feasibility of the project is demonstrated.

Economic/resource savings achieved (if any)	Too early to observe.
Costs and negative externalities experienced and envisaged in coming years	Too early to observe.

A.5.4.2 Technological and innovation impacts

Technical and technological advancement

New, improved, technical expertise	Evonik has had a significant and positive impact on the international scientific world by inspiring other companies to start working on this type of technology. It is now possible to find patents from other companies now entering the field of technology combination. The number of people interested in this area is growing (for cooperation and business opportunities). Universities and academics are interested as well, but Rheticus is a commercialisation-oriented project, hence there is less involvement from universities and academics.
Technological leadership	Evonik is the absolute leader in combined electrolysis and fermentation technology. In gas fermentation technology (done by Evonik), the nearest competitor is LanzaTech. However, Evonik focuses on wider and more complex chemical products.
TRL progression	More complex than just TRL.
Transfer of more advanced technology into the local region	N/a. Own technology development.
Intellectual property/new patents filed	Four patents per year are submitted via the Rheticus project.

Capabilities of local companies

Innovative service provision of local companies	Not observed yet.
Opening of new supporting services (logistics, ICT, infrastructure setting and management)	Not observed yet.
Creation of start-ups, spin-offs	Not observed yet.

A.5.4.3 Social impacts

Employment

New jobs in new value chains	Evonik and Siemens employ 20 people for the Rheticus project.
New jobs in supporting services, logistics, ICT, infrastructure setting and management	Around five people are expected to work on each new plant built. These people would need to be trained.
Fostering knowledge in the region	
Strengthen knowledge base in local research organizations and businesses	N/a
Brain gain in the region through the project	For example, some people started working for this project.
Relocation of companies due to higher attractiveness	
Partnership with universities and PPPs	It would be possible, but only with companies at the moment.
Linkages and partnerships	
New partnerships created within industry, across different industries	N/a
International partnerships created	There is an idea to establish international partnerships, but it depends on the business model chosen. Rheticus is looking for partners and possibilities, but it requires conditions to be met: having a source of renewable energy and of CO2.
Company visibility and image	
Improved visibility for companies' brands	There is very high interest in Evonik as it is an innovative company. The positive image of Evonik increased. The technology would allow companies to play a role in climate change mitigation.
Market potential	
Price competitiveness of the product	Rheticus is looking into profit, it has to be competitive. This is the reason behind the focus on specialty chemicals; the price is higher and therefore it is easier to fit the production price and be competitive. Nowadays, customers (B2B, in the shops) are not willing to pay more for green products, hence it has to be cheaper or competitive with existing products.
Marketing strategy available	N/a
Customers established	Potential companies with whom we are speaking now.

A.5.5. Lessons

	Lessons
Economic aspects	• Since the commercialisation activities are still to come, it is too early to see any direct economic impacts and value added, both for the companies involved and for the regional economy.
Technological and innovation aspect	• R&I and demonstration projects like this can help a region to gain technological leadership. • Involvement of a wider network of scientific and industry actors ensures better adoption of the technologies, establishing synergetic links and achieving better results. • Government assistance can be instrumental in ensuring the presence of green energy suppliers with sufficient capacity for CCU-based production/processes to be carbon neutral.
Social aspects	• In terms of employment, further development of the CCU industry could remobilise a certain number of laid-off workers (but not all, as plants are small scale).
General lessons	• CO2 tax policy is making a business case for the technology. • Growing interest from investors and other partners.

A.6. Case study 6 – Carbstone Innovation technology for construction materials

Case	Carbstone Innovation technology for construction materials
Country/Location	Belgium, Genk and Farciennes
Company(ies)	Orbix NV and Carbstone Innovation NV
Value chain/products	Building blocks, pavers and bricks
Industrial sector	Construction and infrastructure
Market readiness level	TRL 8, TRL 9 soon attained

A.6.1. Background

Orbix is a Belgian company that has been specialised in recovering residual fractions from the stainless-steel industry and extracting natural resources ever since 1996. It has evolved its focus towards circular entrepreneurship. In 2004, Orbix created an new technology called Carbstone Innovation which focuses on valorising waste streams (or by-products), using CO2 to create high-quality building materials (floor tiles, building blocks, pavers, bricks, briquettes, etc.) with a CO2 negative footprint.

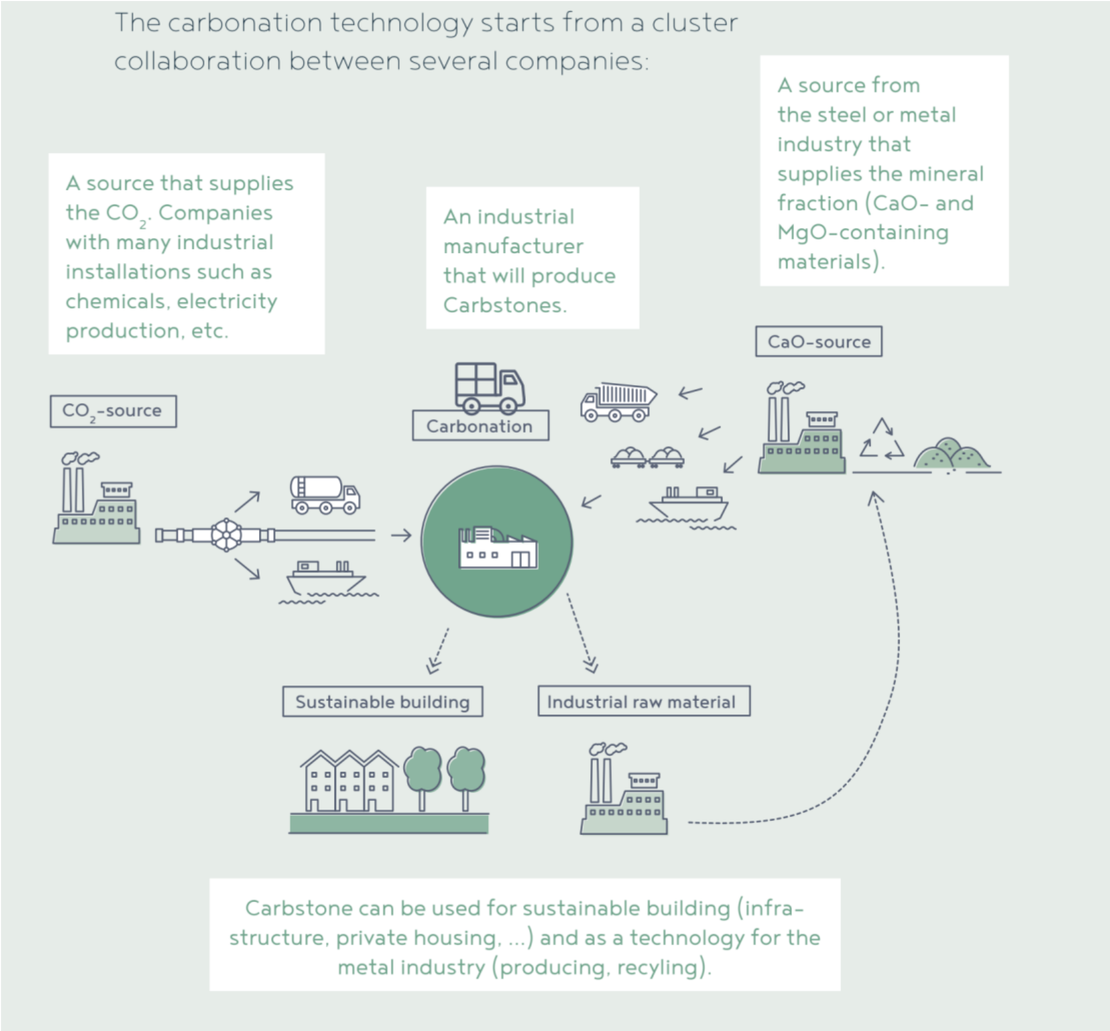
This technology is based on carbonation reactions between minerals containing calcium and magnesium oxides or hydroxides and CO2. As an example, a fine fraction of stainless-steel slags from Orbix, called Carbinox© (released during the breaking and washing process of the Stinox© granulates) has very interesting 'carbonatable' properties and acts as a binder to replace cement. This Carbinox© product is then combined with CO2 to create all forms of building products. That technology makes these products long-lasting and environmentally friendly, since they provide a unique and permanent way to store a substantial quantity of CO2, and to avoid using cement in the process. Furthermore, the product hardening time is also reduced from several days for cement to around 24 hours, which provides additional advantages.

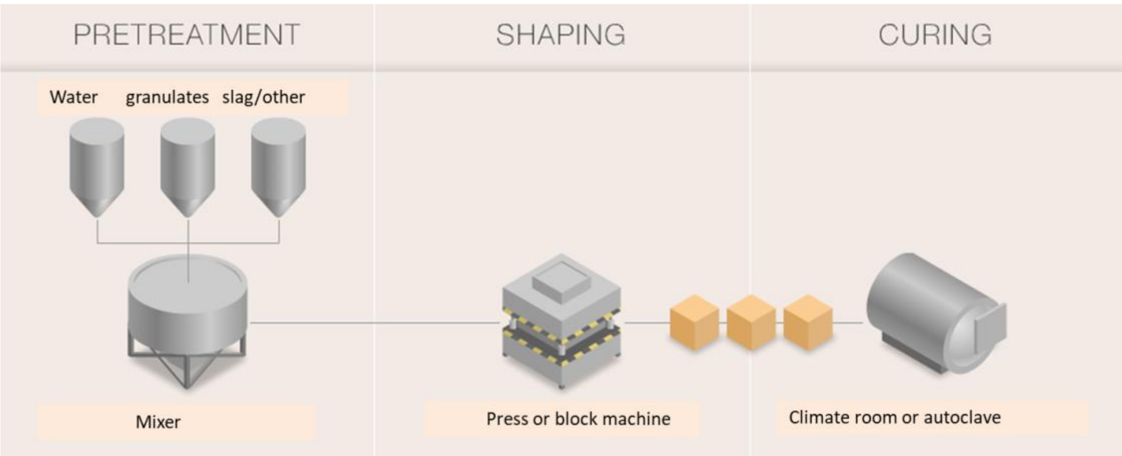
At the moment, the pilot plant in Farciennes is producing limited quantities of pavers and building blocks with the Carbstone Innovation technology. More commercial and industrial scale projects with different partners are in the pipeline in the area of Genk, in the province of Limburg, Belgium.

One of the projects relevant for this study is the Stapsteen project of Orbix implemented in Ghent, which aims to make street pavements with the Carbstone Innovation technology. Stapsteen is a testing and demonstration project, aiming to learn about the best-performing mix for pavement tiles, their environmental and hygiene impact, social and economic aspects etc. In the Stapsteen project, which is led by VITO and the city of Ghent, Orbix is using the slag of ArcelorMittal (and potentially the CO2 emissions of this steelmaker) to create pavements stones with their carbonation technology. The plan was to finalise the project by the end of 2019.

A.6.2. Value chain(s)

Figure 19 Carbstone value chain





Source: Orbix

In the first step, a composition of granulates, sand and binder Carbinox© is mechanically prepared and mixed with water to create a homogeneous mixture. In the second step, the mixture is pressed into a given shape with a hydraulic or vibrating press. Finally, the shaped product is placed in an autoclave or climate room and strengthened appropriately by treatment with CO_2, and finally results in the end product; building elements. In this process, the hardening or drying time of the product is 4-6 times shorter than traditional production with cement, which is seen as an additional advantage.

For the industrial implementation of the Carbstone Innovation technology, three actors are required: a source of CO_2, a source of 'carbonatable' material, and a producer of the final/construction material. Orbix is currently working with different types of materials; residues and waste streams such as different slag types, fly ashes, bottom ashes, etc.

The business model of Orbix is based on the offering of a Carbstone technology licence to projects where value is to be generated from the industrial waste. Hence, rather than producing or selling the final products, Orbix links the waste producers (steel mills), which is often also a CO_2 supplier, with a product manufacturer (concrete-based construction materials), and sets the production process that follows Carbstone technology.

A.6.3. Socio-economic opportunities and obstacles faced by the project

Obstacles challenging the development of the technology and/or project:

- The source of the CO_2 (received or bought) and the cost of capturing and supplying CO_2 are the most important economic factors for the Carbstone product to be economically viable. The cost below €10 per tonne of CO_2 allows the business model to work.
- The standardisation of the final product is important. When making a block from waste, regulations and standards are very stringent due to the possible content of heavy metals (Batch Leaching test – EN12457-4). This requires Orbix to constantly adapt the process and do repeated testing of the new product when working with new slag materials. Such adjustments are needed as the quality and content of slag can vary.
- Another regulation/conformity is to prove the environmental quality of the final product, to ensure it has a low footprint. There are no current norms for products containing CO_2, therefore there is nothing to compare it with, which renders the certification difficult.
- The required ten-year life span certification of the final product is difficult to achieve as there is not enough experience with the product.
- Changing a production plant to adopt Carbstone technology is rather difficult, requiring new facilities where the CO_2 is very well controlled and mastered, which is not easy and expensive.
- The building market tends to be conservative which renders the marketability of the product difficult.
- There is a constant need for R&D, especially when opening a new plant, because depending on the material used, the process changes. See also a note on the standardisation and meeting the environmental quality requirements.

Opportunities and support factors that have been driving the technology development:

- The biggest driver for such innovation is the growing political and societal focus on circular economy principles, concern about climate change and overall ambitions to address sustainability challenges. This motivates companies/entrepreneurs to develop solutions motivated not only by economic benefit, but also by their contribution to sustainability that the entrepreneur can achieve/prove.

A.6.4. Social and economic impact observed

A.6.4.1 Economic impacts

Competitiveness

New business lines/models/product portfolio	Orbix uses a business model that sees Carbstone technology as a new or improved sustainable construction material, as well as savings associated with the faster process (time and energy). This integrated package of technology, together with the Carbinox© binder, is already available for potential customers, and several contracts are being pursued. The company's preferred geographical interest is Belgium, where they want their technology to be commercialised first.
Formation of new markets and value chains in the region	The market for the Carbstone technology seems to be picking up with increased interest from industries, as well as recognition of it within the emission trading market as a carbon sink technology.
Opening of new businesses and value chains in the region	There is no fully functioning commercialised projects with the Carbstone technology in existence today, therefore it is too early to speak about impact.
Relocation of companies to the regions	Relocation of companies/production facilities that can deliver cheap CO2 will be needed to have a profitable business model. It is not likely that this impact will be observed in the current projects (e.g. Genk, Farciennes, etc.) as the format of the project does not require extensive network and service suppliers.
Increased interest from investors, new/envisaged investment flows	Some interest has been generated from investors planning to use this technology. Public funding has been attracted for developing and testing specific products, e.g. pavement tiles under the Stapsteen project in Ghent.
Higher energy and resource independence (from import)	Carbstone technology decreases the need for cement, which is an energy- and resource-intensive material. With the substitution of cement, it helps to reduce energy consumption as well. More efficient and less time-consuming processes offer further energy saving.

Economic benefits and costs

New value chain related revenues, profits, gross value added created (for various companies)	Due to a lack of commercial projects, it is too early to speak about actual economic impacts generated by the technology. However, theoretically the economics of the Carbstone technology-based production is promising, not only through the commercial value added of the product and potential savings in the process, but also through possibilities offered in the emission trading market. Carbon emissions reduced can be converted into emission quotas that can be sold on the carbon market under the European Emissions Trading Scheme, or in existing international carbon market schemes. Moreover, the Carbstone technology has potential to valorise waste by-products including CO2 from steel and other industrial facilities,

	thus reducing a waste product with a considerable negative impact.
Economic/resource savings achieved (if any)	Similar to above: no actual impact has been generated, but theoretical assessments point towards resource-savings (e.g. cement, slags, energy).
Costs and negative externalities experienced and envisaged in coming years	Potential negative externalities can lie within the product quality related challenges: environmental quality of the product when using wastes from the steel industry can vary. Reaching the required safety standards is a constant challenge and potential cost-related risk for Orbix as it requires individual attention in each commercial project.

A.6.4.2 Technological and innovation impacts

Technical and technological advancement

New, improved, technical expertise	Throughout the R&D and testing of the Carbstone technology, Orbix has managed to build strong expertise and experience in this area. At the moment, it is the only technology provider in this area in Belgium. But the company's expertise and technology can be seen as a strong competitor in the international market of similar carbonation technologies.
Technological leadership	Orbix with their Carbstone technology is a clear leader in the Belgian market, but it could be among the leaders in the international market as well (the company has not targeted the international market yet).
TRL progression	Through the R&D and testing activities the technology has been brought to TRL 8, where the prototype system has been successfully tested.
Transfer of more advanced technology into the region	This is the case observed when developing the technology locally (in Belgium), rather than transferring it from abroad.
Intellectual property/new patents filed	Two patents have been filed for Carbinox technology and processes.

Capabilities of local companies

Innovative service provision of local companies	No impact on other local companies has been observed yet.
Opening of new supporting services (logistics, ICT, infrastructure setting and management)	No impact on other local companies has been observed yet. CO2 and material transportation, bricks transportation, ICT technology (machine used).
Creation of start-ups, spin-offs	No start-ups or spin-offs have been created.

A.6.4.3 Social impacts

Employment

New jobs in new value chains *New jobs in supporting services, logistics, ICT, infrastructure setting and management*	Due to lack of commercial projects, impacts have not been observed/evaluated yet. However, application of the technology will certainly create a number of jobs along several sections of the value chain: in CO2 capture, slag processing, carbonation units, as well as in additional support and infrastructure services. Furthermore, temporary jobs have been created at the installation stage; for now, Orbix hired three people (operators and technicians) dedicated to the pilot plant, and a lot of engineers have been hired part-time for the development. Moreover, Orbix needs heavy R&D support, since every time the mixture is changed, research is needed to find the right curing, CO2 concentration, etc.

Fostering knowledge in the region

Strengthen knowledge base in local research organizations and businesses	In R&D and testing activities, Orbix often cooperated with local research organisations and other companies. This has contribute to the creation of knowledge and expertise in the country. An example of such cooperation is the Stapsteen project, which is based on collaborative research and testing activities with Ghent University, VITO as well as other partners.
Brain gain in the region through the project	No impact has been observed on these aspects.
Relocation of companies due to higher attractiveness	No impact has been observed on these aspects.
Partnership with universities and PPPs	As mentioned above in R&D and testing activities, Orbix often cooperated with local research organisations and other companies (e.g. Ghent University and government of Ghent city in Stepstone project).

Linkages and partnerships

New partnerships created within industry, across different industries	The creation of cross-industry partnerships has been confirmed with actors such as CO2 producers, heat producers, block producers, market analysts, and more. All of whom could be involved in the North Sea Port CCU scheme if large-scale production is needed there.
International partnerships created	Orbix confirms it does have international partnerships but because of non-disclosure agreements, these must remain confidential.

Company visibility and image

Improved visibility for companies' brands	Orbix has been dealing with environmental management services since 1996. Over the years, based on the experience gained, and in light of new sustainability trends, it has deliberately transited to a 'zero waste' company that positions itself as contributing to the circular economy model. The impact on technology recipients is still to be seen: the companies that will apply the Carbstone technology are likely

to improve their sustainability performance and boost their visibility as a greener company.

"In 2016, the company was renamed Orbix. […] The name Orbix wasn't chosen by accident, since Orbix refers to 'orbis', which means 'circle' in Latin. In other words, a name that is perfectly in keeping with our vision of circular entrepreneurship. Our company is imbued with circular thinking. And since 2016 it's also a part of our name." (Orbix company website)

In the current model, Carbinox and other materials produced by refining by-products from stainless steel production, as well as carbonation technology, are central. This helps the company to gain visibility, while its innovative technology earned Orbix international recognition: the Global Slag Award and Global Slag Plant, Belfius Smart Award, and VOKA Innovatie Award.

Orbix also participates in international conferences where they present the Carbstone technology: Slag Valorisation Symposium, Global Slag Conference, Carbon Dioxide Utilisation Summit…

Market potential

Cost competitiveness

Cost competitiveness is a challenge that Orbix has to address in a dynamic environment. As stressed above, the cost of CO2 is an important determinant of economic viability and therefore a cost-factor in the project. Keeping the cost below €10 a tonne allows the business model to work.

The cost of products, carbonated building blocks, pavements, etc. will depend on the cost required to ensure the health and safety performance of the new product, which needs to be resolved on the level of individual products.

Overall, there is a good chance that the production cost will still be compatible with traditional products due to efficiencies envisaged in the process. (Check how the cost competitiveness is coming up in Stapsteen.)

Marketing strategy available

The marketing of the Carbstone technology is well established. Orbix only focuses on the marketing of the licence, the marketing of the building elements produced with the technology is the task of the producers who bought the licence.

Customers established

As discussed above, there are a number of customers interested in the technology and with some of them, projects have been initiated.

A.6.5. Lessons

	Lessons
Economic aspects	• In ensuring the economic viability, such technologies and products could benefit from the international emission trading market. It is important to consider and exploit this opportunity.

	• There is good potential for green public procurement instruments to enlarge the market opportunities for carbonation-based construction materials, ensuring the business case for producers. • Cost competitiveness is strong, this has been shown in the business model calculation.
Technological and innovation aspect	• Bringing such technology from idea to market took 15 years. It is important that diffusion of such technologies does not get blocked because of challenges such as CO2 supply cost, or cost competitiveness. The role of policy/regulation in creating favourable condition for the technology is important.
Social aspects	• Carbstone technology has strong potential to bring additional jobs, establish symbiotic linkages, and offer attractive greening opportunities for steel and construction industries, as well as for consumers of the final products.
General lessons	• Development of an industrial symbiosis cluster (steel, construction material manufacture, CO2 source) is key.

A.7. Case study 7 – OCAP – Organic CO_2 Assimilation by Plants

Case	OCAP – Organic CO_2 Assimilation by Plants
Country/Location	The Netherlands
Company(ies)	Linde Group Suppliers: Shell Pernis, Alco Partners/clients: LTO Noord Glaskracht, WUR, Tomatoworld, B-Mex, Letsgrow
Value chain/products	CO_2 to Greenhouses
Industrial sector	Agriculture
Market readiness level	Commercialised

A.7.1. Background

OCAP is the abbreviation for Organic CO_2 for Assimilation by Plants. It started as a joint venture of Linde Gas, a leading gas and engineering company, and Volker Wessels. In 2015, Linde Gas bought out all shares and became a sole owner of OCAP.

In the mid-1990s, the company came up with the idea to deliver CO_2 from industrial sites to greenhouses, to promote crop growth. A common way to generate CO_2 in the greenhouses is to burn natural gas in co-generation plants and boilers, generating heat as a by- product that would be destroyed during the summer months and reused during the cold months.

An alternative was to purchase liquid CO_2 from nearby industrial sites and have it delivered it to the greenhouses in a tanker by road. However, the process was not easy. The capture, compression, liquification and transportation is expensive and requires a lot of energy. The transportation by road also has some disadvantages.

A decade later, a feasible alternative was found. In 2005, OCAP started to supply the first CO_2 by pipeline to horticulturists. The Shell Refinery in Pernis, and later on the bioethanol factory Alco, were connected to an unused 85 km long pipeline, and a 250 km pipeline distribution network was installed, as well as a compression station.

Today, OCAP supplies approximately 500 kilotonnes of CO_2 per year to more than 600 greenhouses at the time of writing. (Note: re-use of 100 kilotonnes of CO_2 by OCAP saves the combustion of around 29 million cubic metres of natural gas and avoids the emission of 51 kilotonnes per annum (tpa) of CO_2). The company is constantly expanding the supply by securing CO_2 from other sources as well. At present, OCAP does not have enough tonnes of CO_2 to fulfil the demand of the greenhouses. In addition, the greenhouses have signed an agreement with the Dutch Government that they will be fully sustainable by 2040, which will create more business opportunities for OCAP, which means even higher demand for CO_2.

It is important to mention that while OCAP is active in the Netherlands, the Belgian market is also in the picture.

Figure 20 Map indicating the area of activity of OCAP

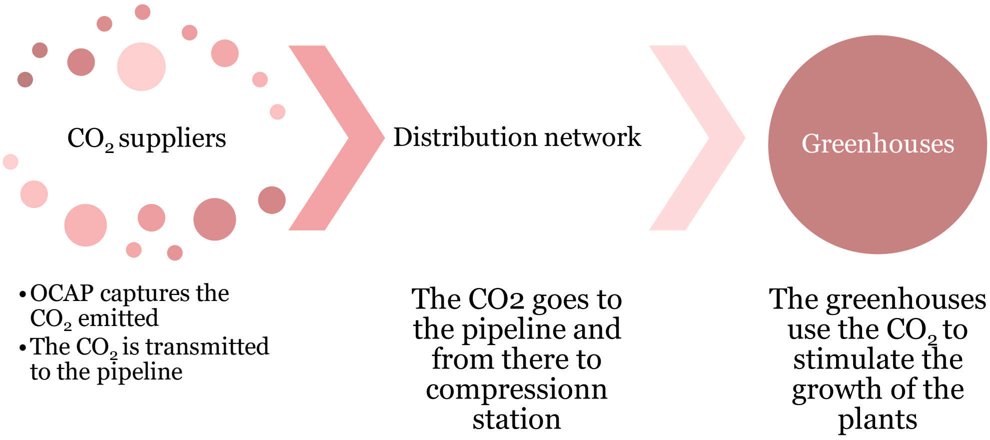
Source: OCAP

A.7.2. Value chain(s)

As it can be seen in the diagram below, the value chain has three simple steps:

1) The first one is the capture of the CO2 emitted from the suppliers. As mentioned, there are different suppliers to OCAP. Once captured, the CO2 goes to the pipeline.
2) Through the pipeline it is distributed to the greenhouses.
3) The greenhouses use the CO2 to stimulate the growth of the plants, instead of creating the CO2 themselves by combustion.

Figure 21 Value chain of OCAP



Source: interpretation based on interviews

A.7.3. Socio-economic opportunities and obstacles faced by the project

Obstacles challenging the development of the technology and/or project:

- The quantity of CO2 available in the flue gas is important; the right concentration is required in the plants. If the concentration is between 6/10% of the flue gas it becomes too expensive to transport the CO2 to the greenhouses, and thus it is necessary to have government subsidies to complement the investment. At the time of writing, there are no subsidies available in Belgium, but they are expected. They will be granted on a case by case basis.
- The activities of OCAP itself are not part of the ETS system, only the fossil CO2 source itself covered. However, it would help the greenhouse sector if the external supply of CO2 can be considered as a CO2 emission reduction for the fossil source, which is currently not the case. A possible solution is, that the current ETS system is adjusted in a way that the fossil CO2 source can subtract CO2 emissions from its balance.
- Constantly changing rules and policies are posing some obstacles.

Opportunities and support factors that have been driving the technology development:

- Extensive public support was one of the important factors driving OCAP's economic viability. Repurposing the 85 km stretch of pipeline (former natural gas pipeline) for CO2 transport purposes at zero cost strengthened the economics of the project.

A.7.4. Social and economic impact observed

A.7.4.1 Economic impacts

Competitiveness

New business lines/models/product portfolio	In 2005, OCAP put in place a business model that relied on a new approach in delivering and controlling the CO2 in greenhouses. This model offers much greater efficiency, convenience, optimisation of the process, and greater resulting productivity. All these made factors OCAP a leader in this market and allows it to expand the business.
Formation of new markets and value chains in the region	While CO2 enrichment in greenhouses in not a new approach, the OCAP technology came to the market with a new, more attractive technology and new value chain which valorised the

Opening of new businesses and value chains in the region	existing CO2 sources, previously seen as industrial emissions. By creating synergetic technology, it offered a win-win solution to industries and farmers.
Relocation of companies to the regions	This has not been the impact of the project.
Increased interest from investors, new/envisaged investment flows	Investment for further expansion was mostly from OCAP.
Higher energy and resource independence (from import)	Not relevant issues in this context.

Economic benefits and costs

New value chain related revenues, profits, gross value added created (for various companies)	The technology is definitely beneficial for the entire sector. Harvests will be increased, and it will boost investment for bigger greenhouses.
Economic/resource savings achieved (if any)	CO2 suppliers have benefited from this technology, allowing them to capture their CO2 emissions and add value to them.
Costs and negative externalities experienced and envisaged in coming years	There seems to be little economic risk associated with investing in or starting to use this technology.

A.7.4.2 Technological and innovation impacts

Technical and technological advancement

New, improved, technical expertise	Over the years, OCAP has fine-tuned the technology and strengthened their expertise. Collaboration with scientific researchers played a strong role in this.
Technological leadership	Today, OCAP is seen as a technology leader in this area. The technology is not diffused across the EU, but it is likely that it will be picking up in the coming years.
TRL progression	The technology is at the end of the TRL, full commercial application stage. However, it is constantly being improved with ongoing monitoring of the data on the productivity of the greenhouses, responses of plants.
Transfer of more advanced technology into the local region	N/a
Intellectual property/new patents filed	N/a

Capabilities of local companies

Innovative service provision of local companies	No significant upgrade, improvements or innovations in the partnering companies/service providers have been observed.

Opening of new supporting services (logistics, ICT, infrastructure setting and management)	An ICT programme for monitoring and assessment of productivity was developed in collaboration with Wageningen University and became a new service or tool under the OCAP management.
Creation of start-ups, spin-offs	No start-ups and spin-offs have been created.

A.7.4.3 Social impacts

Employment

New jobs in new value chains	Not many jobs have been created at OCAP. ICT technologies are helping to manage all sites, keeping the team small.
New jobs in supporting services, logistics, ICT, infrastructure setting and management	Limited or no impact here as well.

Fostering knowledge in the region

Partnership with universities and PPPs	Linde, the matrix organisation of OCAP, developed a computer programme with universities in The Netherlands, mainly the University of Wageningen. The programme can help to predict how much CO2 is needed in the greenhouses and how much will be produced. They also get more details from the greenhouses, such as the sunlight hours, the CO2 that needs to be infused, among others.
Strengthen knowledge base in local research organizations and businesses	Direct access to the live experimentation and the data is extremely beneficial for researchers at Wageningen University. At the same time, their findings also inform OCAP and farmers, which helps them to use the results in their daily activities, gain insights, and adjust CO2 management in the plant growing.
Brain gain in the region through the project	This has not been observed.
Relocation of companies due to higher attractiveness	This has not been observed.

Linkages and partnerships

New partnerships created within industry, across different industries	The model includes partners from agro-sector, industries supplying CO2 and intermediaries that link them. This an example of a small-scale industrial symbiosis.
International partnerships created	No international partnership within the activities in the Netherlands.

Company visibility and image

Improved visibility for companies' brands	The OCAP business is seen as a best practice example in this area and its visibility has grown with its success.

Market potential

Price competitiveness	The market for suppliers of such technology and services is not so big, and prices offered by OCAP so far have been well received by the farmers.
Marketing strategy available	The marketing strategy is pretty straightforward and does not include non-conventional approaches.
Customers established	OCAP has a very large customer base covering over 600 greenhouses that includes argi-farms in such locations as Westland, Bleiswijk, Bergschenhoek and Berkel en Rodenrijs, Zuidplaspolder, Rijenshout, Alsmer, all located in North and South Holland.

A.7.5. Lessons

	Lessons
Economic aspects	• There is good potential for adopting CO2 enrichment in greenhouse-based plant growing in Belgium. If this technology is introduced, it will definitely benefit the entire sector, boosting harvests and investment in bigger greenhouses.
Technological and innovation aspect	• Use of the existing unused pipeline infrastructure was a good technical idea for the OCAP project.
Social aspects	• Application of the CO2 enrichment in the greenhouses in Belgium will surely create new jobs; however, they will be mainly related to secondary employment such as transport of CO2, delivery, IT development, biotechnology, etc. • Greenhouses in Belgium are less aware of the advantage of using CO2 in their crops. There is not a lot of tradition of using CO2 to support and accelerate plant growth. As a consequence, it might be difficult to implement it in Flanders. More information and awareness-raising among Belgian greenhouse farmers about the benefits of the CO2 enrichment in plant growth is needed.
General lessons	• Given the proven technology and benefits achieved in agriculture, plus less stringent requirements towards the source of CO2, Belgium is a strong candidate for taking up this technology.

References

Al-Saydeh, S. A., & Zaidi, S. J. (2018). Carbon Dioxide Conversion to Methanol: Opportunities and Fundamental Challenges. Carbon Dioxide Chemistry, Capture and Oil Recovery, 41.

An, X., Zuo, Y. Z., Zhang, Q., Wang, D. Z., & Wang, J. F. (2008). Dimethyl ether synthesis from CO2 hydrogenation on a CuO− ZnO− Al2O3− ZrO2/HZSM-5 bifunctional catalyst. Industrial & Engineering Chemistry Research, 47(17), 6547-6554.

Bertos, M. F., Simons, S. J. R., Hills, C. D., & Carey, P. J. (2004). A review of accelerated carbonation technology in the treatment of cement-based materials and sequestration of CO2. Journal of hazardous materials, 112(3), 193-205.

Bian, J., Xiao, M., Wang, S. J., Lu, Y. X., & Meng, Y. Z. (2009). Carbon nanotubes supported Cu–Ni bimetallic catalysts and their properties for the direct synthesis of dimethyl carbonate from methanol and carbon dioxide. Applied Surface Science, 255(16), 7188-7196.

Brennan, L., & Owende, P. (2010). Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. Renewable and sustainable energy reviews, 14(2), 557-577.

Centi, G., & Perathoner, S. (2009). Opportunities and prospects in the chemical recycling of carbon dioxide to fuels. Catalysis Today, 148(3-4), 191-205.

COM(2020) 98 final, A new Circular Economy Action Plan: For a cleaner and more competitive Europe, Brussels, published on 11 March 2020

CORESYM (2017) 'CarbOn-monoxide RE-use through industrial SYMbiosis', prepared by Metabolic, available at https://www.metabolic.nl/publications/coresym-carbon-monoxide-re-use-through-industrial-symbiosis/

Cuéllar-Franca, R. M., & Azapagic, A. (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. Journal of CO2 utilization, 9, 82-102.

Fernández-Dacosta C., van der Spek M., Hung C.R., Oregionni D.G., Skagestad R., Parihar p., D.T. Gokak, Hammer Strømman A., Ramirez A. (2017) Prospective techno-economic and environmental assessment of carbon capture at a refinery and CO2 utilisation in polyol synthesis, Journal of CO2 Utilisation, Volume 21, October 2017, Pages 405-422,

Jiang, Z., Xiao, T., Kuznetsov, V. Á., & Edwards, P. Á. (2010). Turning carbon dioxide into fuel. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 368(1923), 3343-3364.

Kokal, S., & Al-Kaabi, A. (2010). Enhanced oil recovery: challenges & opportunities. World Petroleum Council: Official Publication, 64.

Li, L., Zhao, N., Wei, W., & Sun, Y. (2013). A review of research progress on CO2 capture, storage, and utilization in Chinese Academy of Sciences. Fuel, 108, 112-130.

Li, Y., Horsman, M., Wu, N., Lan, C. Q., & Dubois-Calero, N. (2008). Biofuels from microalgae. Biotechnology progress, 24(4), 815-820.

Markewitz, P., Kuckshinrichs, W., Leitner, W., Linssen, J., Zapp, P., Bongartz, R., ... & Müller, T. E. (2012). Worldwide innovations in the development of carbon capture technologies and the utilization of CO 2. Energy & environmental science, 5(6), 7281-7305.

Metz, B., Davidson, O., De Coninck, H., Loos, M., & Meyer, L. (2005). IPCC special report on carbon dioxide capture and storage. Intergovernmental Panel on Climate Change, Geneva (Switzerland). Working Group III.

Pieri T., Nikitas A., Castillo-Castillo A., Angelis-Dimakis A. (2018). Holistic Assessment of Carbon Capture and Utilization Value Chains, Environments 2018, 5, 108

Robert M. Handler, David R. Shonnard,Evan M. Griffing, Andrea Lai, Ignasi Palou-Rivera (2015) Life Cycle Assessments of LanzaTech Ethanol Production: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas Feedstocks. Industrial & Engineering Chemistry Research 55(12)

Styring, P., Jansen, D., De Coninck, H., Reith, H., & Armstrong, K. (2011). Carbon Capture and Utilisation in the green economy (p. 60). New York: Centre for Low Carbon Futures.

Yu, K. M. K., Curcic, I., Gabriel, J., & Tsang, S. C. E. (2008). Recent advances in CO2 capture and utilization. ChemSusChem: Chemistry & Sustainability Energy & Materials, 1(11), 893-899.

Zhou, X., Su, T., Jiang, Y., Qin, Z., Ji, H., & Guo, Z. (2016). CuO-Fe2O3-CeO2/HZSM-5 bifunctional catalyst hydrogenated CO2 for enhanced dimethyl ether synthesis. Chemical Engineering Science, 153, 10-20.

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