Project no. 723678

“**The next Generation of Carbon for the Process Industry**”

Coordination and Support Action

Theme [SPIRE 5] – Potential use of CO_2 and non-conventional fossil natural resources in Europe as feedstock for the process industry

Deliverable D2.2:
Report on fully integrated and intensified value chain concepts for industrial symbiosis

Due date of deliverable: 31st October 2017

Actual submission date: 23rd November 2017

Start date of project: 1st September 2016 Duration: 24 months

Organisation name of lead contractor for this deliverable: DECHEMA

Release no.

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Table of Contents

1. Executive Summary

This report indicates the potential and the technological possibilities for the implementation of industrial symbiosis related to gaseous waste streams, in particular carbon dioxide (CO_2) and carbon monoxide (CO). The report summarises most promising approaches on the latest developments and projects using CO_2 or CO streams to generate valuable products in Europe. In this document the term ‘industrial symbiosis’ is used for collaborations between different sectors or enterprises, in which materials, energy, water and by-products as well as waste are exchanged. Typically, side streams of one company or sector is used as raw material or energy supply by another sector or company. The focus here is on CO_2/CO containing streams.

The most relevant sources of CO_2 related to mass for further usage of carbon in other sectors are from steel manufacturing, cement industry and chemicals production. The most relevant amount of CO can be obtained from steel manufacturing. Within this report various value chains linking different industrial sectors and companies are presented.

At the Kalundborg Eco-industrial park in Denmark, the first full commercial realised industrial symbiosis was established: More than 30 exchanges of energy, water and material between the involved companies were realised. However, the idea to use CO_2 or CO as raw material for chemical production was not considered in Kalundborg at that time. Nevertheless, the Kalundborg example depicts the motivation and opportunities for industrial symbiosis and releases space for further concepts that can be implemented such as CO_2 utilisation in order to use waste streams that were not considered as valuable raw material in the past.

The most prominent example within this report in respect to CO_2/CO utilisation is the linkage of steel manufacturing with chemicals production. Two very large cooperation projects are funded under this topic, the Steelanol and Carbon2Chem project. This underlines the importance and potential of coupling these two sectors. Further symbiotic effects could be exploited by linking CO_2 outputs of chemical sites with the production of new chemicals. Activities at Rotterdam Harbour Industrial complex can be taken as examples. Linking CO_2 streams from chemical production to agriculture is currently implemented in the Netherlands by distributing waste CO_2 via distribution network from Rotterdam Harbour Industrial park to greenhouses all over the country. Finally, the potential of coupling CO_2 originated by bioprocesses with chemical or biochemical production has been investigated. Most important is CO_2 coming from digestion processes. The main pathway here is methanation to produce SNG. Further approaches focus on the production of agricultural fertiliser.

Moreover, the report highlights Power-to-X-concepts as key for sector coupling and an extension of industrial symbiosis. The importance of this approach can be deduced by the number of large collaborative research projects supported by funding agencies such as the ongoing Kopernikus P2X project, funded by the German Federal Ministry of Education and Research.

Industrial symbiosis in terms of CO_2/CO waste stream usage is a promising approach. However, to generate high valuable and quality products from CO_2, appropriate CO_2 and CO capture, separation and conditioning processes have to be implemented prior to the actual

CO_2 conversion process. The classification of the carbon capture and separation methods are based on different physicochemical processes, like absorption, gas-solid reactions, adsorption, cryogenic methods, membrane separation techniques or processes based on natural incorporation.

Future looking concepts and further potential symbiotic relationships can be employed by using the outcome of deliverable 2.1. The deliverable 2.1 Value chains highlights products and synthesis pathways were CO_2 or CO are used as raw material. Large companies or SMEs may use the deliverable as checklist in order to identify gaps and business cases that can be installed in industrial parks in order to use CO_2 or CO streams, which are otherwise vented to the atmosphere. IP ownership as well as revenue questions must be considered and well-defined while exploring new symbiotic relationships.

2. Introduction

The term ‘industrial symbiosis’ was first defined by a station manager in Kalundborg as "a cooperation between different industries by which the presence of each…increases the viability of the others, and by which the demands of society for resource savings and environmental protection are considered"[1]. The term industrial symbiosis refers to collaborations between different sectors or enterprises, in which materials, energy, water and by-products as well as waste are exchanged. Typically, side streams of one company or sector is used as raw material or energy supply by another sector or company. One example of industrial symbiosis is the electricity-based heating and steam generation by the chemical industry as demand side management and service to the power sector. The fast response time of this technology allows valorisation of intermittent surplus supply of renewable electricity, hence improving flexibility in the power supply. In return, the chemical industry can benefit from periods with low electricity prices. Another element is the valorisation of off-gases provided by other industries for chemical production. The products and synthesis pathways described in deliverable 2.1 are characterised by a high demand for carbon dioxide or carbon monoxide as feedstock. Sources of carbon monoxide are also important to consider as many processes involve syngas. This report consequently aims at describing industrial symbiosis opportunities whereat process industries manage demand and supply, in which the chemical industry valorises side process gas streams of CO_2 and/or CO from other sectors.[2]

This report aims to summarise the opportunities that can be retrieved by industrial symbiosis and in the broader sense by sector coupling, whereat renewable energy is used as primary energy for the electrification of sectors such as heat and transport. An assessment of the environmental and economic potential will be carried out in work package 4 of the CarbonNext project and will be presented in the appropriate reports. This present report comprises various examples of industrial symbiosis that are already put into practice or currently under preparation. The approach of industrial symbiosis is not yet implemented at many industrial sites and at an industrially relevant scale. That is why this report focuses mainly on R&D projects with industrial claims as just no industrial scale sites “working in symbiosis field” in relation to CO_2 or CO utilisation.

The basic idea for both, industrial symbiosis and sector coupling, is the link between sectors, whereas industrial symbiosis are considered to connect energy and material in- and outputs as well as the mutual exchange of knowledge at a regional level from at least one industry to another and sector coupling’s purpose is the connection between the sectors electricity (form carbon low sources), heat and transport. The electrification of the sectors heat and transport increases the demand for renewable energy and shall displace fossil fuels.

One example that can be seen as industrial symbiosis and/or sector coupling is the integration of Power-to-X technologies and concepts into industrial production value chains. Power-to-X

[1] Chertow, Marian R (2007). ""Uncovering" Industrial Symbiosis." Journal of Industrial Ecology 11.1: 11-30. Print

[2] A. Bazzanella, F. Ausfelder, DECHEMA, CEFIC Technology Study “Low carbon energy and feedstock for the European chemical industry”, ISBN: 978-3-89746-196-2, Frankfurt am Main 2017.

concepts are involving various technologies for electricity conversion, energy storage, and reconversion pathways using surplus energy caused through fluctuating renewable energy supply and demand. The most relevant pathways in respect to carbon dioxide and carbon monoxide are Power-to-Gas and Power-to-Liquids. In the present report Power-to-Heat will not be considered as it does not involve the utilisation of CO_2 or CO. Power-to-Gas concepts are using electricity to split water into hydrogen and oxygen by electrolysis. The evolving hydrogen can further be injected into the natural gas grid, used as fuel in fuel cell systems (e.g. transport) or can be used as basis chemical for a quantity of processes in industrial production. Moreover, combining the hydrogen with carbon dioxide using methanation converts the two gases to methane to be used as natural gas. Additionally, the hydrogen can also be used to upgrade the quality of biogas. The umbrella term Power-to-Liquids comprises technologies converting electricity, water and carbon dioxide into synthetic fuels (Power-to-Fuel) or into valuable chemicals for further usage in the chemical industry (Power-to-Chemicals). Prominent examples in this context are liquid natural gas (LNG), methanol, long-chained alcohols and oxymethylene ethers (for blending diesel fuels). Thus Power-to-X depicts being a convenient method to link the transport, energy and chemical sectors by using symbiosis effects related to CO_2 / CO origination and utilisation.

The present report gives an overview of existing and promising examples for industrial symbiosis for carbon outputs from industrial production processes and carbon originated by bio processes and points out the possibilities to use P2X technologies to link sectors like energy, transport and chemical industry.

All these concepts and technologies described in the present report have demand for pure carbon dioxide respectively monoxide as feedstock. This requires efficient carbon capture, separation and conditioning technologies to upgrade the CO_2 and CO streams coming from industrial processes before utilisation as feedstock for further processing. Therefore, those separation and conditioning processes are indispensable for exploiting industrial symbiosis potentials in this field. The processes to separate carbon dioxide from an industrial flue gas or exhaust gas streams are based on different physicochemical principles like absorption techniques, methods using gas-solid reactions, adsorption techniques, cryogenic methods, membrane separation techniques and processes based on natural incorporation. The present report includes a list with promising techniques for CO_2 separation processes.

Deliverable 2.1 Value chains and 2.2 Industrial symbiosis shall help large industries or SMEs to indentify opportunities where further symbiotic effects can be deployed by using CO_2 or CO containing streams for further usage.

3. CCU concepts for industrial symbiosis

Concept of Industrial symbiosis

The most prominent and representative example for industrial symbiosis is the Kalundborg Eco-Industrial Park being the first comprehensive realisation of industrial symbiosis: In Kalundborg, Denmark, several companies located in the small city have created a symbiosis network sharing energy, water and materials. The first industrial activities started in 1959. Nevertheless, a symbiotic CO_2 or CO management was not established nor thought of in 1959. The Kalundborg example, however, is the best model in order to describe the idea of industrial symbiosis in general. Thus, the first example, even without the utilisation of CO_2 or CO, shall outline the concept of industrial symbiosis. The following examples show where alternative carbon sources can be used for further processing.

In order to promote and advance the symbiosis the *Symbiosis Center Denmark* was founded in 2015. It facilitates a number of activities that all focus on spreading the symbiosis mentality to more companies in Region Zealand and the rest of Denmark. *Symbiosis Center Denmark* is supported by Region Zealand.

The map below shows the different partners and sectors that are coupled with each other.

Figure 1: Map of Kalundborg; The coloured boxes are containing the different industrial partners / sectors of Kalundborg Symbiosis[3]

- The pink area: *Statoil Refining Denmark* [Norwegian multinational oil and gas company]
- Red area: *Dong Energy* [largest energy company in Denmark]
- Green area: *Kalundborg forsyning* [water and heat supplier, waste disposer, for Kalundborg citizens]
- Light blue area: *Gyproc Saint-Gobain* [French producer of gypsum board]
- Blue area: *Kara Noveren* [Danish waste treatment company]
- Orange area: *Kalundborg Kommune* [Municipality]

[3] http://www.symbiosis.dk/en/, (accessed on 17.10.2017)

- The violet area: *Novozymes* and *Novo Nordisk* [Danish companies; largest enzyme producer in the world and largest producer of insulin in the world]

The following figure gives an overview on the material, water and energy flow between the different partners of Kalundborg industrial symbiosis.

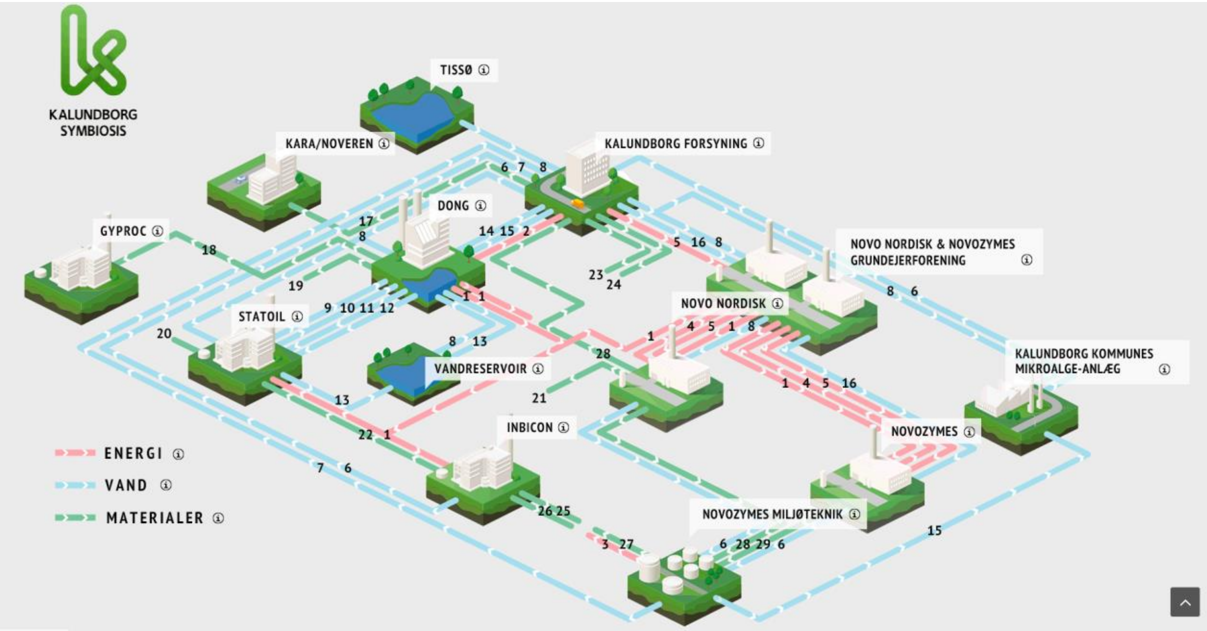


Figure 2: Kalundborg Symbiosis - material, water and energy streams (the numbers are counting the number of different flows)[4]

The figure highlights which partner interacts with each other. The entities that interact most are the power plant *Asnaes Power* (*Dong Energy*), *Novo Nordisk* & *Novozymes* and *Kalundborg Forsyning*. In total there are about 30 exchanges between partners.

In 2018 they will implement a biogas plant to convert 300,000 tons biomass per year into natural gas and fertiliser (equivalent to energy of 4,000 households). Additionally, in 2019 wood chips will replace coal as energy source in the power plant (producing green steam, electricity and heat). Furthermore, an algae production site will be integrated in Kalundborg Symbiosis using residual streams from the local industry.

[4] http://www.symbiosis.dk/en/, (accessed on 24.10.2017)

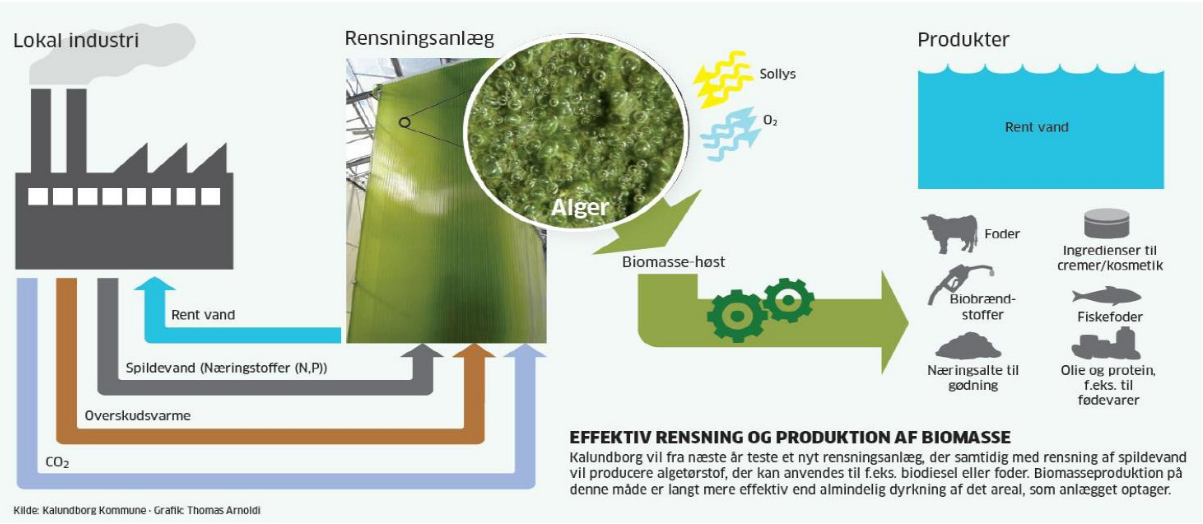


Figure 3: Integration of algae production in Kalundborg Symbiosis[5]

The algae reactors will use CO_2, excess heat and nutrients containing wastewater to produce high value biomass for further usage in industry (as basis for many different chemicals etc.).

Industrial sources of CO_2 as starting point for advanced industrial symbiosis

A number of industrial sources of CO_2 are to be considered for CO_2 conversion into valuable products. In the case the CO_2 crosses industrial sectors or at least company boundaries, it can be seen as industrial symbiosis. The table below provides an overview of large industrial CO_2 sources with typical amounts and CO_2 concentrations. From a carbon capture point of view, sources of high concentration appear most attractive, as energy demand but also cost of capture depend on the concentration of CO_2. More detailed information on CO_2 sources in Europe can be found in the CarbonNext deliverable 1.1 Mapping of CO_2/CO sources.

Table 1: Large industrial CO_2 sources and key parameters[6]

	Total available amount in EU [Mt][7]	**Amount per unit production**	**Typical CO_2 concentrations in source gas [vol. %]**
Steel plants	110	1.2-1.5 t CO_2/t steel	14-27
Cement plants	114	0.6-1.0 t CO_2/t cement	15-33
Chemical plants (example NH_3)	23	1.8 t CO_2/t NH_3	Close to 100

[5] Per Møller, Head of Symbiosis Center Denmark, "INDUSTRIAL SYMBIOSIS- POWERING UP THE GREEN TRANSITION TOWARDS A CIRCULAR ECONOMY", at DECHEMA PRAXISforum Power-to-X, 18.10.2017, Frankfurt am Main

[6] A. Bazzanella, F. Ausfelder, DECHEMA e.V., CEFIC Technology Study "Low carbon energy and feedstock for the European chemical industry", ISBN: 978-3-89746-196-2, Frankfurt am Main 2017.

[7] EU ETS data 2015, http://www.eea.europa.eu/data-and-maps/data/data-viewers/emissions-tradingviewer-1

Many current chemical processes, especially those via syngas production are emitting substantial amounts of CO_2 due to the nature of the respective process and its feedstock. Some of these production routes provide relatively pure CO_2, and such sources should be considered as first priority as already stated in deliverable 1.1. Processes providing close to 100% CO_2 include ethylene oxide, ammonia production (the latter often directly utilising the CO_2 for subsequent urea production), natural gas cleaning, but also fermentation processes, e.g. bioethanol production. Other industrial sources include steel and cement plants, providing off gas concentrations of CO_2 considerably lower, but often still higher than those in flue gas from fossil fired power plants. Depending on the target product of the chemical process, hydrogen and CO_2 supply require a specific match of the feed streams. Generally, sources for carbon dioxide as flue gases will be present and the stream needs to be separated, purified and pressurised in order to be used in the subsequent processes. The size of the carbon dioxide stream will define the scale of the hydrogen production. The table below provides an overview of the typical size of carbon dioxide streams from some potential carbon dioxide sources, the corresponding stoichiometric hydrogen streams for a given process and the corresponding product stream.

***Table 2: Typical CO_2-sources and their respective stochiometric volume flows for Power-to-Gas and Power-to-Liquid applications*[8]**

CO_2-Source		Methanation		Methanol production		Fischer-Tropsch fuels	
	Volume flow m^3/h	**H_2-stream m^3/h**	**CH_4 m^3/h**	**H_2-stream m^3/h**	**CH_3OH t/h**	**H_2-stream m^3/h**	**-CH_2- t/h**
Biogas plant	500	2,000	500	1,500	0.7	1,500	0.3
Gasification of biomass	2,100 (+1,400)	8,400 (+4,200)	2,100 (+1,400)	6,300 (+2,800)	2.8 (+1.8)	6,300 (+2,800)	1.2 (+0.8)
Ammonia plant	30,000	120,000	30,000	90,000	39	90,000	17

3.1 Steel production linked to chemical industry

Steel manufacturing provides sources of CO, CO_2 and CO_2/CO mixed streams which can be attractive for chemical valorisation. A number of research projects have been started to explore such industrial symbiosis schemes. 60% of the steel in Europe is produced via the basic oxygen furnace (BOF) process. In a blast furnace (BF) pig iron is extracted from iron ore using coke. The formed blast furnace gas is usually used for generating electricity. The iron from the blast furnace is then further refined and converted to steel in the BOF. Depending on the plant,

[8] A. Bazzanella, F. Ausfelder, DECHEMA e.V., CEFIC Technology Study "Low carbon energy and feedstock for the European chemical industry", ISBN: 978-3-89746-196-2, Frankfurt am Main 2017.

20-30% of scrap is added to this process, primarily to regulate the temperature. In this BF-BOF route, process gases are generated in the coke plant, the BF and the BOF converter. These off-gases are usually recovered and used to generate electricity and steam. European integrated steel mills therefore mostly include a power plant. The route avoids emissions of toxic CO, and allows for self-sufficiency of steel plants in terms of electricity.

However, the power plants are rather inefficient and produce power at 30 and 40% efficiency compared to modern gas-fired power plants running at up to 60% efficiency. Table 3 shows typical parameters of the steel production off-gases. BF gases by far comprise the highest volume flow, but BOF gases are particularly interesting due to the high concentration of CO. Furthermore, the CP gas is characterised by high hydrogen contents. The availability of these gases from European steel production has been estimated using the listed concentrations and extrapolating based on the European production of crude steel via the oxygen route, which was 101 Mt in 2015[9]. The resulting numbers have subsequently been used to calculate the amount of methanol that could be produced with these gases.

It is evident, that off-gases from the steel industry would provide a large potential for chemical manufacturing. CO actually has a very high use potential and would supply enough carbon for more than 50 Mt methanol p.a.

Table 3: Composition of steel production off-gases and potentials for chemical production[10]

Steel production off-gases	**Coke plant**	**Blast furnace**	**Basic oxygen furnace**
Volume [m³/t steel]	150	1,500	75
CO [vol%]	6.8	22	70
Amount CO in Europe [Mt]	0.6	37.8	10. 8
Equivalent to methanol [Mt]	**0.7**	**43**	**12.3**
H_2 [vol%]	61	2	1.5
Amount H_2 in Europe [Mt]	0.38	0.25	0.02
Equivalent to methanol [Mt]	**2**	**1.3**	**0.1**
CO_2 [vol%]	1.7	22	13.5
Amount CO_2 in Europe [Mt]	0.3	64.2	3.6
Equivalent to methanol [Mt]	**0.2**	**47**	**2.6**

It is quite obvious that electricity generation from process hydrogen in the steel industry on the one hand, and hydrogen production from electricity by the chemical industry on the other hand

[9] https://www.thyssenkrupp.com/de/carbon2chem/ (accessed 17.10.2017)

[10] A. Bazzanella, F. Ausfelder, DECHEMA e.V., CEFIC Technology Study "Low carbon energy and feedstock for the European chemical industry", ISBN: 978-3-89746-196-2, Frankfurt am Main 2017.

does not constitute the most efficient use of energy and feedstocks. Enlarging energy and feedstock streams beyond the battery limits of individual sectors can create substantial efficiency and CO_2 abatement potentials. However, it will be an enormous effort to define business models and contractual frameworks that would leverage such potentials. For instance, in the case of the depicted flue gas streams of the steel industry used for chemical production, a reasonable compensation for the additional electricity demand of the steel sector would need to be offered to the steel producer. It has also to be pointed out, that a stronger dependence between the sectors is created on the basis of such coupled productions, which does not only entail advantages.

Below three exemplary research projects are listed to give an insight of what is currently going on related to the usage of steel production CO_2/CO streams. At the beginning of the chapter the ethanol process form *LanzaTech* is highlighted as *LanzaTech* is a pioneer in developing processes to enable industrial symbiosis and sector coupling.

3.1.1 Example *LanzaTech* process

LanzaTech is a trailblazer in the use of steel manufacturing off-gases for ethanol production. They strike a new path by utilising the CO from blast furnace gas to produce ethanol in a gas fermentation process using acetogenic microbes. Until now there have been already four demonstrations of the *LanzaTech* process at industrial scale:

- *LanzaTech*'s process has been demonstrated at pilot-scale since 2008 using waste flue gas streams from the *BlueScope Steel* mill in Glenbrook, NZ.

- The first 100,000 gallon/year precommercial facility with leading steel producer *Baosteel* in Shanghai met and exceeded all production targets in 2012.

Figure 4: Baosteel production site; precommercial facility with LanzaTech process [11]

- *LanzaTech*'s second pre-commercial facility using steel mill waste gases is in operation near Beijing with *Capital Steel*.

ArcelorMittal has started a collaboration with *LanzaTech* in 2012, focusing on the ethanol productivity and upscaling of the technology for a 5 Mt integrated plant. Within the Steelanol project a further upscaling step to realise a demonstration plant in the harbour of Ghent producing 47 kt of ethanol per year is targeted (This collaboration is described in more detail in the next chapter 3.1.2 due to its high relevance)

3.1.2 Example Steelanol Project

Steelanol is a close-to-the-market project on advanced bio-fuel production from carbon-rich industrial waste gas. The aim of this industrial driven project is to allow for the capture and reuse of carbon emitted by the steel industry without the need to rebuild the BAT (Best Available Technologies) steel plant while supplying the transport sector with high grade biofuel, that does not compete in any way with food crops or land for food crops.[12] The project is led by *ArcelorMittal* in Ghent, Belgium. The other partners in the consortium are, *LanzaTech* (gas fermentation), *E4Tech* (Life Cycle Assessment) and *Primetals Technologies Austria* (engineering, automation, key equipment and commissioning). Associated partners are *Siemens VAI* (EPC partner) and *DOW* (chemicals production). The costs of the project are designated at about €15 million with an EU contribution of more than €10 million.[13]

[11] http://www.vlaamseklimaattop.be/sites/default/files/atoms/files/ArcelorMittal%20-%20project%20Steelanol.pdf

[12] http://www.steelanol.eu/en (accessed 17.10.2017)

[13] http://cordis.europa.eu/project/rcn/195267_en.html (accessed 17.10.2017)

Currently 40% of the carbon is leaving the process as CO which is today burned into CO_2 for heat and power. In the project the novel gas fermentation technology from *LanzaTech* captures the CO-rich gases from the steel production and converts the carbon to fuels and chemicals. Thus, this process brings underutilised carbon into the fuel pool via industrial symbiosis addressing a potential to make material impact on the future energy pool with >100s of billions of gallons per year.

The *AcelorMittal* steel production site is located near the Rodenhuyze docks, a large integrated bio-energy production site operational. This basis involves:

- *Bioro*: production of 250,000 t/yr biodiesel
- *AlcoBiofuel*: production of 150,000 m^3/yr bioethanol
- *Electrabel*: production between 80-180 MW power from biomass
- *BioBaseEurope*: Dutch/Belgian multipurpose pilot plant for bio based processes and products

The following photo shows the entire industrial complex of *AcelorMittal* in Ghent including the different areas and processes of steel production. The Steelanol plant will be integrated within the steel plant gaining all positive effects of industrial symbiosis.

Figure 5: AcelorMittal steel production site in Gent, Belgium[14]

[14] http://www.vlaamseklimaattop.be/sites/default/files/atoms/files/ArcelorMittal%20-%20project%20Steelanol.pdf

The following figure gives an overview on the different process steps of the Steelanol concept. The carbon rich off gasses from the blast furnace of the production get separated, treated and conditioned to feed the bio reactor. Here the microbes convert the CO into bio ethanol for further usage in blending fuels for the transportation sector.

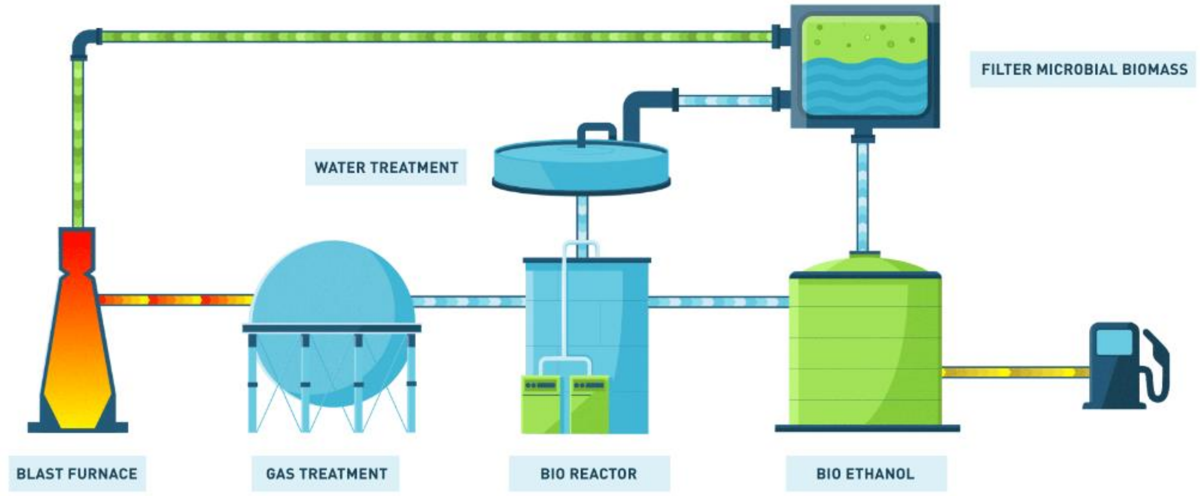


Figure 6: Steelanol concept[15]

A more detailed flow sheet is shown in the next figure.

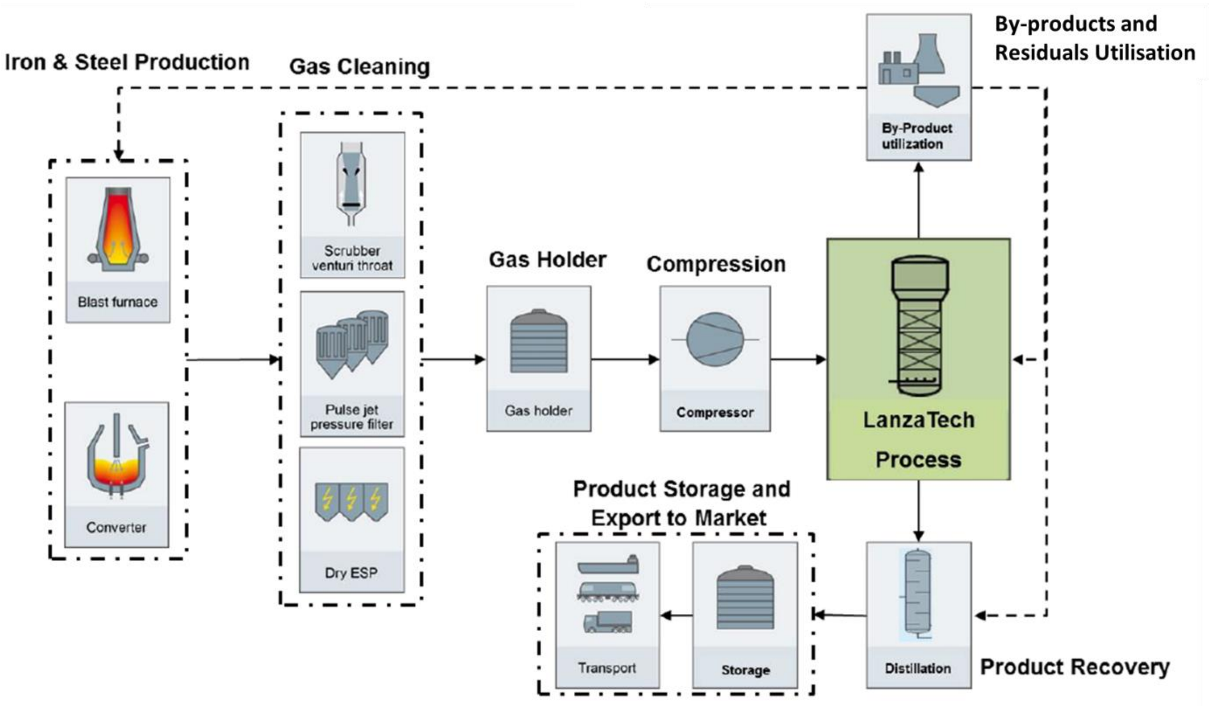


Figure 7: Detailed flow sheet of Steelanol process steps (taken from [7])

15 http://blog.germany.arcelormittal.com/helferchen-machen-biodiesel-aus-abgasen/ (accessed 18.10.2017)

The Steelanol website states "The construction of the €87 million flagship pilot project, which will be located at *ArcelorMittal Europe*'s steel plant in Ghent, Belgium, is anticipated to commence in 2016, with bioethanol production expected to start mid-2017. Construction will be in two phases, with phase one providing an initial capacity of 16,000 tonnes of ethanol per annum by mid-2017 and phase two, which will be completed in 2018, bringing the total capacity to 47,000 tonnes of ethanol per annum."[16] They assume that this amount of ethanol will be sufficient to fuel half a million cars with ethanol blended gasoline. The plant is still on-track.

According to *ArcelorMittal* and Steelanol publications the following three phases plan has been set up to enhance and accelerate the implementation of the Steelanol concept at various industrial sites all over Europe. This is one of the most promising examples of industrial symbiosis currently under development in Europe.

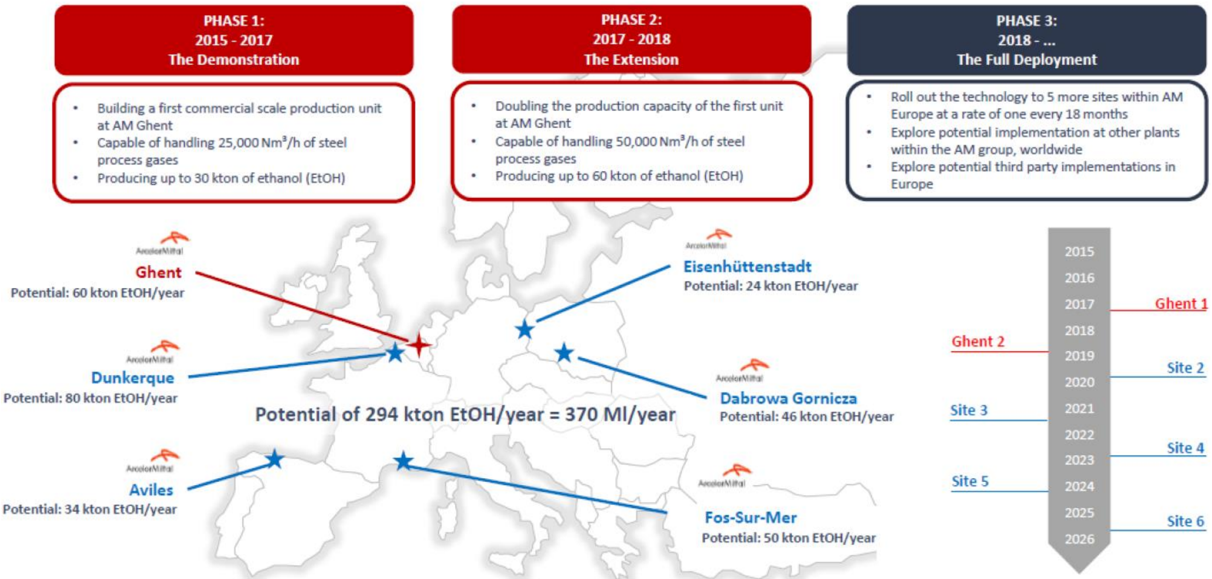


Figure 8: Concept of different phases of implementation of the Steelanol concept at European industrial (steel production) sites (taken from [7])

3.1.3 Example Carbon2Chem

The Carbon2Chem® project, funded by the German Ministry for Education and Research (BMBF), aims to convert off-gases from metallurgical processes (smelting) within the steel production sector into basic chemicals to substitute fossil raw materials. As energy source only surplus electrical energy from renewable sources shall be used. The CO and CO_2 containing gases will be converted into preliminary products for fuels, plastics and fertilisers.

The project started on March 15, 2016 with 18 partners from industry and academia. The initial phase will take four years. The total budged for Carbon2Chem is indicated to be about €84 million thereby getting funded by the BMBF with €62 million.

[16] http://www.steelanol.eu/en/news/partnership-for-breakthrough-87m-biofuel-production-facility (accessed 20.10.2017)

In Germany 6% of the total CO_2 emissions are produced by the steel industry. The rise in costs for ETS (European Emissions Trading Scheme) certificates in 2021 and cheap competitors from China suggest big challenges for European steel producers. One solution is to establish sustainable production routes and to reduce greenhouse gas emission by using effects from industrial symbiosis.

So, the objective of the project is to couple the steel sector with chemical production. Within the project a technical centre will be installed on-site at the steel production side Duisburg, located in the Ruhr area, comprising pilot plants for converting CO_2 into above mentioned valuable substances. Enabling the direct use of flue gases for chemical conversion on-site, is the cornerstone for coupling the sectors by industrial symbiosis. Carbon2Chem assumes to apply their modular approach at more than 50 comparable steel production sites. According to an official statement it is assumed to achieve an industrial scale for the Carbon2Chem technologies in about 15 years.

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% N_2, 23% CO, 21% CO_2, 10% H_2 and 2% CH_4). Carbon, hydrogen and nitrogen form the basis for 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 form the basis for methanol. Methanol - one of the most widely produced organic chemicals - can be used to power cars and aircraft or to synthesis other chemicals. Currently most of the carbon needed to produce methanol is obtained from fossil fuels such as natural gas.

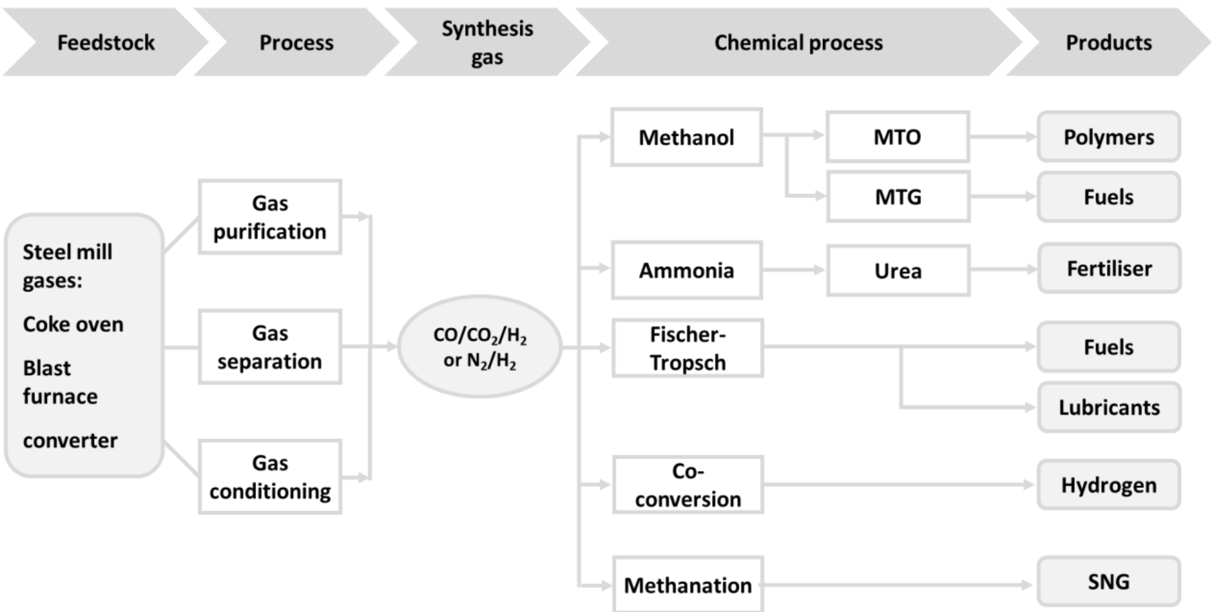


Figure 9: Carbon2Chem approach (adapted from Carbon2Chem®)

The Carbon2Chem consortium partners are representing the three national key sectors energy supply, steel production and chemical industry. In Germany these sectors employ more than half a million people and generate an overall turnover of more than €264 billion. Bringing together these sectors at one industrial site (as Duisburg steel production side in Carbon2Chem) has a high potential by using industrial symbiosis effects.

3.1.4 Example Carbon4PUR

Starting point for the Carbon4Pur project is the fact that the EU process industry needs to become less dependent on fossil fuels as source of carbon, and to reduce the greenhouse effect by decarbonising the economy. Carbon4PUR will tackle the two challenges at the same time by transforming the CO_2/CO containing flue gas streams of the energy-intensive industry into higher value intermediates for market-oriented consumer products.

The Carbon4PUR's industrially driven, multidisciplinary consortium will develop and demonstrate a novel process based on direct chemical flue gas mixture conversion, while avoiding expensive physical separation, thus substantially reducing the carbon footprint, and also contributing to high monetary savings. Both the consortium and the work are organised along the full value chain starting with the provision and conditioning of industrial emissions from a steel to a chemical company in line with the concept of industrial symbiosis, going through the transformation into chemical building blocks – lactones and cyclic carbonates – which both will be further transformed into polymer intermediates and flow into desired sustainable polyurethane applications of rigid foams and coatings. LCA and technology evaluation will be done and replication strategies to transfer the technology to other applications will be elaborated. The distinctive feature of the developed process is avoiding resource-intense separation of the gas components before the synthesis, and developing a chemo-catalytic process to deal directly with the gas mixture instead. The challenge and innovation are coming up with an adjustable process in terms of on-purpose and demand tailor-made production of required products, taking into account all variables at the same time: the available flue gases characteristic from the steel plant, material and process parameters, and the market requirements for the end product, thus flexibly involving the whole value chain with best results and possibly lower the prices.

One main aspect in Carbon4PUR will be industrial symbiosis related to the case study in the project. The experts will work out an evaluation of the technical and economic feasibility of a process implementation in the Port of Marseille Fos, as prime industrial symbiosis case investigated in Carbon4PUR; The work will include a feasibility assessment of connecting the infrastructure (distance, potential pipeline length, investments, legal requirement, safety) to lay the foundation for future detailed studies. Furthermore, they aim to develop a best practice case for industrial symbiosis for replications or learnings for other industrial sites and (CO/CO_2) recycling projects in Europe. Finally, the goal is to assess the potential for replication of the investigated case to other sites in Europe via mapping of sources and industrial infrastructures and identification of preferable locations which would offer promising conditions for industrial symbiosis.

The project is a Research and Innovation Action funded under the SPIRE topic within the European Horizon 2020 programme. The consortium consists of 14 partners from industry, academia, research organisations and one public body. The project's budget is about €7.8 million. The three years project has started its work in October 2017.

3.1.5 FReSMe – From Residual Steel Gases to Methanol

The main aim in the FReSMe project is to implement an 'Emissions-to-Liquids' technology in a Swedish steel manufacturing plant (*Swerea MEFOS* facility in Luleå, Sweden), demonstrating how residual blast furnace gases can be turned into liquid fuel. The low carbon intensity methanol produced from the carbon capture and synthesis plant will be utilised by one of the consortium partners, Swedish ferry operator *Stena* which operates the world's first methanol fueled passenger ferry, the *Stena Germanica*[17]. The FReSMe project will leverage infrastructure from the STEPWISE research project (http://www.stepwise.eu/home/), at the *Swerea MEFOS* facility in Luleå, which separates CO_2 from blast furnace gas and from the MefCO_2 project (see chapter 3.2.4) which demonstrates how the system can utilise intermittent renewable electricity sources.[18]

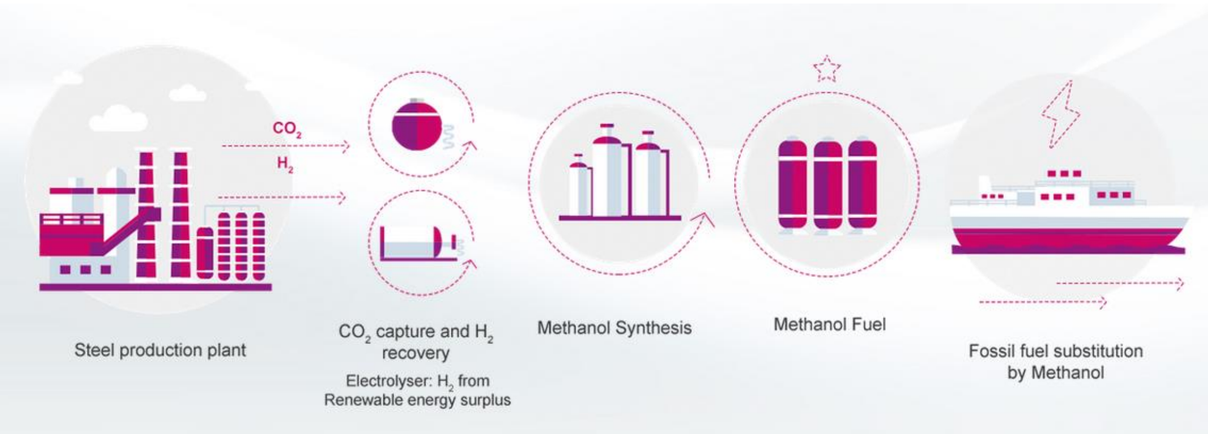


Figure 10: FReSMe concept (taken from [13])

This concept is a promising approach for industrial symbiosis and a good example for coupling sectors, here the steel production sector with the transport sector.

This research and innovation action has an overall budget of 11.4 million Euro and has started in November 2016[19]. The project will last four years. Within this framework the following timeline and planning towards a real testing onboard the ferry has been worked out.[20]

[17] https://www.stenalinefreight.com/news/Methanol-project (accessed on 14.11.2017)

[18] http://carbonrecycling.is/fresme-project/ (accessed on 14.11.2017)

[19] http://cordis.europa.eu/project/rcn/205958_en.html (accessed on 14.11.2017)

[20] http://www.fresme.eu/ (accessed on 14.11.2017)

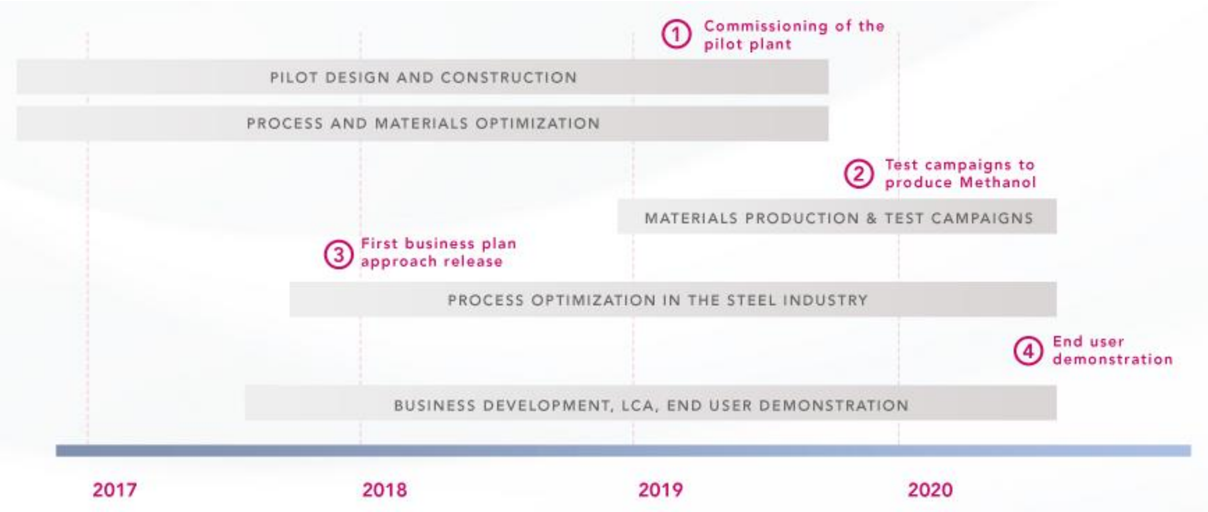


Figure 11: Timeline for FReSMe project progress (taken from [13])

The consortium of FReSMe project consists of 11 partners, mainly from industry. Amongst other *SSAB*, a Major European steel producer is providing the adequate environment in the steel industry to demonstrate the concept. Beside partners from academia further companies involved in FReSMe are *Tata Steel* (The Netherlands), *Carbon Recycling International* (Iceland), *Stena Rederi* (Sweden), *Array Industries* (The Netherlands), *Kisuma Chemicals* (The Netherlands), *SWEREA MEFOS* (Sweden).

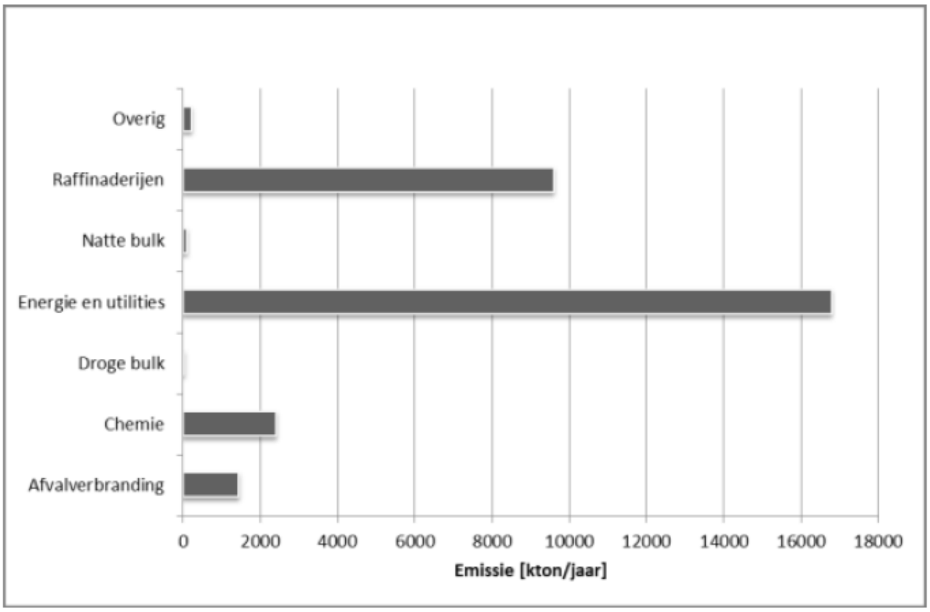
3.2 CO_2 sources originated by industrial emissions linked to chemical industry

The examples of projects from chapter 3.1 are pointing out the potential for symbiotic usage of CO_2 and CO streams from steel plants for the production of valuable products. Beside this, also CO_2 emissions from chemical plants are highly interesting as feedstock for onsite conversion into various chemical substances. In 2014, the chemical industry emitted 245.1 Mt of CO_2 in Europe. CO_2 sources from the chemical industry such as e.g. hydrogen or ammonia production are very pure - the concentration of those CO_2 sources can be up to 100%. This section describes first approaches of industrial symbiosis starting from the chemical sector. Although the transition from a fossil based energy system towards renewable energy usage is proceeding quite fast there will still be a neglectable amount of CO_2 emission from the power sector. This has also to be taken into account at least for the next two decades as relevant source for CO_2 and CO. Therefor this carbon containing waste streams are also shown here.

3.2.1 Example Rotterdam Harbour Industrial Complex

The Rotterdam Harbour Industrial Complex provides optimal conditions to catch up and obtain a top position on industrial application of CCU process. Industrial symbiosis can be realised by the combination of CO_2 and hydrogen infrastructure, nearby wind parks in combination with CO_2 point sources and various prospective industrial clients.

The following table gives an overview on current CO_2 emissions in Rotterdam Harbour Industrial Complex per sector:



Source: DCMR, 2016: inventarisatie-en-vergelijking-jaaremissies-Rijnmond-2007-2015.

***Figure 12: CO_2 emission per sector in the Rotterdam HIC area (2015)*[21]**

The main emitters of CO_2 are refineries, power generation, chemical sites and waste incineration. By far the energy sector is the largest CO_2 source by far followed by the petrol industry. Currently Plant One Rotterdam is realising an infrastructure which demonstrates realistic capture of CO_2 for use in various CCU pilot processes. Hence, Plant One Rotterdam is a test facility for sustainable process technology. These pilot processes should successively deliver the starting points for demonstration and full-scale realisation of the processes and contribute to the required reduction of CO_2 emissions in RHIC.

[21] http://www.deltalinqs.nl/sites/www.deltalinqs.nl/files/documenten/a6_marktstudie_ccu_voor_hic_-_ce_delft_3k44_ccu_market_options_rotterdam_harbour_def.pdf; page 7

Large CO_2 emitter	CO_2- and CCU-infrastructure	CCU process
Alco Shell Uniper Engie AVR	Linde-OCAP CO_2-line Air Liquide hydrogen Wind power landing Electrolysis (chlorine and planned hydrogen	Greenhouses

Current status

CCU process	Company type	Expected annual CO_2 uptake	CO_2 uptake
Algae	Algae cultivator for specialty products	Limited, depends on market for algae product	Short term
Polyols	Polyurethane base material manufacturer	120 kton	Mid term
Di-isocyanates	Polyurethane base material manufacturer	400 kton	Mid term
Mineralisation	Mineralisation developing companies (silicate, asbestos, metal slag based)	300 kton	Long term / eternal
Methanol	Petrochemical companies (admix, DME and MTG) Chemical companies, polymers and resins (MTO, formaldehyde)	40 Mton	Short term

Future potential

Figure 13: Major contributors Attractive CCU projects for Rotterdam HIC (adopted from [14])

Developing CCU in Rotterdam Harbour Industrial Complex requires three major types of stakeholders: CO_2 sources, CO_2 and CCU-supporting infrastructures and the utilisation processes connected to it. The Complex has a unique position, as it already houses all of these three; see table/figure above for major contributors.[22]

[22] http://www.deltalings.nl/sites/www.deltalings.nl/files/documenten/a6_marktstudie_ccu_voor_hic_-_ce_delft_3k44_ccu_market_options_rotterdam_harbour_def.pdf; page 5

Depending on market conditions, CCU has the potential for the storage or reuse of limited (hundreds of ktons) up to very large amounts of CO_2 (tens of million tons). Specialty production with algae, mineralisation and polyols for polyurethane are early candidates to achieve positive business cases on the short to mid-term due to their limited energy consumption and high added value products. They can act as a stepping stone for larger projects in the future.

There are also ample large volume CCU opportunities for the longer term, whereat methanol is a strategically important, while being a platform chemical for oil free production of olefins (MTO process) and gasoline (MTG process) as well as for admixture in fuels. However, the business case for CCU methanol is still far from profitable without a support scheme.

Next steps to be taken in the Harbour Industrial Complex is to comprise the identification of high value creating CCU opportunities and promoting symbiosis between industrial parties. New supply chains are to be set up, enabling this industrial symbiosis required for CCU. This includes the delivery of captured CO_2, heat integration for the capture, use of currently available residual materials, creation of products with added value in other sectors, etc. Setting up of these new CCU supply chains requires the organisation of joint projects with strategic partners.[23]

CE Delft has been undertaken an evaluation on existing routes for the utilisation of CO_2. The different conversion processes have been surveyed according to their current status in technology development with a special focus on scale and commercial availability. The aim was a selection of suitable processes for integration in the Rotterdam Harbour Industrial Complex. Of the identified technologies, the following have been demonstrated on a small/medium commercial scale or have been implemented commercially:

- Thermochemical and microbiological production of methane by CO_2 hydrogenation.
- Thermochemical production of methanol by CO_2 hydrogenation.
- Production of linear polypropylene or polyethylene carbonates by carbonation of propylene or ethylene epoxides.
- Production of dimethyl carbonate (DMC) by carbonation of ethylene oxide into cyclic ethylene carbonate and subsequent transesterification of the produced with methanol.
- Further processing of DMC into aromatic carbonates (*Asahi Kasei* process).
- Production of polyether carbonate polyols by copolymerisation of CO_2 with a starter molecule (mono-, di- and poly-ols; alkoxylated oligomers of glycols) and an alkylene oxide/epoxide.
- Production of ethanol (and several other oxo-chemicals) by fermentation of CO/CO_2 containing gases.
- Carbonation of minerals, ashes and slags.

[23] http://www.deltalings.nl/sites/www.deltalings.nl/files/documenten/a6_marktstudie_ccu_voor_hic_-_ce_delft_3k44_ccu_market_options_rotterdam_harbour_def.pdf; page 5

The following table is taken from the *CE Delft* study giving an overview on possible CO_2 utilisation routes including the results of the assessment, substantiated by the Technology Readiness Level (TRL).

***Table 4: Evaluation for CCU technologies for application at Rotterdam Harbour Industrial Complex*[24]**

Previous study	This study	TRL		Selected for next analysis
Methanol	Thermochemical production (ICR)	7	Semi commercial scale demo plant operational (Iceland)	X
Carbamates		2	No sufficiently selective catalyst	
Poly-urethane	Polyols via carbonation of epoxides and oligomeric alcohols (Bayer and Novomer)	6-7	Two semi-commercial scale demo plants operational	X
Linear and cyclic organic polycarbonates	Linear polycarbonates from expoxide carbonation (Novomer)	7	Semi commercial scale demo plant operational (Novomer)	X
Aromatic polycarbonates	By way of epoxide carbonation (Asahi Kasei)	9	5 commercial plants operational	X
	By way of alcohol carbonation (Asahi Kasei)	6	Pilot plant has been financed	X
	Shell process with CO_2, ethylene or propylene and phenol	6	Pilot plant has been financed	X
Mineralisation and utilization in cement and concrete	Solidia	9		X
	Carbstone	9		X
	Green Minerals	4	Capture with asbestos conversion option	X
	Carbon8 Aggregates	9		X
Carbon monoxide/syngas		2	No sufficiently selective catalyst, problems with carbon deposition	
Ureum (and melamine)		9	Market saturated	
Organic acids (e.g. formic acid, acetic acid)	Photanol technology	3-4	Only very small pilot plants for testing	
Koppelingen naar ethanol en hogere alcoholen/aldehyden	Ethanol from gas fermentation (Lanzatech)	6-8	Demonstrated on pilot scale, first-of-a-kind commercial scale installation under construction (Arcelor Mittal Ghent)	X
Electrochemical production routes	Liquid Light Corp, Evonik	2-4	No pilot plant build yet, Laboratory Component Testing	
	Coval (formic acid)	2-3	No pilot plant build yet, Laboratory Component Testing	
Methane production	Thermochemical production Etogas	6-7	Semi commercial scale demo plant operational (Werle)	
	Microbiological production MicrobEnergy	6-7	Semi commercial scale demo plant operational (Allendorf)	X

The described status of industrial symbiosis at Rotterdam Harbour Industrial Complex is June 2017.

3.2.2 $MefCO_2$ - Synthesis of Methanol from captured CO_2 using surplus electricity

This European Horizon 2020 project, with *Carbon Recycling International (CRI)*, *Hydrogenics Europe* and *Mitsubishi Hitachi Power Systems Europe* as large industrial partners (8 partners in total), will work on the design, construction and testing of systems to demonstrate the utilisation of intermittent renewable energy sources and CO_2 for the production of sustainable fuels and chemicals.[25] $MefCO_2$ aims to produce green methanol as energy vector from captured CO_2 and hydrogen produced using surplus renewable energy. The technology is being designed in a modular intermediate scale, with the aim of being able to adapt it to varying plant sizes and gas composition.[26]

The following figure shows the $MefCO_2$ approach:

24 http://www.deltalings.nl/sites/www.deltalings.nl/files/documenten/a6_marktstudie_ccu_voor_hic_-_ce_delft_3k44_ccu_market_options_rotterdam_harbour_def.pdf; page 14

25 http://carbonrecycling.is/mefco2-project/ (accessed on 14.11.2017)

26 http://www.mefco2.eu/mefco2.php (accessed on 14.11.2017)

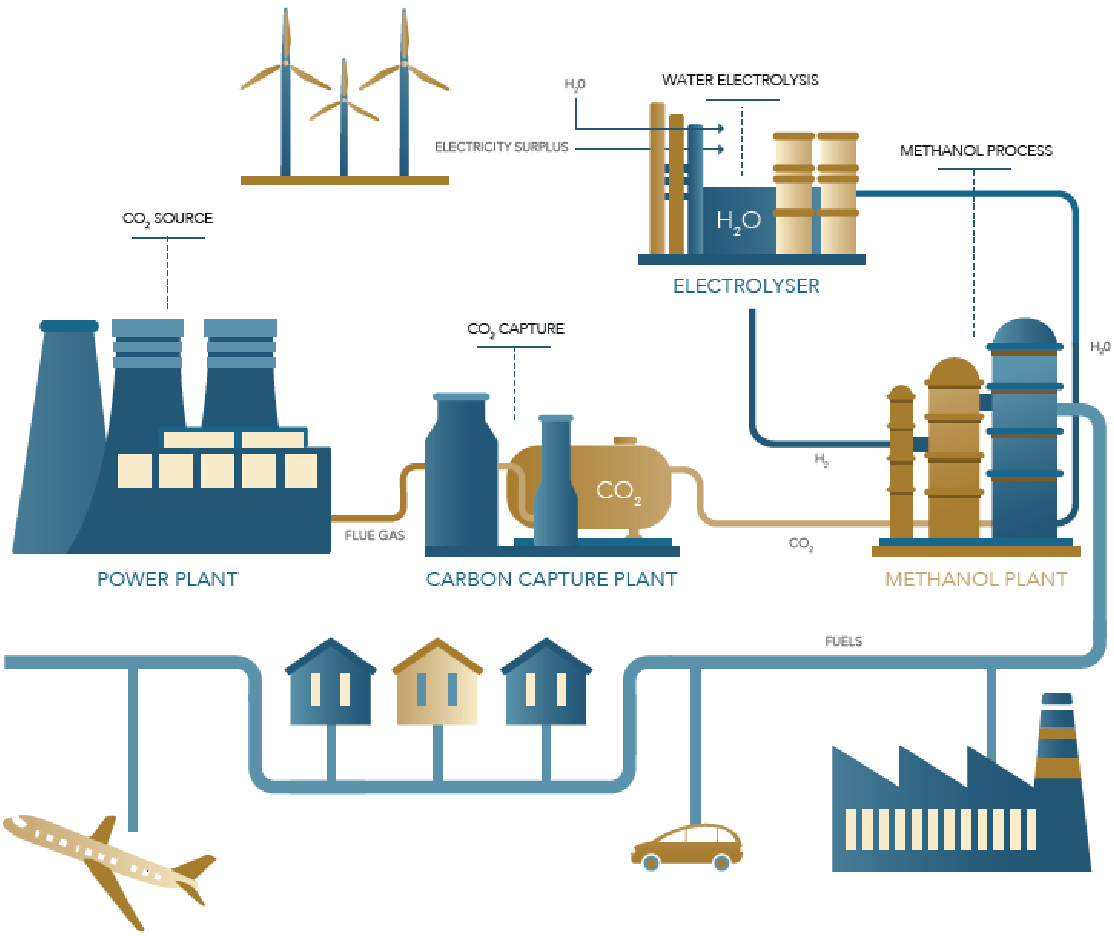


Figure 14: Flow diagram of MefCO$_2$ project (figure taken from [16])

The concept of MefCO$_2$ is a promising approach to implement industrial symbiosis. Flue gas from one company can be used in the methanol production process of another site. Finally, the methanol can serve as basis for further conversion into formaldehyde, formic acid or acetic acid in a third production process. Furthermore, within the flow chart the carbon capture process has a very important position for the success of the overall concept. In chapter 4 of this deliverable report, the different carbon capture (separation and conditioning) technologies get described, categorised and shortly evaluated related to the individual status of development. The project runs from 2015 to 2018 with an overall budget of about €11 million. MefCO$_2$ is funded under the SPIRE research programme.

3.3 CO_2 sources originated by industrial emissions linked to bio industry

The two chapters above are handling with carbon dioxide and monoxide containing streams mainly from steel or chemicals production to be used as source for various applications in the chemical industry. Chapter 3.3 deviates from that and compromises symbiotic relationships, where the bio industry is engaged. The bio industry provides a wide branch of pathways for

CO_2 utilisation. On the one hand side, CO_2 can be used directly for greenhouses, on the other hand, specific microorganisms are able to activate the molecule for further processing. The CO_2 streams in this chapter are originated by diverse industrial emission. These are amongst others from power plants, petro industry, sewage digestion and biogas plants.

3.3.1 OCAP Network

In the Netherlands a CO_2 network for greenhouses called *OCAP (**O**rganic **C**O₂ for the **A**ssimilation in **P**lants)* has been established. The CO_2 used for the greenhouses is produced at Shell during the production of H_2 in an oil gasifier, and during the production of bio-ethanol at *Abengoa* in Europoort Rotterdam. *OCAP* supplies this CO_2 via a pipeline with an extensive distribution network (see figure below).

By doing so this system links the chemical production sector with the bio industry. As the two CO_2 production sites and the operators of the appropriate greenhouses are all in the area of Rotterdam and Den Haag this CO_2-network is an interesting example for industrial symbiosis.[27]

This enables greenhouses to save about 115 million cubic metres of natural gas a year, which would otherwise be used in the greenhouses to produce the CO_2. The greenhouses annual CO_2 emissions are reduced by about 205 ktpa.[28]

[27] www.ocap.nl (accessed on 11.10.2017)

[28] Zero Emission platform report on carbon capture and utilisation, April 2016 (http://www.zeroemissionsplatform.eu/library/publication/265-ccu.html)

Figure 15: OCAP - CO_2 infrastructure (taken from [19])

3.3.2 Photanol

The Photanol process is one of the possible approaches evaluated to be suitable for industrial symbiosis at Rotterdam Harbour Industrial Complex. In Photanol's microbiological process CO_2 is converted by cyanobacteria into organic alcohols and acids in a reaction with water. Oxygen and biomass are by-products.

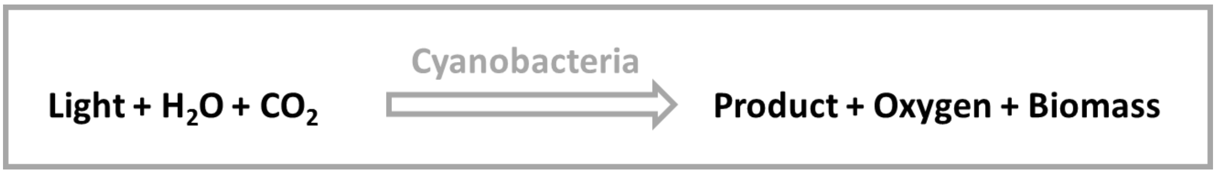


Figure 16: Photanol process: Photo-fermentation

Photanol are a platform renewable chemicals company that utilises proprietary engineered cyanobacteria to process carbon dioxide and sunlight into valuable chemical products. Their patents are based on the genetic modification of cyanobacteria to produce a broad range of biochemicals. These bacteria are natural photo synthesisers, drawing energy from (abundant and free) sunlight and carbon from (abundant and problematic) CO_2.

Current efforts in development are focussing on lactic acid. In cooperation with *AkzoNobel* several other strains of bacteria are being developed. These strains will produce acetic acid, butanol and a 'compound X' (market size > $ 1 billion/a) (RVO, 2013). In addition, development of strains for production of flavours and fragrances are being developed (Hamacher, 2014). Other substances that could be produced include terpenes and polyols.

The Photanol concept could produce drop in raw materials for existing production processes in the Port of Rotterdam petrochemical industry, e.g. polyols and also produce raw materials for new industries, in particular lactic acid.[29]

The following figure is showing the current status in development and application of the Photanol approach. Currently they are upscaling their process in order to achieve a commercial and industrial relevant scale to be implemented in an industrial environment and complex.

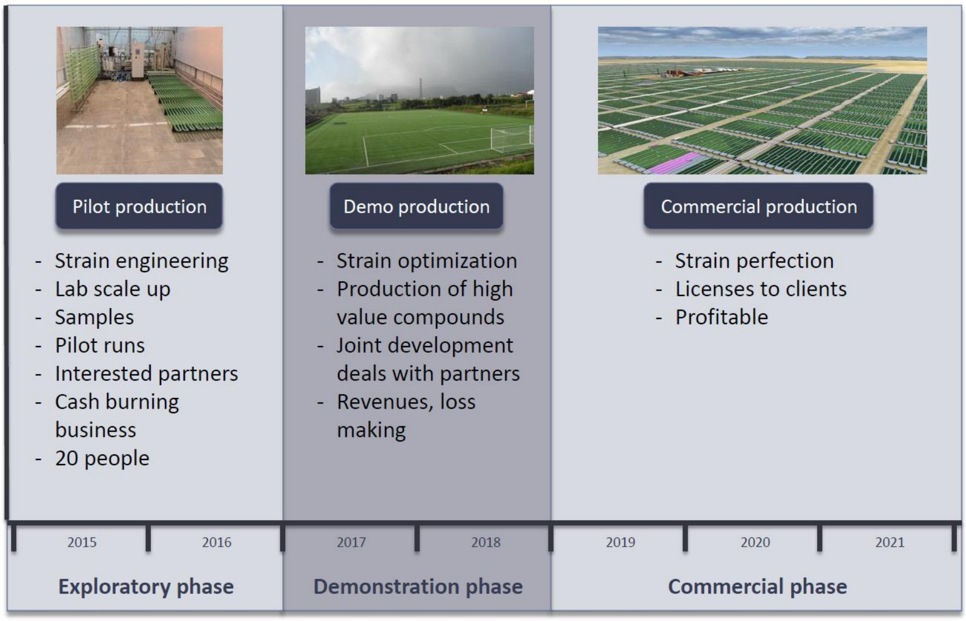


Figure 17: Photanol concept for commercial implementation[30]

Photanol identified possible value chains for connecting the industrial sectors. The triangle figure below shows the symbiosis between CO_2 emitters (sources), the platform companies (converting the CO_2) and the users (companies using the products).

---

[29] http://www.deltalinqs.nl/sites/www.deltalinqs.nl/files/documenten/a6_marktstudie_ccu_voor_hic_-_ce_delft_3k44_ccu_market_options_rotterdam_harbour_def.pdf; pages 35 and 36

[30] https://www.bio.org/sites/default/files/WorldCongress/Dirk%20den%20Ouden.pdf (accessed 13.10.2017)

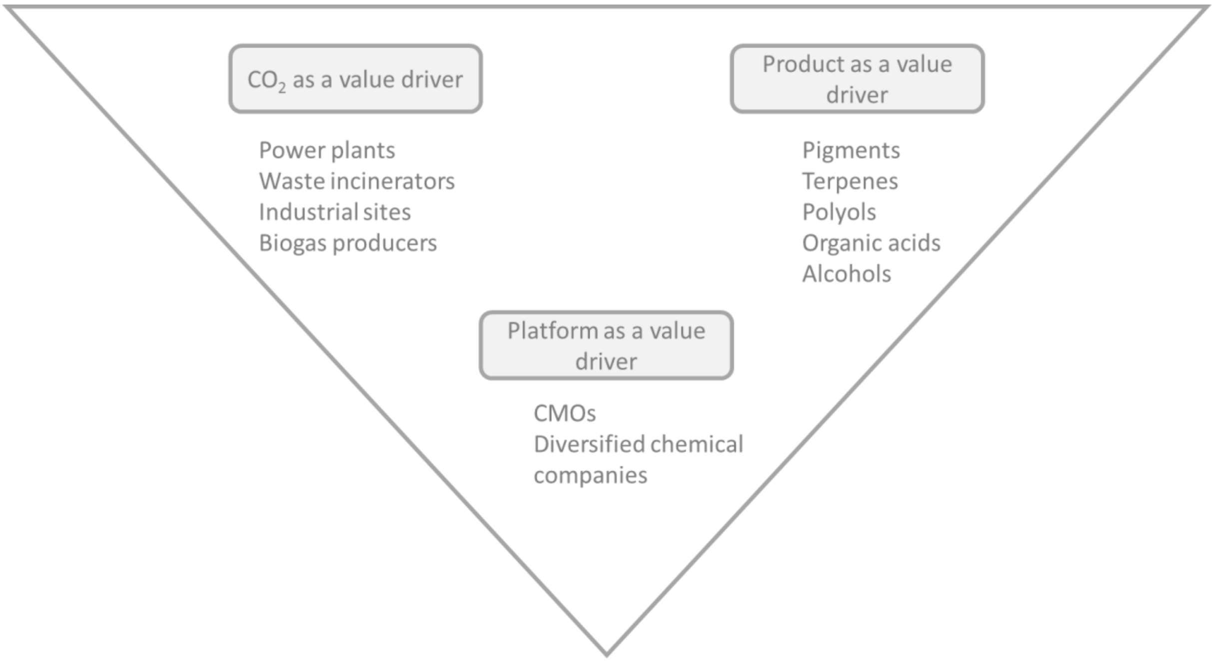


Figure 18: Photanol – possible value chain (adapted from [20])

3.3.3 BioElectroPlast – bioelectrochemical production of bio plastic material

The BioElectroPlast project is working on the production of bioplastics by using carbon dioxide from flue gas streams. The planned process converts flue gas, air and electrical current into the bio polymer Polyhydroxybutyrate. The material is a biodegradable plastic that is already widely used. The core idea is the usage of an isolated microorganism which is resisting even extreme conditions and environments as they are in industrial CO_2 containing flue gas. The partners from academia, *Karlsruhe Institute of Technology* and the *University of Freiburg*, are supported by the *EnBW AG*, a large energy company in Germany. The project pilot plant will be tested onsite the coal-fired power plant at the Rhine Port in Karlsruhe. By doing so the researchers will be able to process real flue gas from industrial combustion processes.

If the BioElectroPlast process will be able to directly use the flue gases (e.g. from power plants or chemicals production) this would allow the multiple application of the technology at many industrial complexes enabling industrial symbiosis. The project started in September 2016 and will take three years. The budget allocated for this activity is about €1.6 million.[31]

[31] http://www.chemieundco2.de/fileadmin/user_upload/01_BioElectroPlast_RED.pdf

3.3.4 MIKE - Methanation of CO_2 from biogas by microbial electrosynthesis

This project is funded by the German Federal Ministry of Education and Research. In MIKE they are going to use microbial electrosynthesis for methanation of CO_2 in biogas in order to increase the methane output of an industrial biogas plant and therefore to reduce the cleaning effort. In microbial electrosynthesis electroactive microorganisms take up electrons from a cathode for the reduction of CO_2 to different chemical products (e.g. methane). In contrast to other processes, the microbial electrosynthesis (MES) has very high cathodic electron efficiency (> 80%). The energy source (electrons, current) for the envisaged process will be from renewable energies. After technical and scientific work on the development of a lab scale MES reactor the integration of the MES pilot plant into one of the biggest industrial biogas plants at the industrial park Höchst in Frankfurt, Germany, will be the main goal in MIKE project.[32]

The partners in this research project are *Infraserv GmbH & Co. Höchst KG*, *Ifn FTZ GmbH*, *Provadis School of International Management and Technology* and the *DECHEMA Forschungsinstitut*. With Infraserv Höchst as industrial (chemical) complex (platform) the project has a partner for direct implementation of technologies and approaches to facilitate industrial symbiosis. Some facts on *Infraserv Höchst industrial park*: 460 ha, over 90 companies, approx. 22,000 employees, investment volume: €6.65 billion (since 2000), over 800 buildings, 120 production plants, 72 km of roads, 57 km of railway tracks, 800 km of pipelines, 2 mn t of cargo handled per year[33]. These figures show the general potential at that industrial complex with optimum infrastructure to put industrial symbiosis into effect.

3.3.5 Microbiological methane synthesis

Microbiological methane synthesis from CO_2 and H_2 is a technology being developed by Krajete GmbH and by MicrobEnergy GmbH, a subsidiary of the Viessmann Group.

Together with Audi, the Viessmann Group has realised a pilot plant at Allendorf with a production capacity of 55 Nm^3 Synthetic Natural Gas/hr in 2016, utilising CO_2 from a sewage sludge digestion plant (DENA, [2015]). Methane or SNG is produced by the reaction of CO_2 with H_2. The required H_2 is produced with a PEM electrolysis cell. The process consumes H_2 in a kg:kg ratio to CO_2 of 4:44. H_2 utilisation rate seems to be 98-99 % and the produced SNG seems to contain only a few percent H_2.

[32] http://dechema-dfi.de/en/MIKE+%E2%80%93+Methanation+of+CO2+from+biogas+by+microbial+electrosynthesis.html, (accessed on 26.10.2017)

[33] http://www.infraserv.com/en/referenzen/standortbetrieb_industriepark_hoechst/index.html, (accessed on 27.10.2017)

Figure 19: Pilot plant at Allendorf (taken from [14])

3.3.6 Agricultural fertiliser from biomass and waste CO_2

CCm Research (UK) are developing an agricultural fertiliser synthesised from pellets of cellulosic biomass such as agricultural wastes, mineral solutions and waste CO_2[34]. An aqueous solution of ammonia and calcium nitrate is used to capture CO_2 from the flue gas of an anaerobic digestion (AD) plant, which reacts to form a solution containing ammonium nitrate and calcium carbonate. Digestate from the AD plant (the cellulosic fibre which is remaining at the end of the AD process that was not digested) is dried and made into solid pellets. These pellets are then soaked in the ammonium nitrate and calcium carbonate solution described previously. The soaked pellets are then dried which forms cellulosic fibre, containing ammonium nitrate, coated in a calcium carbonate Ca_2CO_3 (lime) coating. The mineralisation process forming the calcium carbonate is highly exothermic and the excess heat is transported back to the AD plant for use in its pasteurisation step. Extensive field trials appear to show that the fertiliser pellets perform well so an industrial pilot plant is under development.[35]

In this example, waste biomass and CO_2 are being shared in one direction, and then waste heat is being shared back in the other direction - so there is a direct benefit to both parties. and it is relevant to smaller scale situations rather than the massive industrial scale facilities often discussed.

[34] Innovate UK (2016). CCm Research develops carbon dioxide utilisation process for value added materials. Available at: https://www.ktn-uk.co.uk/perspectives/ccm-research-develops-carbon-dioxide-utilisation-process-for-value-added-materials Accessed September 2017.

[35] CCm Research (2017). Using waste to create valuable products and a better environment (video). Available at: https://www.ktn-uk.co.uk/perspectives/ccm-research-develops-carbon-dioxide-utilisation-process-for-value-added-materials Accessed September 2017

3.4 Power-to-X: CO_2 as link between chemistry electricity, heat and transport

Power-to-X concepts are involving various technologies for electricity conversion, energy storage, and reconversion pathways using surplus energy caused through fluctuating renewable energy supply and demand. The most relevant pathways in respect to carbon dioxide and carbon monoxide are Power-to-Gas and power-to-Liquids. Power-to-Gas concepts are using electricity to split water into hydrogen and oxygen by electrolysis. The evolving hydrogen can further be injected into the natural gas grid, used as fuel in fuel cell systems (e.g. transport) or can be utilised as basis chemical for a quantity of processes in industrial production. Moreover, combining the hydrogen with carbon dioxide using methanation converts the two gases to methane to be used as natural gas. Finally, the hydrogen can also be used to upgrade the quality of biogas. Power-to-Liquids comprises technologies converting electricity, water and carbon dioxide into synthetic fuels (Power-to-Fuel) or into valuable chemicals for further usage, e.g. in the chemical industry (Power-to-Chemicals). Prominent examples in this context are liquid natural gas (LNG), methanol, long-chained alcohols and oxymethylene ethers (for blending diesel fuels). Hence Power-to-X depicts being a convenient method to link the transport, energy and chemical sectors by using symbiosis effects related to CO/CO_2 origination and utilisation.

Potential future demand for Power-to-X technology in the electricity, transport and chemical sectors

Even conservative forecasts predict that by 2050 around 40 GW of Power-to-X storage capacity will be required in Germany. This demand is shared approximately equally between the mobility and chemical sectors. Even under conditions that encourage Power-to-X development (favourable cost trends and early market maturity), if grid expansion proceeds at the ideal rate, Power-to-X technology will only be deployed at a later stage and for long-term energy storage. If, however, grid expansion is severely delayed, as seems likely from the present perspective, then the prevailing conditions will be different and Power-to-X technology will become established at an earlier date.[36]

3.4.1 Kopernikus P2X Project

The German Ministry for Education and Research is currently funding 4 large research collaboration projects, called Kopernikus projects, that are focused on the understanding, design and further development of the complex future energy systems and thus enabling the energy revolution (transition, German ‘Energiewende’). One of these activities is the

[36] Prof. Dr. Michael Sterner, et al., Chemical Energy Storage, Energy Networks and Energy Storage Research Group (FENES), OTH Regensburg, published in A. Bazzanella, D. Krämer (editor), DECHEMA e.V., Ergebnisse der BMBF-Fördermaßnahme „Technologien für Nachhaltigkeit und Klimaschutz – Chemische Prozesse und stoffliche Nutzung von CO2“, ISBN: 978-3-89746-190-1, Frankfurt am Main, June 2017

Kopernikus P2X project comprising 48 partners form academia, industry and socio-economics, collaborating in 64 working groups. The budget for the first three years (project begin was in September 2016) is €38.3 million at a contribution from industry of €8.3 million.

The project identified five fields of action that to push Power-to-X technologies towards application in the main fields energy, transportation and chemistry. From technological side work has to be done on material and process-design, electrolysis and catalysis. From the other side issues sustainability and system integration are topics to be focused in order to address ecological, societal, political and economic aspects. The honeycomb Figure 20 depicts the approach of linking fields of action and application within the Kopernikus P2X project.

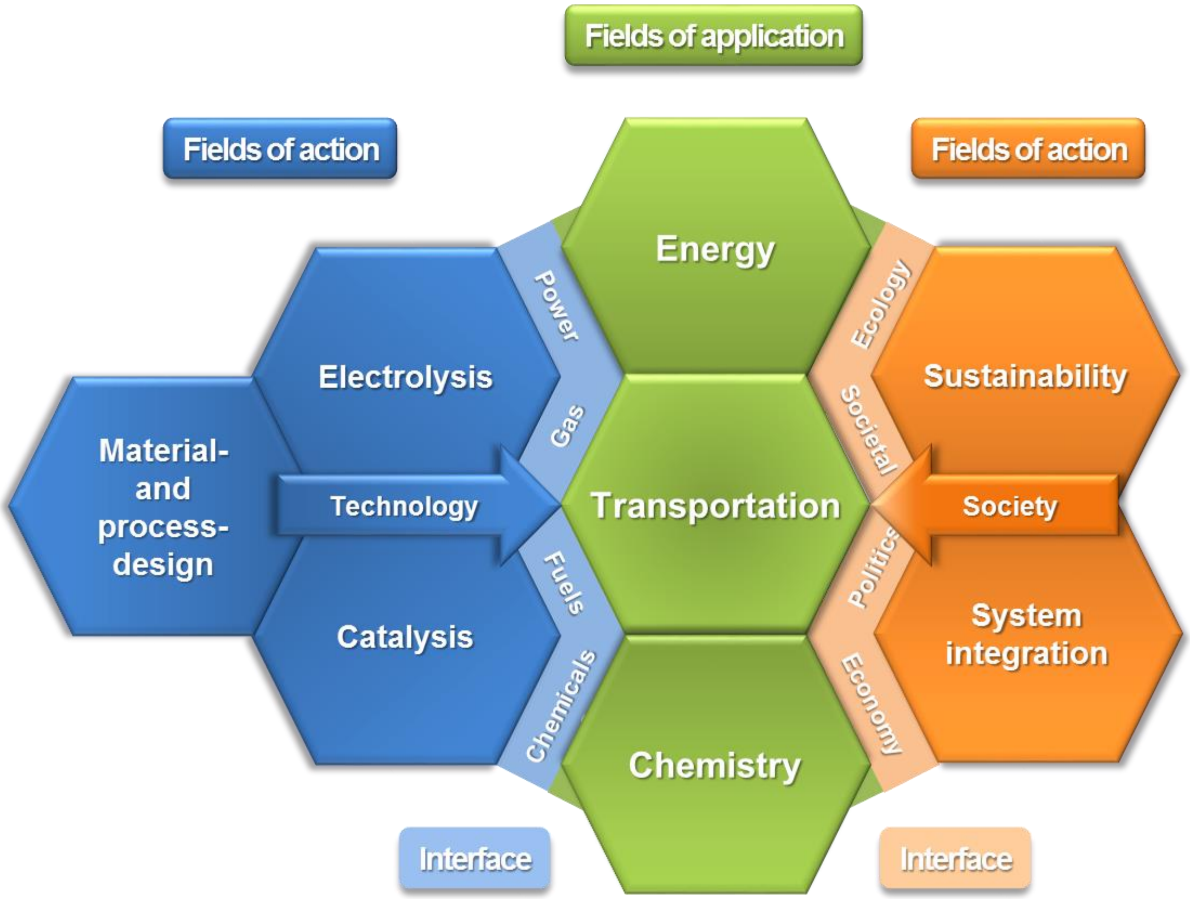


Figure 20: Linking the fields of action and application in Kopernikus P2X[37]

Based on that approach the scientific and technical work has been structured into six research clusters (RC) and a Roadmapping activity. The Basis for all value chains is water, electricity from renewable sources and CO_2. Beside a pure hydrogen pathway (RC-A1/B1) the focus is on the Co-electrolysis of water and carbon dioxide in order to produce syngas (H_2 + CO) for further synthesis of chemicals (methane, hydrocarbons, alcohols) and fuels (oxymethylene ether (OME)).

[37] Taken from the presentation for public audiences, copyright© by DECHEMA e.V., RWTH Aachen Univesity, Forschungszentrum Jülich e.V.

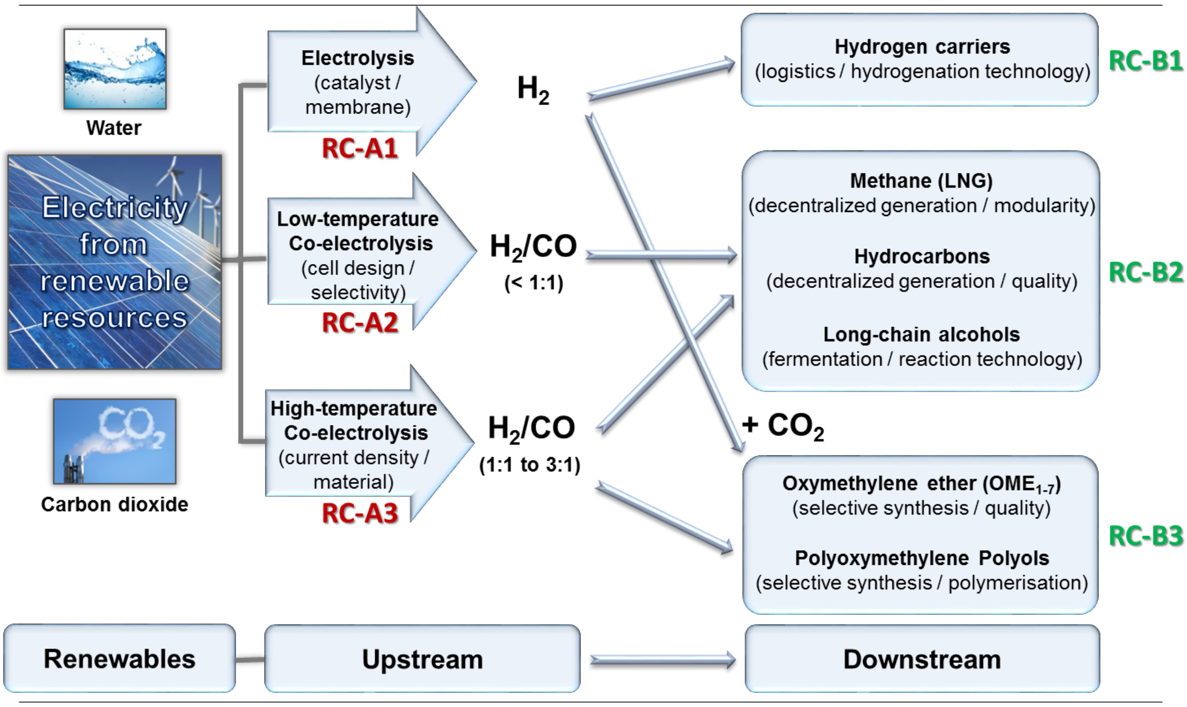


Figure 21: Kopernikus P2X technological approach (taken from [27])

For implementing Power-to-X technologies into an industrial environment the project defined a couple of guiding principles:

- High CO_2 reduction at maximal added value
- Integration of decentralised and autarkic solutions
- Scalability and modularisation
- Societal needs and acceptance
- Exportability

Especially a high CO_2 emission reduction, scalability and modularisation are very important to use Power-to-X for industrial symbiosis. Exportability and societal aspects are more relevant regarding coupling sectors with each other and thereby stepping into people's daily lives and environment as well as crossing borders between neighbouring countries.

Power-to-X applications are highly relevant in industrial symbiosis if waste streams from one company cannot directly be used as source for another and need a certain level of conditioning (e.g. production of syngas, etc.).

3.4.2 CELBICON Project

CELBICON project, cost-effective CO_2 conversion into chemicals via combination of Capture, electrochemical and biochemical conversion technologies, is funded under Horizon 2020 with a budget of over €6 million.

Their work is divided into two lines of development:

1) High pressure processing line tailored to the production of a PHA bioplastic and pressurized methane via intermediate electrochemical generation of pressurised syngas followed by specific fermentation steps;
2) Low pressure processing line focused on the production of value-added chemicals by fermentation of CO_2-reduction water-soluble C1 intermediates.

The following figure is showing the two lines of development, the high- and low-pressure line.

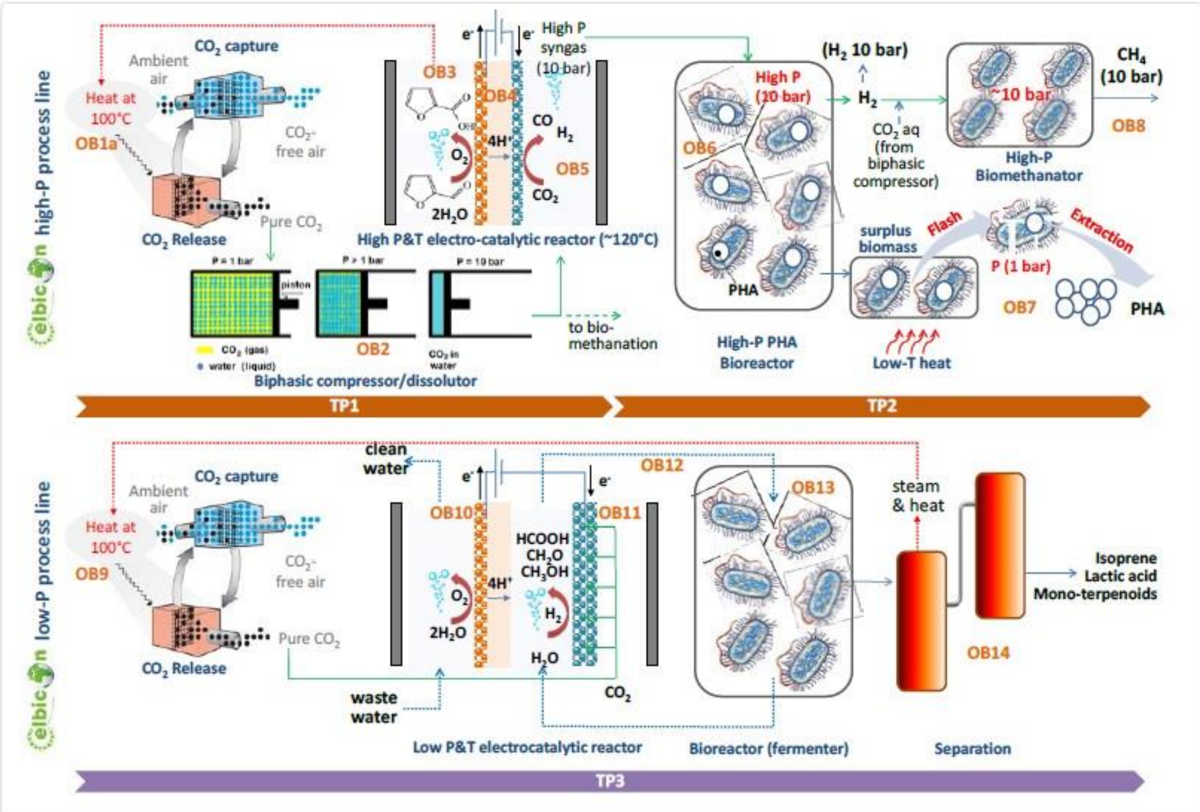


Figure 22: CELBICON processing lines for CO_2 capture and production of valuable chemicals[38]

The aim of the project is to capture the CO_2 from the atmosphere. In general, the subsequent steps of processing the CO_2 can also be applied to CO_2 from alternative sources like waste gas streams in the context of industrial symbiosis. The CELBICON process steps comprise an electrochemical conversion of CO_2 via PEM electrolysis, promoting CO_2 reduction at their cathode in combination with an oxidation carried out simultaneously at the anode. This is followed by bioreactors carrying out the fermentation of the CO_2-reduction intermediates (syngas, C1 water-soluble molecules) to form valuable products (bioplastics like Poly-Hydroxy-Alkanoates - PHA -, isoprene, lactic acid, methane, etc.).[39]

[38] http://www.celbicon.org/pages/home.aspx (accessed on 26.10.2017)

[39] http://cordis.europa.eu/project/rcn/200178_de.html (accessed on 26.10.2017)

3.4.3 Fraunhofer Lighthouse Project - Electricity as a Raw Material

Ten Fraunhofer Institutes led by the *Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT* are working together on the Fraunhofer lighthouse project "Electricity as a Raw Material". This project started in 2016 and will run three years. The aim of the collaborating Fraunhofer Institutes is to develop and optimise processes that enable renewable power to be used to synthesise important base chemicals.

Within the project they focus on two lines:

1) The electrochemical production of ethene and assorted alcohols as the building blocks for a wide range of organic chemicals
2) The electrochemical production of hydrogen peroxide (H_2O_2) from oxygen and hydrogen.

The first line is interesting for the use of carbon dioxide containing waste gases. Under this topic the project is focusing Power-to-Chemicals pathways and not on Power-to-Gas to generate e.g. methane as a direct fuel for combustion. The aim is to produce high valuable chemicals that have a much higher price than natural gas.[40]

3.5 Direct use of CO_2

Carbon dioxide can also be used physically without changing the CO_2 molecule by chemical conversion. The CO_2 molecule is predestined for a direct use because it has a couple of useful properties:

- Inflammable
- Not toxic
- Inert
- Easy access of super critical status
- Low global warming potential compared to other cooling agents

Consequently, there a several options for the CO_2 molecule to be used for industrial as well as for consumer applications:

- In the beverage industry, CO_2 is used to keep the carbonic acid inside the beverages.
- CO_2 is used as foaming-agent and solvent in fire extinguishers.
- The food industry uses CO_2 as inert gas to enlarge the shelf life of food.
- CO_2 is used as cooling agent for various technical processes.
- Use of CO_2 for decaffeination of coffee.
- CO_2 is serving as cleaning agent in the textile industry.
- CO_2 usage as an extractant;
- CO_2 is used for the impregnation of timber.

[40] https://www.fraunhofer.de/en/research/lighthouse-projects-fraunhofer-initiatives/fraunhofer-lighthouse-projects/electricity-as-a-raw-material.html (accessed on 26.10.2017)

- Enhanced Oil/Gas Recovery (EOR, EGR): Within this method the CO_2 is injected / pressed into natural gas or oil fields in order to increase the delivery pressure and the yield of the deposit. Thereby around 20 million tons of CO_2 get stored underground annually. EOR and EGR is mainly an instrument to extend the profitability of the exploitation of an oil or gas deposit.

The CO_2 can be applied in solid, liquid or gaseous form. Furthermore, the direct physical use of CO_2 is not energy intensive. However, the CO_2 will be released into the atmosphere after usage. Thus, a decrease of CO_2 emissions is not possible by direct CO_2 usage. The only exception is EOR, EGR.

3.6 Overview examples of CO_2 value chains for industrial symbiosis

The following table summarises the examples of CO_2 value chains identified to be suitable to contribute to industrial symbiosis (IS).

Example	**CO_2 source**	**User of CO_2 stream**	**Current level for implementation (IS)**
Kalundborg Symbiosis	7 main partners with more than 30 exchanges (not just CO_2, also water, energy and material)	Main user of waste streams is amongst others *Novo Nordisk/Novozymes* for chemicals production	The first full commercial realisation of industrial symbiosis
Steel production linked to chemical industry (chapter 3.1)			
***LanzaTech* process**	Steel production sites	Production of (bio)ethanol	Various pilots at industrial and commercial relevant scale
Steelanol	*ArcelorMittal* steel plant Ghent	(Bio)ethanol production site; usage of bioethanol as fuel	Industrial scale production plant under construction
Carbon2Chem	*Thyssenkrupp Steel* production site Duisburg	Fuels, plastics & fertiliser production; Mainly ammonia and methanol	Industrial scale production plant planned, currently under specification

Carbon4Pur	Steel manufacturing at the Port of Marseille Fos	Production of polyurethane as polymer foams and coatings	Ongoing project; industrial relevant scale chemical production envisaged
FReSMe	CO_2 from steel production	Production methanol to serve as fuel (transport sector), primarily for ships (ferry).	Ongoing project (until 2020); Demonstration of low carbon intensity methanol as fuel in *Stena Line* ferry in 2020
CO_2 sources originated by industrial emissions linked to chemical industry (chapter 3.2)			
Rotterdam Harbour Industrial Complex	CO_2 mainly from refineries, power generation, chemical production and waste treatment	Algae, polyols and di-isocyanates production; mineralisation	Short- to mid-term uptake
MefCO$_2$	CO_2 from flue gas of power generation plant	Production of methanol for applications in transport sector, households (heating) and as basis chemical in chemical industry	Ongoing project (until 2018)
CO_2 sources originated by industrial emissions linked to bio industry (chapter 3.3)			
OCAP	*Shell* during the production of H_2 in an oil gasifier & during production of bio-ethanol at *Abengoa* in *Europoort Rotterdam*	CO_2 for Greenhouses (via distribution network)	Commercial implemented
Photanol	Not specified yet; CO_2 from power plants, waste incinerators, industrial sites and biogas producers	Alcohols and organic acids	Demo production phase

BioElectroPlast	CO_2 from flue gas (from power plants or chemicals production)	Production of bioplastics (bio polymer Polyhydroxybutyrate)	Current work at laboratory scale; pilot plant scale envisaged for second half of the project.
MIKE	CO_2 in biogas	Methanation of CO_2 in biogas by microbial electrosynthesis	Current work at laboratory scale; pilot plant scale envisaged for second half of the project.
Microbiological methane	CO_2 from a sewage sludge digestion plant	SNG	Pilot plant at Allendorf, Germany
Agricultural fertiliser from waste CO_2	CO_2 from the flue gas of an anaerobic digestion (AD) plant	Production of agricultural fertiliser	Process under development by *CCm Research* (UK)
Power-to-X: CO_2 as link between chemistry, electricity, heat and transport (chapter 3.4)			
Kopernikus P2X	Various CO_2 sources from industry	Methane (LNG), hydrocarbons, long-chain alcohols, OME (fuels)	Different TRL depending on technology; laboratory scale up to pilot scale
CELBICON	CO_2 capture from the atmosphere (air)	PHA bioplastic and C1-intermediates (isoprenes, lactic acid, ono-terpenoids)	Different TRL depending on technology; laboratory scale up to pilot scale, pilot under construction
Fraunhofer Lighthouse Project	No concrete CO_2 source specified	Production of ethene and assorted alcohols	Different TRL depending on technology; laboratory scale up to pilot scale, pilot under construction

3.7 Industrial symbiosis analytical framework

There are many aspects that have to be taken into account when evaluating and analysing the potential and feasibility of an industrial symbiosis.

Aspect	Detail	Comment
What is exchanged	Focussing here on CO and CO_2 Other chemicals Heat Waste (for mineralisation)	An industrial symbiosis, like e.g. Kalundborg, is exchanging as many streams as possible and not just focussed on CO_2.
Physical aspects	Physical distance between plants Existing connections / pipelines Security aspects Cross border aspects	These aspects are partially dependent on each other. E.g. a short physical distance is reducing costs for pipelines etc and the risks. Cross border exchanges are requiring a closer look on the regulatory framework
Legislative aspects	Waste directive Local permitting Safety aspects	These aspects have to be taken into account individually for each possible exchange of material, waste, energy or liquid/chemical.
Public support aspects	subsidies public 'pressure' innovation support/subsidies	These issues are varying related to the country, region and industrial sector.
Economic aspects	Is there a win-win or just one party has benefits? Is there a business case? How relevant for future? Do the industries work already together/know each other? Competitors or not?	In principle each exchange between two parties (companies) is a business contract/transaction that has to be advantageous for both partners.

An interview with *Global Green Growth Forum (3GF)* on industrial symbiosis[41] has has pointed out the main barriers on the one hand and the big overall potential of industrial symbiosis on the other hand. The interview was conducted with *Peter Laybourn*, the founder of *International Synergies (ISL)* and the National Industrial Symbiosis Programme and *Rachel Lombardi*, the

[41] https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=0ahUKEwjHxdmG_ovXAhXmQJoKHafrAIUQFggzMAE&url=http%3A%2F%2F3gf.dk%2Fen%2Fabout-3gf%2Fanalytical-framework%2Fportaits-of-ppps%2F~%2Fmedia%2F3gf%2FDocuments%2FPartnership%2520portraits%2FINDUSTRIAL%2520SYMBIOSIS.pdf&usg=AOvVaw2tyR6JEqjvMFClbGPkGXP_ (accessed on 25.10.2017)

Director of Business Development for *ISL* with international experience in business and academia (Yale, McKinsey, IBM)[42]:

Question: What are the barriers to making it happen?

“Mindsets are the primary barrier. It’s not so difficult to think systemically but it doesn’t come naturally. People are not trained to work outside their sector and therefore need someone to help them open their eyes and see everything as a resource not as waste. There are additional barriers or enablers such as policies and regulation, organisational priorities, technical challenges but the lack of systems thinking and cross sector working remains key.”

Question What is the potential for scale?

“Industrial symbiosis is a solution ready to be scaled. We have estimated that the potential global impact of large scale industrial symbiosis could be around $ 7,7 billion per annum from an annual investment of only $ 213 million.”

[42] http://www.international-synergies.com/ (accessed on 13.11.2017)

4. Separation and conditioning

4.1 Introduction to the need for CO_2 separation and conditioning

The main idea behind the CO_2 separation and conditioning, capturing carbon dioxide and then binding it long-term or reusing it in continuous closed cycles, is the contribution to the reduction of CO_2 emissions, beside the transition transitioning from an energy system based on fossil fuels to one based on renewable sources of energy.

The technologies used for the capture and storage of carbon dioxide are generally referred to by the abbreviation CCS, which stands for 'carbon capture and storage' or 'carbon capture and sequestration'. The abbreviation CCU refers to carbon capture and utilisation, which is the entire process chain comprising the separation or capture of the CO_2, compression of the gas under high pressure so that it can be transported economically, and finally, utilisation as a feedstock for the production of useful products. Technologies within the CCU portfolio include Power-to-X technologies in which available excess electric power drives electrolytic processes whose products are combined with captured CO_2 to synthesise new products.[43] For this see also chapter 3.4. on Power-to-X technologies in the context of industrial symbiosis.

The following figure shows the interlock of carbon capture, excess and renewable energy and the various Power-to-X technologies. This overview contains only the technology pathways with the use of carbon dioxide, directly via carbon capture or indirectly via synthesis gas.

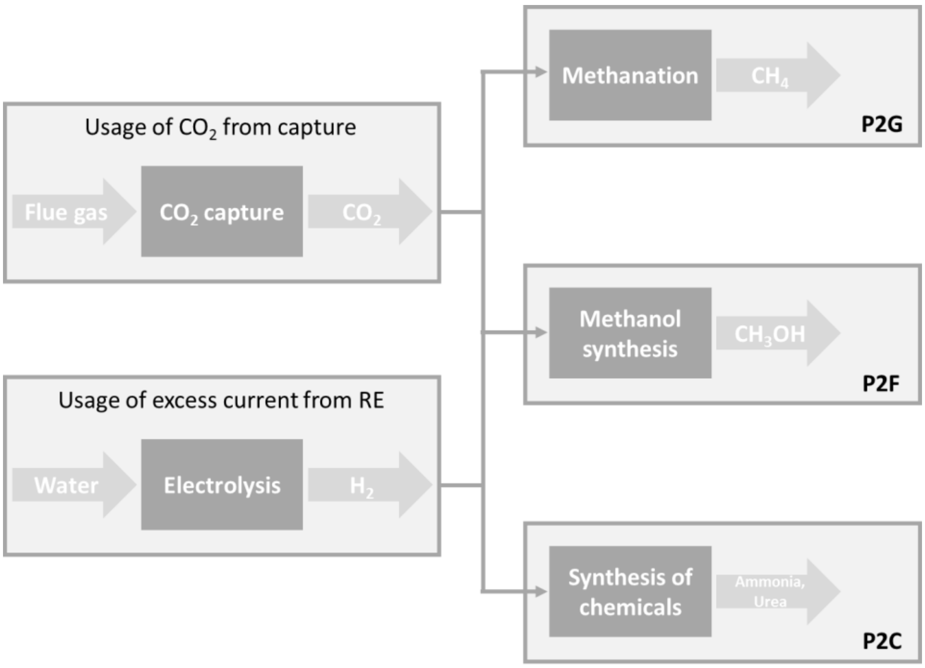


Figure 23: CCU and Power-to-X technologies (adapted from [26])

[43] K. Görner, "Carbon Capture" publ. in ‚Ergebnisse der BMBF-Fördermaßnahme „Technologien für Nachhaltigkeit und Klimaschutz - Chemische Prozesse und stoffliche Nutzung von CO_2"', ISBN: 978-3-89746-190-1, Frankfurt am Main, 2017, p.178-197

The need for CO_2 separation and conditioning has several reasons:

- Separation of CO_2 from other constituents of flue gas
- Increasing its concentration
- Achieving the desired CO_2:H_2 ratio
- Preventing "poisoning" of the catalysts used for CO_2 conversion reaction
- Monitoring of CO_2 quality for subsequent process steps
- Control and adjust the temperature of CO_2 for subsequent process steps
- A buffer tank for upgraded CO_2 could be necessary to guarantee constant CO_2 stream to the CO_2 conversion step

4.2 Classification and status of carbon capture and separation processes

The most common way to classify the different processes for carbon capture and separation from an industrial flue gas or exhaust gas stream is based on a number of different physicochemical processes:

- Absorption techniques
- Methods using gas-solid reactions
- Adsorption techniques
- Cryogenic methods
- Membrane separation techniques
- Processes based on natural incorporation

These physicochemical processes are further classified and detailed in the following figure. This classification is based on the physical and chemical principles applied, the chemical absorbents, physical absorbents or adsorbents and/or special methodologies used.

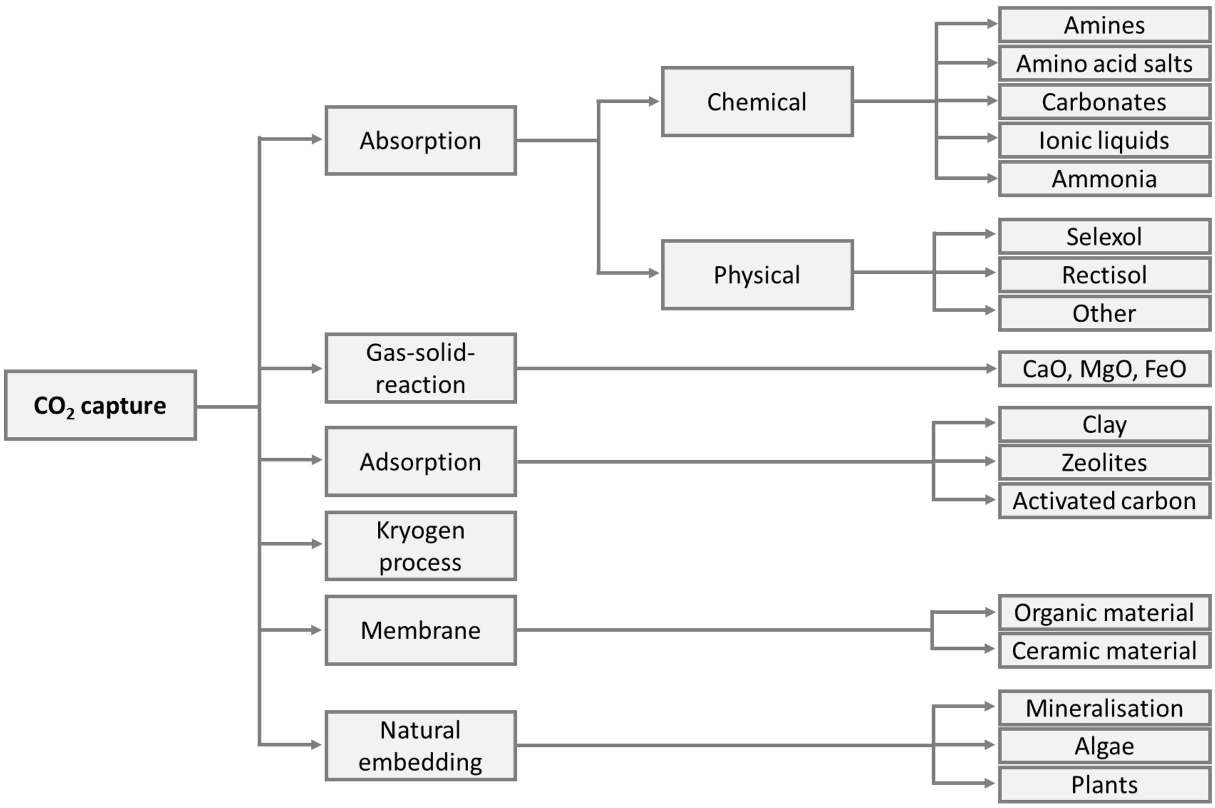


Figure 24: Classification of CO_2 capture systems[44]

Chemical absorption techniques

In carbon capture by chemical absorption, the CO_2 in a flue gas stream initially bonds chemically to an absorbent (also referred to as the ‘solvent’). The CO_2-enriched absorbent and the flue gas are separated and the CO_2 is then stripped from the absorbent by thermal desorption after which it can be utilised for other purposes. Chemical absorption technology is the most common of the carbon capture processes.

Physical absorption techniques

If atoms or molecules are dissolved in liquids, the process is referred to as physical absorption. When physical absorption is used for carbon capture, the CO_2 is physically bound to the absorbing material (absorbent) by intermolecular forces (typically van der Waals forces). The resulting equilibrium can be described at low concentrations of solute by Henry’s law (ideal dilute solution) and at high concentrations of solute by Raoult’s law (ideal solution).

Methods using gas-solid reactions

In this group of carbon capture methods, a gas-solid reaction is used to bind the CO_2 to a solid, typically a solid metal oxide. The CO_2 is chemically bound as a carbonate. The apparatus in which the reaction takes place is known as a carbonator. The most frequently used solid is calcium oxide (CaO), which is an inexpensive material that reacts with CO_2 to form calcium

[44] Adapted from: Fischedick, M.; Görner, K.; Thomeczek, M. (Hrsg.): CO_2: Abtrennung, Speicherung, Nutzung [CO_2: Capture, Storage, Utilisation]. Springer-Verlag Berlin Heidelberg, 2015

carbonate ($CaCO_3$). After the CO_2-depleted flue or exhaust gas and the carbonate have been separated, the latter is then thermally decomposed in a calcinator to regenerate CaO and CO_2. The high purity CO_2 is then collected and utilised elsewhere, while the CaO is returned to the carbonator.

Adsorption techniques

The physical adhesion of molecules onto a surface (interface) is known as physical adsorption or physisorption, as it is not the result of chemical bonding but of purely physical (van der Waals) forces. When used for carbon capture, the carbon dioxide becomes attached to the surface of the adsorbent. However, as the CO_2 molecules also have a propensity to leave (i.e. desorb from) the surface, an equilibrium becomes established between the opposing processes of adsorption and desorption. The position of this equilibrium will depend on the pressure, the concentration of the species being adsorbed, and the temperature, properties and size of the adsorbing surface.

Cryogenic methods

Cryogenic carbon capture techniques use the fact that different gas components exhibit different condensation and sublimation temperatures. Cryogenic capture is a physical separation method. It typically involves condensing out components such as water vapour from the flue gas stream. For it to work as a carbon capture technique, the flue gas must not contain any components with condensation temperatures lower than that of carbon dioxide. This is why cryogenic capture is used in combination with the oxy-fuel process in which the fuel undergoes combustion in pure oxygen (rather than air) thus ensuring that lower boiling nitrogen is not present in the flue or exhaust gas stream.

Membrane separation techniques

This group of carbon capture techniques use membranes to separate atoms and/or molecules. Depending on their size, these particles either pass through the pores of the membrane material at different rates or are retained by the membrane. Membrane gas separation is a purely physical separation method. As membrane separation occurs without the need for heat energy, it usually uses less energy than other (thermal) separation techniques. One disadvantage is the large membrane areas that are required, which leads to very large filtration units or plants.[45]

[45] K. Görner, “Carbon Capture” publ. in ‚Ergebnisse der BMBF-Fördermaßnahme „Technologien für Nachhaltigkeit und Klimaschutz - Chemische Prozesse und stoffliche Nutzung von CO2“‘, ISBN: 978-3-89746-190-1, Frankfurt am Main, 2017, p.178-197

The follow table gives an overview on the current status of the different carbon capture methods.

Table 5: Status, potential and research requirements of the different carbon capture methods

Option	Absorption based processes (chem. & physic.)	Gas-solid reaction	Adsorption - based processes	Oxyfuel/cryogenic methods	Membrane-based processes	Natural embedding	Chemical Looping
Additional energetic effort	High (15-20% of a given plant output)	Unknown	High (20% of a given plant output)	Presently very high due to cryogenic air separation	Unknown	Low, depending on embedding method	High (15-20% of a given plant output)
Cost	>20 €/t CO_2 (Sequestration)	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
State of technology	Experience on industrial scale	Concepts and Pilot Plant trials	Pilot Plant trials	Concepts and Pilot Plant trials	Laboratory Scale	Concepts and Pilot Plant trials	Pilot Plant trials
Time horizon	Medium-term	Medium-term	Long-term	Medium-term	Long-term	Long-term	Long-term
Research requirements	Absorption media: -increased lifetime -fast loading and unloading -reduced heat for regeneration	-carbonation reaction -Selection metal oxide -design carbonator, calcinatory -thermal decomposition process	Adsorption media: -increased lifetime -fast loading and unloading	-Development of robust membrane-based processes for air separation (Oxygen carrier membrane)	-Development of robust membrane-based processes for CO_2 separation.	-Embedding reaction -Long-term stability, safety	-Development of highly selective oxygen carriers with good long-time stability -Engineering concepts for cycling solids with minimum loss of material -Extend pilot plant trials
	-Further development of flue gas scrubbing techniques						

5. Conclusions

The utilisation of CO_2 or CO containing gases for value added processes is a further contribution to industrial symbiosis on regional level as well as a potential link to couple industry sectors supra-regionally. The large, unused emissions from the steel, cement and chemical industries can be seen as a starting point for symbiotic relationships crossing the boundaries between industry sectors or companies.

On the one hand, technological hurdles such as efficient, economically justifiable capturing processes, a sufficient infrastructure and sound utilisation pathways are crucial, however, on the other hand, dealing with dependencies between companies within established industrial symbiosis scenarios, such as revenue distribution, IP ownership, as well as political frameworks such as funding, incentives, taxes, etc are tasks to be addressed.

The implementation of industrial symbiosis requires the willingness of different industry sectors to co-operate and to find a business case where all involved partners have a clear and mutual benefit. This is demanded by a new mind-set of decision makers. Furthermore, it is decisive that either greenhouse-gas emissions are cut or at least equal while raw materials such as fossil fuels are replaced. Hence, there is a need for clear and transparent revenue allocation, defined IP ownership and life cycle analysis (LCA) in order to assure that the cooperation is sustainable. An LCA is crucial in order to allocate reasonably which party receives credits and in which amount. IP ownership as well as revenue questions must be considered and well-defined while exploring new symbiotic relationships. Especially IP questions will be relevant as the recipient of carbon rich flue gases needs to know details about the composition and characteristics – usually confidential information. For symbiotic relationships, the development, ownership and maintenance of the infrastructure must be assured, too. In some cases, the involved companies are not prepared to undertake this task. Public private partnerships (PPP) can be the solution in order to step in and establish the infrastructure that is necessary. Furthermore, as the example in the present report shows, public funding was crucial to kick-off projects while the financial risk for companies is reduced. Also, specific programmes on industrial symbiosis, such as the UK based National Industrial Symbiosis Programme (NISP), help companies with knowledge transfer on utilising material streams, energy, water and other assets as well as finance investigations and ventures. Such programmes accelerate eco-innovation and push the envelope of best practise.

Many research projects show that a wide implementation of CCU processes in industrial parks are technical feasible, however, as long as fossil resources remain at a low price, CCU concepts seem not to become competitive without political regulations. Nevertheless, the price for fossil fuels will increase and a political movement towards new regulations in respect to CCU are underway. EU regulations such as the Renewable Energy Directive (RED), the Waste Directive and the EU ETS for example are under negotiation at the moment, whereat CO_2 utilisation may become considered for support. However, regulations will remain complex as they may differ from country to country or even from region to region.

The EU strongly supports the idea of a circular economy and carbon containing gases are included within the EU Circular Economy Package. The package and the reference to using CO_2 in particular will build confidence in the community to evaluate and start with new projects in the context of industrial symbiosis.

The examples provided in this report show that the process industries are keen and ready to scale-up industrial symbiosis, whereat ecological and economic benefits will certainly be achieved. The next subsequent steps are large scale projects, which demonstrate the state of the art over a long period of time in order to prove the stability of the process.

Stakeholders, especially SMEs, may seek and study business options summarised in deliverables 2.1 and 2.2. The documents shall also serve as access to information on CO_2 utilisations pathways for potential first-time users and experts.

6. Bibliography

[1] Chertow, Marian R (2007). ""Uncovering" Industrial Symbiosis." Journal of Industrial Ecology 11.1: 11-30. Print

[2] A. Bazzanella, F. Ausfelder, DECHEMA e.V., CEFIC Technology Study "Low carbon energy and feedstock for the European chemical industry", ISBN: 978-3-89746-196-2, Frankfurt am Main 2017.

[3] http://www.symbiosis.dk/en/

[4] Per Møller, Head of Symbiosis Center Denmark, "INDUSTRIAL SYMBIOSIS-POWERING UP THE GREEN TRANSITION TOWARDS A CIRCULAR ECONOMY", at DECHEMA PRAXISforum Power-to-X, 18.10.2017, Frankfurt am Main

[5] EU ETS data 2015, http://www.eea.europa.eu/data-and-maps/data/data-viewers/emissions-tradingviewer-1

[6] https://www.thyssenkrupp.com/de/carbon2chem/

[7] http://www.vlaamseklimaattop.be/sites/default/files/atoms/files/ArcelorMittal%20-%20project%20Steelanol.pdf

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

[9] http://cordis.europa.eu/project/rcn/195267_en.html

[10] http://blog.germany.arcelormittal.com/helferchen-machen-biodiesel-aus-abgasen/

[11] http://carbonrecycling.is

[12] http://cordis.europa.eu/project/rcn/205958_en.html

[13] http://www.fresme.eu/

[14] http://www.deltalings.nl/sites/www.deltalings.nl/files/documenten/a6_marktstudie_ccu_voor_hic_-_ce_delft_3k44_ccu_market_options_rotterdam_harbour_def.pdf

[15] "CCU market options in the Rotterdam Harbour Industrial Complex" Publication code: 17.3K44.51, Delft, June 2017

[16] http://www.mefco2.eu/

[17] https://www.stenalinefreight.com/news/Methanol-project

[18] www.ocap.nl

[19] Zero Emission platform report on carbon capture and utilisation, April 2016 (http://www.zeroemissionsplatform.eu/library/publication/265-ccu.html)

[20] https://www.bio.org/sites/default/files/WorldCongress/Dirk%20den%20Ouden.pdf

[21] http://www.chemieundco2.de/de/projekte/elektro-und-photokatalytische-aktivierung-von-co2/

[22] http://dechema-dfi.de/en/MIKE+%E2%80%93+Methanation+of+CO2+from+biogas+by+microbial+electrosynthesis.html

[23] http://www.infraserv.com/en/referenzen/standortbetrieb_industriepark_hoechst/index.html

[24] Innovate UK (2016). CCm Research develops carbon dioxide utilisation process for value added materials. Available at: https://www.ktn-uk.co.uk/perspectives/ccm-research-develops-carbon-dioxide-utilisation-process-for-value-added-materials

[25] CCm Research (2017). Using waste to create valuable products and a better environment (video). Available at: https://www.ktn-uk.co.uk/perspectives/ccm-research-develops-carbon-dioxide-utilisation-process-for-value-added-materials

[26] A. Bazzanella, D. Krämer (editor), DECHEMA e.V., Ergebnisse der BMBF-Fördermaßnahme „Technologien für Nachhaltigkeit und Klimaschutz – Chemische Prozesse und stoffliche Nutzung von CO_2“, ISBN: 978-3-89746-190-1, Frankfurt am Main, June 2017

[27] Kopernikus P2X-presentation for public audiences, copyright© by DECHEMA e.V., RWTH Aachen Univesity, Forschungszentrum Jülich e.V.

[28] http://www.celbicon.org

[29] http://cordis.europa.eu/project/rcn/200178_de.html

[30] https://www.fraunhofer.de/en/research/lighthouse-projects-fraunhofer-initiatives/fraunhofer-lighthouse-projects/electricity-as-a-raw-material.html

[31] http://www.international-synergies.com

[32] Fischedick, M.; Görner, K.; Thomeczek, M. (Hrsg.): CO_2: Abtrennung, Speicherung, Nutzung [CO_2: Capture, Storage, Utilisation]. Springer-Verlag Berlin Heidelberg, 2015