Distribution: General

Final Report

Market study report CCU

Miet Van Dael

Study accomplished in the framework of the EnOp project

2019/SCT/R/1876

December 2018

VITO NV
Boeretang 200 - 2400 MOL - BELGIE
Tel. + 32 14 33 55 11 - Fax + 32 14 33 55 99
vito@vito.be - www.vito.be

BTW BE-0244.195.916 RPR (Turnhout)
Bank 375-1117354-90 ING
BE34 3751 1173 5490 - BBRUBEBB

ACKNOWLEDGEMENT

We acknowledge financial support from the European Fund for Regional Development through the cross-border collaborative Interreg V program Flanders-the Netherlands. This report is a result from the EnOp project (https://www.brightlands.com/region-growth/governmental-support/project-enop-1).

SUMMARY

Within the interreg project 'EnOp' researchers from the Netherlands, Belgium and Germany work on seven different technologies for the conversion of CO_2 to energy carriers and chemicals. One of the activities within the project is to provide a good insight into the CCU (i.e. carbon capture and utilization) market. Therefore, we discuss in this market the reasons for CCU interest, the CO_2 supply and demand, we provide a brief overview of CO_2 capture technologies and provide some details on sustainability aspects, the EU ETS system and RED II. We end the report with a short discussion of public perception and acceptance.

Many different reasons are identified for the interest in CCU. According to our own Delphi study, the main reasons are the potential CO_2 emission reduction, the replacement of current carbon feedstocks and the integration with renewable energy. The most important risks that we identified are the high costs and a lack of supporting regulation. However, the experts believe that CCU developments will increase at a fast pace in the next decade with optimizations and commercialization.

Many studies are performed to identify the CO_2 availability, however, the estimated numbers vary widely between the studies. A capturable CO_2 amount in the range of 1.5 to 2 gigaton annually is accepted as a feasible number. When interpreting the numbers, it is important to take into account that the emissions per sector can change over time as more efficient processes are designed or alternative sources become available on the market. The four large industrial CO_2 emitters that are often mentioned by experts as interesting capture sources are cement, steel, ammonia and ethylene manufacturers.

CO_2 is not available for free as it should be captured, purified and, depending on the site location, also transported. Different capture and separation technologies exists and the costs depend on the CO_2 amount, CO_2 concentration, partial pressure, as well as the concentrations of contaminations such as N_2. CO_2 is used in various industries and for a large diversity of applications. It is clear that the CO_2 supply is much larger than the CO_2 demand and that the main bottleneck will be the cost at which the CO_2 can be captured and made available. The question is sometimes raised whether focus should first be put on the production of large markets such as fuel production or rather smaller markets with high value chemicals. We believe that smaller, high-value markets might be more interesting to focus on in the beginning.

To have a clear idea of the environmental impact of CCU technologies one can use an LCA approach. However, for a fair comparison, the need for a standardized LCA assessment for CCU technologies is identified by several researchers and organizations. Based on the assessments that have already been performed, it is clear that the use of renewable energy is crucial for the environmental sustainability of CCU technologies. Two other aspects that are important when speaking about the potential of CCU in climate mitigation change are the amount of CO_2 that can be sequestered and the time over which it can be sequestered. Both aspects are also important with regard to the legal aspects.

Finally, purely technical, environmental or economic benefits do not guarantee success of innovative products and technologies and the question 'how do potential customers perceive these products and technologies' is also important.

TABLE OF CONTENTS

Acknowledgement I

Summary II

Table of Contents III

List of Figures IV

List of Tables V

CHAPTER 1 Introduction 1

CHAPTER 2 Market overview 2

2.1. Reasons for CCU interest 2
2.1.1. Delphi Study and Scenario Development 3

2.2. CO_2 availability 4
2.2.1. Power sector 7
2.2.2. Steel Industry 8
2.2.3. Cement Industry 9
2.2.4. Ethylene and Ethylene oxide Production 9
2.2.5. Ammonia Production 9
2.2.6. Biogas Production 10
2.2.7. CO_2 Emitters in Flanders and The Netherlands 10

2.3. CO_2 capture – purification – transport 14
2.3.1. CO_2 capture, concentration and purification 14
2.3.2. CO_2 transport 20

2.4. Electricity and Hydrogen market 21

2.5. End-products 22
2.5.1. Methanol market 24
2.5.2. Syngas market 26
2.5.3. Formic acid market 26

CHAPTER 3 Sustainability aspects 28

CHAPTER 4 Legal aspects 30

4.1. EU ETS 30

4.2. Renewable Energy Directive II (RED II) 32

CHAPTER 5 Public perception and Acceptance 34

CHAPTER 6 Conclusion 37

References 38

LIST OF FIGURES

Figure 1: Global CO_2 emissions 5

Figure 2: Greenhouse gas emissions broken down per sector[2] 5

Figure 3: Origin CO_2 emissions per source 6

Figure 4: Total emissions (blue bars) and point sources (orange line) per industry in Europe 7

Figure 5: ETS and biogas/biomass companies in Flanders 11

Figure 6: Emissions (in ton CO_{2eq}) ETS companies in Flanders 11

Figure 7: Emissions (in ton CO_{2eq}) ETS companies in the Netherlands 12

Figure 8: Share of companies in Flanders according to CO_{2eq} emissions 12

Figure 9: Overview of CO_2 capture technologies 15

Figure 10: Working range CO_2 capture technologies 17

Figure 11: Methanex' methanol contract price in Europe 25

Figure 12: Diffusion Theory of Rogers 35

LIST OF TABLES

Table 1: Reasons for CCU interest according to literature ___ 3

Table 2: Steel gas composition ___ 8

Table 3: Biogas composition ___ 10

Table 4: Number of companies and emissions per sector in Flanders ___ 13

Table 5: Top 20 emitters in Flanders ___ 13

Table 6: CO_2 emissions, concentrations, capture cost and partial pressure per CO_2 source ___ 19

Table 7: Electricity prices for non-household consumers in $€_{2017}$/kWh ___ 21

Table 8: Production rates, CO_2 use in compounds and price ___ 23

CHAPTER 1 INTRODUCTION

A transition to a low-fossil chemical sector is necessary, but will also know many challenges. Some of these challenges are outside the control of the sector itself. For example the availability of low carbon energy, the availability of and access to alternative feedstock and uncompetitive production costs compared to other areas with e.g. no or limited incentives towards decarbonization. To make the transition possible, high investments will be necessary.

Carbon capture and utilization (CCU) is the process of converting CO_2 emissions into building blocks for new products like plastics and fuels. CCU is often mentioned in relation to carbon capture and storage (CCS). It should be clear that both concepts are technologically intertwined by the step of carbon capture, however, they have different basic motivations and logics. CCU is likely to help increase resource security and is more economic driven, whereas CCS is developed against the background of direct climate mitigation and as such more environmentally driven.

In the development of CCU processes, many stakeholders are involved and it is important to correctly understand the motivations of the different stakeholders for their interest in CCU. One has to make sure that communication strategies are adapted to these motivations to guarantee that all stakeholders are in favor of the developments. Stakeholders are amongst others companies with CO_2 emissions, companies interested in CO_2 conversion processes, companies interested in the end-products, government, employees, customers and the general public.

CCU processes can provide different services to the market and, therefore, the reasons for interest in CCU development are quite broad. One important reason for interest is resource security for carbon-based chemical industry (both industrial products and fuels). CCU processes can target various end-products from polymers and specialty chemicals to fuels. Captured CO_2 can act as a replacement for fossil resources, which makes it possible to minimize the extraction of finite resources. A second reason is storage of renewable energy. Due to the intermittent character of renewable energy, researchers are searching for processes that can be operated flexible. CCU processes are one of the potential solutions as they can store the renewable energy in a chemical form, both as a fuel or chemical end-product. Both services need to be further investigated to identify the real potential and in this project we will provide information that allows us to help answer this question.

The report is structured as follows. In Chapter 2 we describe insights into several market aspects. We start with a description of the main reasons for CCU interest. In this part we also describe the Delphi study on future CCU scenarios in the Flanders/the Netherlands region that we performed ourselves. Next we give more insight into the three main steps of the CCU value chain, i.e. (1) the capture of CO_2, (2) the purification, separation and transport of the CO_2 and (3) the conversion of CO_2 into products. Here we also give an overview of CO_2 emitters in the region (i.e. Flanders – the Netherlands). We will not go into detail in the conversion process themselves, nor on the downstream processing (DSP). In Chapter 3 we give more information on sustainability aspects of CCU technologies. In Chapter 4 we briefly describe some legal aspects related to the renewable energy directive (RED) and emission trading system (ETS). In Chapter 5 we provide an overview of the research that has already been done about public acceptance. Finally, in Chapter 6 we provide our main conclusions.

CHAPTER 2 MARKET OVERVIEW

In this chapter we will give more insight in the market aspects of the value chain of CCU. Note that the value chain of CCU can be complex as minimally three activities are involved, i.e. (1) the CO_2 emissions, (2) the capture, purification and/or transport of the CO_2 and (3) the CO_2 conversion and DSP. Depending on the specific case study these activities can be operated by one or multiple partners. Furthermore challenges exists in matching the CO_2 demand for different operation scales in combination with the market size of the end-products and the CO_2 supply. CO_2 point sources often emit large amounts of CO_2, whereas the market of high-value specialty chemicals is rather small and quickly saturated. Also, the capture of CO_2 is expensive and a certain minimum amount needs to be captured to cover the investment costs. Therefore, bulk chemicals and fuels or a combination of these high-volume products with high-value specialty chemicals might be the first options to focus on and make sure the CCU market will be established. However, to have environmentally friendly processes, a large amount of renewable energy needs to be available. Because of the latter, focus will probably first be on high-value products to prove the potential of CCU. For the reasons mentioned, it will probably not be possible to use all the CO_2 produced by an industrial plant. This is also concluded by Atsonios, Panopoulos, and Kakaras (2016). If for example the flue gases of a typical 300 MWe coal fired power plant undergoes to hydrogenation, the required power for water electrolysis is 1.77 GWe. This is technically infeasible and economically unprofitable. As a reference: according to a monitoring report of the federal planning office it is estimated that the total installed capacity of renewable energy in Belgium will evolve to ca. 11 GWe by 2030. To make sure that CCU will be established several action points are formulated within the SET implementation plan. To enable competitive CO_2 valorization the following four points are important: (1) cost competitiveness; (2) energy efficiency; (3) modular approaches and (4) optimal location for different CO_2 utilization paths.

We start this chapter with an overview of reasons for CCU interest and a summary of the main results of our own study concerning the factors that will influence the implementation of CCU value chains in the region Flanders-the Netherlands. Next we describe the CO_2 availability and give an overview of emitters in our region. We briefly describe options for CO_2 capture and purification. Next we give more insight into the end-use of the captured and purified CO_2. In this report we will mainly focus on the end-products that are targeted within the EnOp project. Finally, we give an overview of expected electricity and H_2 prices.

2.1. REASONS FOR CCU INTEREST

Many reasons are identified to explain the interest in CCU technologies. The majority of the reasons are related to climate change mitigation or environmental benefits in general and energy security. Only a small number of reasons is linked to competitiveness or innovation (Bennett, Schroeder, & McCoy, 2014). The reason for this can be that CCU and CCS are sometimes combined in studies and/or that in the beginning focus was mainly on CCS. An overview of often used arguments for CCU interest in various literature sources is provided in the table below. The table is far from complete, however, we only want to show the large variety of arguments that are used. Since the number of reasons that are provided for CCU interest is large and diverse, in the next section we describe the results of our own study within the EnOp project. We did a study to identify the most important reasons for CCU interest in the region Flanders-the Netherlands. In our study we clearly made a distinction between CCU and CCS to avoid any confusion.

Table 1: Reasons for CCU interest according to literature

Reasons for CCU interest
To create a revenue stream for CO_2 abatement from fossil fuel use based on consumer demand for CO_2-containing products.
Avoid greenhouse gas emissions
Alternative for carbon capture and storage (CCS)
Energy security
To make use of specific attributes of CO_2 in commercially competitive applications
To remediate inorganic wastes from industrial processes
To decarbonize the process industry and transportation sector
Sequestration of significant quantities of CO_2 in building materials
Energy storage options
CCU can provide revenues to fund (partially) CCS projects
Replace fossil or biobased feedstock
Feedstock and price security
Contribute to a circular economy
Reduce the complexity of chemical reaction pathways
Cost control for the supply of fuels

2.1.1. DELPHI STUDY AND SCENARIO DEVELOPMENT

In a study in collaboration with the Hasselt University and ULiège we used a Delphi study in combination with scenario development to identify the various factors that need to be considered, examined and monitored to support the establishment of a CCU market in the next 10 years in the region Flanders – the Netherlands. By explaining how these factors behave and how they interact, we provide an exploration of the elements that will influence the success of companies and the environment in which they operate. In this report we will only briefly describe the results. For a detailed description of our study, we refer to the manuscript ‘Exploring the future of carbon capture and utilisation by combining an international Delphi study with local scenario development’ that is published in the journal ‘Resources, conservation and recycling’.

The Delphi results show that the main selling point for CCU technologies remains the potential CO_2 emission reduction, although the scenario exercises and the literature review do mention stringent preconditions that need to be met for this benefit to be reaped. Other benefits, such as CCU replacing current carbon feedstocks while providing an abundantly available source of carbon, will help avoid the depletion of finite resources. Furthermore, we discovered important risks that can seriously hinder the establishment of CCU technologies. High costs, a lack of supporting regulation and technological setbacks were indicated as barriers that could prevent CCU pathways from making it to the market successfully. However, numerous advancements are being made in the technological process. Experts predict that their development will increase at a fast pace in the next 10 years with higher levels of optimization and commercialization. The integration with renewable energy was also seen as an important development in the future, where CCU can, for example, act as an energy storing system.

We further explored the interaction between the Delphi factors by gathering experts’ opinions on their impact and uncertainty. This allowed us to separate the factors that will have a high impact on the development of the sector – such as the government, cost development, technological developments and the behavior of competitors – and factors that will have a low impact on the sector, such as the contribution to the circular economy, storage time and the dependence on fossil fuels.

Four possible scenarios for the CCU sector in 2030 were created based on two high-impact factors with large uncertainty, i.e. the role of the government and cost development.

The most appealing scenario ‘CCU paradise’ is characterized by a strong cooperation of industry and government, together they establish a structured vision about the direction in which they want the sector to evolve and about how they will manage this. This structured vision is well communicated towards consumers, instigating opportunities for economies of scale. In the least appealing scenario ‘CCU hell’, government efforts are stimulating other sectors, together with failing industry initiatives due to a lack of R&D results. Without these critical elements, consumers will not be on board, which eliminates the possibility of lowering production costs. The two other scenarios, ‘CCU purgatory’ and ‘Saint industry’, are the less-than-optimal scenarios in which either the government or the industry takes the initiative to establish the sector, with varying degrees of success. In the case of governmental support for CCU, no matter how many subsidies the sector receives, companies are still reluctant to choose CCU related production methods when initial R&D results are unfavorable, thus not successfully establishing the sector. When the industry takes the lead for CCU development, initial start-up of the sector will move slowly, but cost reduction allows companies to sell their products at a more competitive price, leading to increased consumers’ take-up. Given these possible scenarios, we see that industry and governmental initiatives and cooperation are crucial elements in the establishment of the CCU sector and thus a starting point for future research and strategy planning.

2.2. CO_2 AVAILABILITY

Globally around 35 gigaton of CO_2 per year (see Figure 1) are emitted with the majority coming from anthropogenic sources (Anderson & Peters, 2016; Fuss et al., 2014). An overview of the share of greenhouse gas emissions per sector is provided in Figure 2. In the paper of Naims (2016) it is mentioned that the total amount of capturable emissions from point sources is approximately 12.7 gigaton. Of this only 2% are high-concentration sources. In a document from the global CCS institute it is reported that circa 0.5 gigaton of low cost, high concentration CO_2 is available per year as a by-product of mainly natural gas processing and fertilizer plants. An additional 18 gigaton CO_2 is available at a higher cost from power, steel and cement plants (Brinckerhoff, 2011). Von der Assen et al (2016) mention a worldwide total emission of 7.6 gigaton CO_{2eq} when only looking at point sources with more than 0.1 million ton emissions per year. Of these large emitting sources, 78% are fossil-fueled power plants. In their paper, Oei, Herold, and Mendelevitch (2014), used a European database (EU27 plus Switzerland and Norway) with a total number of implemented emission sources in 2010 of 2,725. These have combined 2.1 gigaton CO_2 emissions annually. From the total number of facilities, 1,476 (i.e. 54%) are fossil-fueled power plants (they included waste, natural gas, lignite and coal fueled power plants with emissions over 100,000 ton annually) with total CO_2 emissions of 1.5 gigaton annually. The other 1,249 (i.e. 46%) facilities are industrial (iron and steel production, cement and clinker production and oil refineries) and have combined emissions of 0.6 gigaton CO_2 per year. Another report estimates the potential CO_2 supply from point sources greater than 100,000 ton per year at 18 gigaton per year in total. From these CO_2 emissions 70% is coming from power generation plants (Brinckerhoff, 2011).

From the above literature overview, it is clear that the estimated amount of CO_2 that can be utilized differs largely between 7.6 to 18 gigaton. In general a capturable CO_2 amount in the range of 1.5 to 2 gigaton annually is accepted as a feasible number (Armstrong & Styring, 2015; Centi & Perathoner, 2011; Oei et al., 2014). One has to take into account that the emissions per sector can be changed over time as more efficient processes are designed or alternative sources become available on the market.

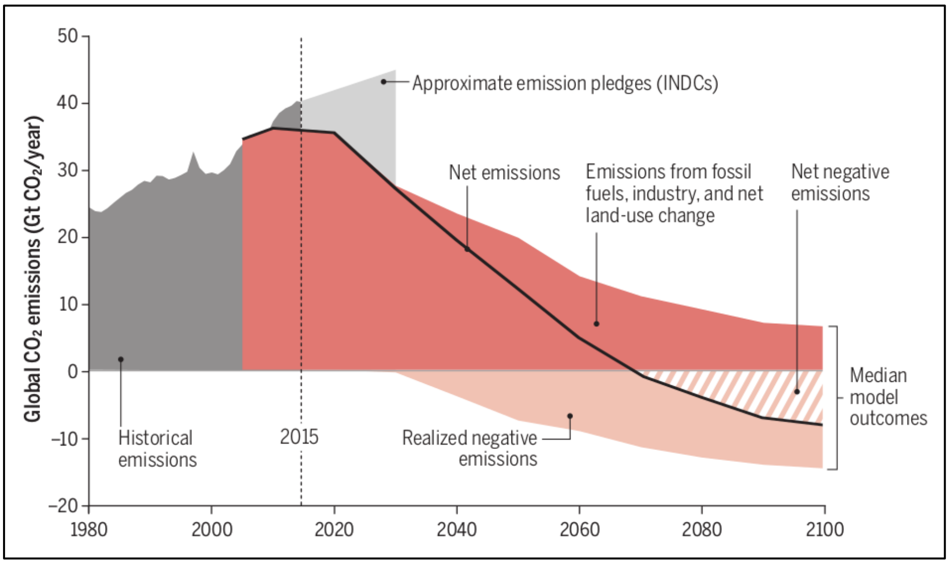


Figure 1: Global CO_2 emissions
(Anderson & Peters, 2016)

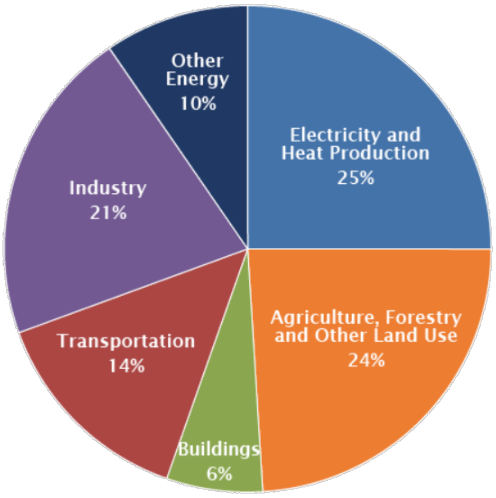
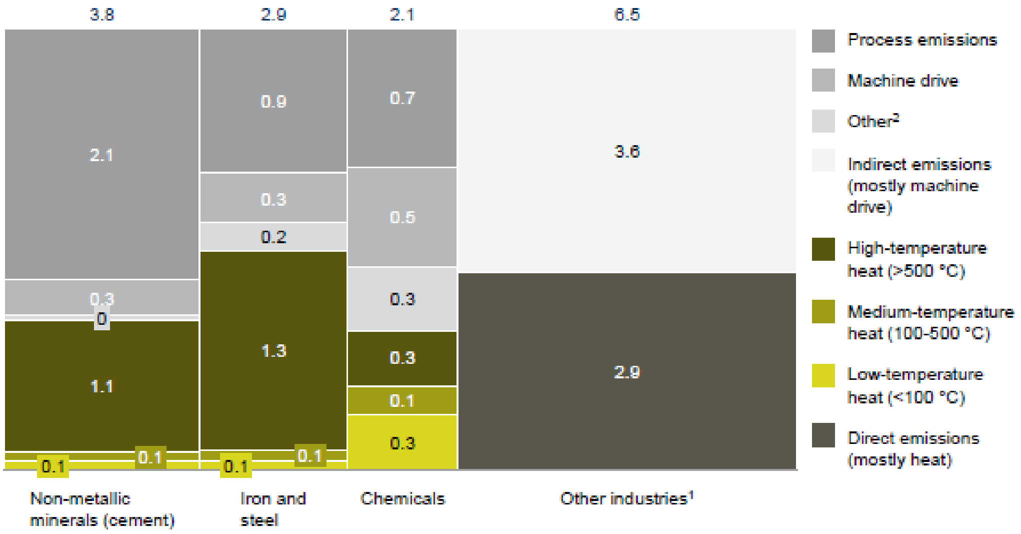


Figure 2: Greenhouse gas emissions broken down per sector[2]

The four large industrial CO_2 emitters that are often mentioned by experts as interesting capture sources are cement, steel, ammonia and ethylene manufacturers. Together they emit ca. 45% of industry's CO_2 emissions on a global level. This is 3 gigaton for cement, 2.9 gigaton for steel, and within the chemical sector 0.5 gigaton for ammonia and 0.2 gigaton for ethylene production. Within these production processes, 45% of the CO_2 emissions come from the feedstock, 35% come from burning fuel to generate high-temperature heat and the remaining 20% results from other energy requirements. Figure 3 gives an overview of the emission origin per source. Note that in many other industrial processes, the emissions result from low to medium temperature heat and electricity consumption (de Pee et al., 2018).


40% of emissions in industry are related to fuel combustion for heat

Gton CO_2/yr per emission source, 2014

NOTE: Differences in totals due to rounding
1 Includes food and tobacco, construction, mining, machinery, nonferrous metals, paper and pulp, transport equipment, textiles and leather, wood and miscellaneous industry
2 Includes emissions related to electrochemical processes, process refrigeration and cooling, and all emissions from nonprocess energy use, such as on-site transport and facility HVAC
3 This graph does not differentiate in emissions source for other industries

SOURCE: IEA data from World Energy Statistics © OECD/IEA 2017 IEA Publishing; Enerdata: global energy and CO_2 data; expert interviews

Figure 3: Origin CO_2 emissions per source
(de Pee et al., 2018)

Within Europe the total GHG emissions in 2015 were approximately 4451 million ton of which ca. 75% are CO_2 emissions, i.e. 3.4 gigaton[1,2]. Within the CarbonNext project they estimated the CO_2 emissions within Europe for the most interesting CO_2 sources based on the paper of Naims (2016) and the E-PRTR database published by the European Energy Agency. The total CO_2 emissions per year in Europe of the most interesting CO_2 sources amount to over 0.35 gigaton. The iron and steel and cement industry have the highest total amount of CO_2 emissions, however, they also have many separate point sources, respectively 0.151 and 0.119 gigaton CO_2 emissions and 93 and 212 point sources with annual CO_2 emissions over 100,000 ton. Whereas the hydrogen, Natural Gas, Ethylene oxide, Ammonia, Paper and pulp and Coal to Power facilities have lower total emissions, but also only a few point sources, i.e. 3 to 35 point sources with annual CO_2 emissions over 100,000 ton. Note that the number of ammonia plants might be underestimated in this study. Figure 4 gives a graphical overview of the numbers.

The chemical industry is energy intensive. In 2014 the fuel and power consumption of the EU chemical industry was approximately 19.5% of the overall EU industrial energy consumption. The CO_2 emissions amounted to 0.12 gigaton, however, are lowering due to energy efficiency measures. The main chemical building blocks that combined emit two-thirds of the total chemical industry greenhouse gas emissions are ammonia, urea, methanol, ethylene oxide, propylene, chlorine and the aromatics BTEX (Bazzanella & Ausfelder, 2017).

---

[1] https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-6/assessment-1

[2] https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

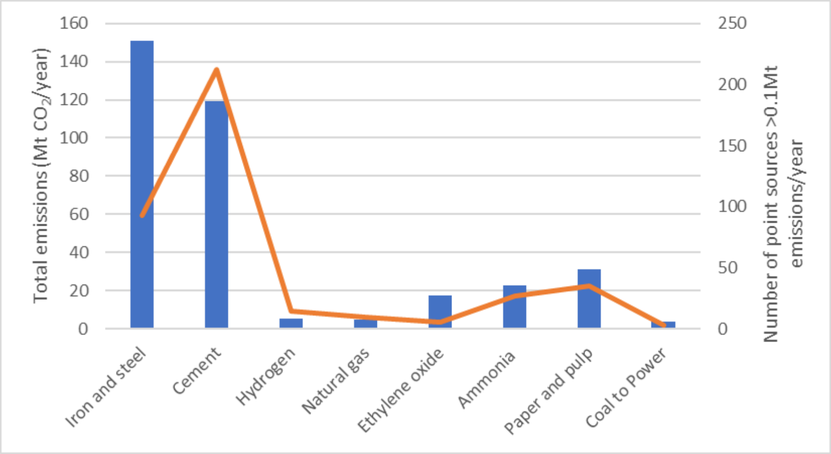


Figure 4: Total emissions (blue bars) and point sources (orange line) per industry in Europe Based on the CarbonNext project.

Especially the chemical processes of ethylene oxide and ammonia production, natural gas processing and steam-methane reforming for hydrogen production are interesting as first sources for CO_2 capture because of the high purity, i.e. over 95% (Leeson, Mac Dowell, Shah, Petit, & Fennell, 2017). Targeting first these high purity CO_2 sources is also concluded by Naims (2016) and von der Assen (2016). Natural gas processing results in a high purity CO_2 stream because natural gas cannot be used directly after extraction. CO_2 and acid gases such as H_2S must first be removed. The removal of these gases is typically done via an amine adsorption process. The partial pressure of the CO_2 is 0.5 to 44 bar. Most natural gas processing facilities in Europe have annual CO_2 emissions below 500,000 ton[3]. High CO_2 concentrations can also be found in ethanol fermentation, i.e. up to 90% and the flow is 50 ton per hour. For other CO_2 sources it can in general be stated that flue gases have CO_2 concentrations of 10 to 15% and are available at a rate of 700 ton per hour.[4] For some interesting industries, more details are provided in the next paragraphs.

Next to emissions from point sources, also CO_2 that is directly available in the atmosphere is a potential source (see paragraph 2.3.1).

2.2.1. POWER SECTOR

Although power generation plants are the largest CO_2 emitting group, the capture of CO_2 has significant efficiency losses (i.e. 10-30%) of the output energy and as a consequence these companies lack business incentives for large scale CO_2 capture (Naims, 2016). The reason that the energy is lower when a post combustion capture is added to a power plant is that the steam needed for solvent regeneration is no longer available for power production itself. The limiting factor of a power plant is the boiler, and thus no additional steam can be made (Assen, Müller, Steingrube, Voll, & Bardow, 2016). To illustrate the large emissions of the power sector we add as an example the CO_2 production of a 400 MW natural gas combined cycle gas turbine (CCGT) with a 60% lower heating value (LHV) efficiency. Such an installation generates 3230 ton CO_2 per day at a 100% capacity factor (Bennett et al., 2014). A 1000 MW coal-fired power plant can emit 6 to 8 million ton CO_2 annually. An oil-fired power plants emits circa 25% less and a natural gas CCGT emits 50% less (Khoo & Tan, 2006). Emissions from coal power generation are also less interesting as the gas purification will be more expensive due to the contamination with sulphur and heavy metals.

---

[3] http://carbonnext.eu/Deliverables.html

[4] https://ec.europa.eu/energy/sites/ener/files/documents/26_eelco_dekker-conker.pdf

2.2.2. STEEL INDUSTRY

On a global scale, the steel industry emitted 2.9 gigaton CO_2 in 2014 (i.e. 7% of global emissions) (de Pee et al., 2018). Circa 180 large integrated steel mills exists with an average emission of 3.5 million ton CO_2 per year, however, also many smaller plants exists with an average emission size of 170 kiloton CO_2 per year (Leeson et al., 2017). Specifically in the steel industry, most waste gases in Europe are used for heat or power production. In the report of Metabolic (2017) the authors mention a range from 25% for all steel waste gases to 50% for all blast furnace (BF) gases that is used in electricity production. In other regions, the waste gases are often flared and lost. Although the energy produced with the waste gases needs to be replaced, the authors say that any other energy source has lower CO_2 emissions per unit of electricity, and as such, from an environmental point of view it might be beneficial to use the waste gases for other purposes. In total almost 2 ton of waste gases are produced per ton of steel, of which 1.3 to 1.5 ton CO_{2eq} (Metabolic, 2017). Also other authors state that off gases of the steel industry are interesting because of the high amount of CO and H_2 that can be valorized as syngas. The amount in Europe is sufficient to supply 55 million ton of methanol (Bazzanella & Ausfelder, 2017). This is confirmed by another study in which it is stated that with 77% of the European steel waste gases, the European demand for ethanol, methanol and 0.1% of European fuels can be produced (Metabolic, 2017). A disadvantage is that the emission points are spread over the steel plant. The largest emission point is the blast furnace (BF) and of these emissions, circa 65% can be captured (Leeson et al., 2017).

Waste gases from steel industry consists typically of 15 to 25 % CO_2 and 18 to 30% CO and other compounds such as nitrogen, hydrogen and methane. The challenge is the large share of nitrogen (i.e. 40 to 50%) in the waste gases. It is very challenging to separate nitrogen from CO because the molecules are quite similar. Another aspect that has to be taken into account is the water content of the gases. The gases are saturated with water (i.e. 4%). In the BF and BOF (i.e. basic oxygen furnace) gas, dust is present. In the coke oven gas aromatic compounds, H_2S and HCN can be found. The temperature of the gases is typically around 300 °C. A more detailed overview of the typical European steel off-gases composition is provided in the report of Metabolic (2017). A summary is provided in Table 2.

Because of the composition, some pretreatment will be necessary. One option is to purify and remove the impurities with the goal to mainly retain the CO and H_2, however, larger volumes of gas need to be treated and as a consequence the infrastructure needs to be larger. Another option is to separate the CO, however this is a more expensive option and the H_2 is not retained, although H_2 is also valuable (Metabolic, 2017).

The largest iron and steel production plant in Belgium is located in Gent, i.e. Arcelor Mittal. In the Netherlands the plant of Tata Steel Ijmuiden BV in Velsen-Noord is interesting with emissions of almost 6 million ton per year.

Table 2: Steel gas composition

Concentration (%) Component	BF gas	BOF gas	Coke plant gas	Converter gas
CO_2	20-30	10-20	1.5-2.5	14
CO	18-35	50-70	5-7	70
N_2	40-60	15-30	6-10	16
H_2	2-4	1-2	58-65	2
BF = Blast Furnace; BOF = Basic Oxygen Furnace				

2.2.3. CEMENT INDUSTRY

On a global scale, the cement industry emitted about 3 gigaton CO_2 in 2014. A large amount of cement industry plants exists and the average individual emissions are 0.79 million ton CO_2 per year (Leeson et al., 2017). These emissions result from the combustion of fuel to heat cement kilns (i.e. 40% of emissions) and the calcination of calcium carbonate ($CaCO_3$) into calcium oxide ($CaO + CO_2$) (i.e. 60% of emissions). In total ca. 0.75 ton CO_2 is emitted per ton cement (de Pee et al., 2018). The flue gases of a rotary kiln in the cement industry amounts to approximately 25 vol% (i.e. 14 to 33%). From the boilers the emissions have a CO_2 concentration of approximately 9% and the temperature amounts to 260 °C.

In Belgium a large cement facility is located in Gaurain-Ramecroix with over 1 million ton CO_2 emissions per year.

2.2.4. ETHYLENE AND ETHYLENE OXIDE PRODUCTION

Ethylene is mainly produced from Naphtha (i.e. 43%) and ethane (i.e. 35%). On a global scale the ethylene production accounts for 0.2 gigaton CO_2 emissions annually. The emissions result from the steam cracking process. Approximately 1.6 ton CO_2 per ton ethylene is emitted (de Pee et al., 2018).

Ethylene oxide is produced from ethylene by direct oxidation. During this ethylene oxide production, a gas is removed in the absorption phase with a CO_2 content between 30% and 100%. Other components in the gas are H_2O, acetaldehyde and traces of formaldehyde. The CO_2 stream is typically vented. According to the Global CCS Institute, the total amount of CO_2 produced from ethylene oxide production is between 1.5 and 6.2 million ton annually or on average around 0.15 million ton per year for a typical ethylene oxide production facility. This is based on the chemistry of the production process that would result in 0.33 ton of CO_2 generated per ton of ethylene oxide. The partial pressure of the CO_2 is 2 bar.

Examples of production facilities in Flanders with high CO_2 emissions are INEOS and BASF Antwerpen. In the Netherlands the largest facilities are DOW Benelux BV in Hoek and Shell Nederland Chemie BV in Moerdijk.

2.2.5. AMMONIA PRODUCTION

Globally, ammonia production results in 0.5 gigaton CO_2 emissions on a yearly basis, i.e. circa 1.1 ton CO_2 per ton ammonia. The conventional processes emit almost pure flows of CO_2. In the water gas shift reaction air is added to the mix of CO and steam to make CO_2 and H_2. After this step the CO_2 is eliminated and the pure flow of CO_2 with a mixture of N_2 and H_2 results. It accounts for approximately 66% of the CO_2 emissions from ammonia production, the other 33% results from the combustion of fuel for heat and compression (de Pee et al., 2018). According to the International Fertilizer Association (IFA), around 36% of CO_2 from ammonia production is already removed from the syngas. Of this around 33% is used for urea production and 2.2% is sold for other purposes (e.g. enhanced oil recovery). In the study of McKinsey&Company (2018) it is mentioned that 55% of the CO_2 emitted during the water-gas shift reaction is combined with ammonia to produce urea. This is in the same range as wat the IFA is putting forward and what can be found in the work of Naims (2016). This means that only around 50% of the total CO_2 emissions from ammonia production are available. The Global CCS Institute reports average CO_2 emissions per ammonia plant of approximately 800,000 ton and a partial pressure for CO_2 of 5 bar.

A large facility in the Netherlands is YARA Sluiskil BV.

2.2.6. BIOGAS PRODUCTION

Depending on the feedstock, the specific biogas composition is different (see Table 3). Typical the CO_2 content varies between 19% and 38%. The CO_2 content is highest for biogas resulting from household waste. The major component of biogas is methane which varies from 50% to 75%, with higher concentrations for biogas resulting from wastewater treatment or agricultural waste. Other components in biogas are N_2, O_2, H_2S, NH_3 and H_2O. In the paper of Dimitriou et al. (2015) the use of biogas as potential CO_2 source is evaluated. The authors argue that biogas is especially interesting as it is also an important source of H_2. The methane can be used to produce hydrogen via e.g. steam reforming. Biogas can be upgraded using different technologies to green gas with over 90 vol% CH_4, resulting in a separated, concentrated CO_2 stream, however, this flow is rather small and amounts to around 0.7 ton per hour.

Biogas producers vary in size and are typically geographically distributed. An overview of the biogas producers in Flanders and the Netherlands is provided in section 2.2.7.

Table 3: Biogas composition[5]

%vol	Household waste	Sludge	Agricultural waste
CO_2	38-34	33-19	33-19
CH_4	50-60	60-75	60-75
N_2	5-0	1-0	1-0
O_2	1-0	< 0.5	< 0.5
H_2O	6 (40°C)	6 (40°C)	6 (40°C)

2.2.7. CO_2 EMITTERS IN FLANDERS AND THE NETHERLANDS

For the EnOp project we made a list of the ETS companies in the region Flanders-the Netherlands using the verified emissions of 2016. We also made a list of the biogas and biomass installations. Figure 5 provides an overview of all the 206 ETS companies, as well as the 192 biogas and biomass installations in Flanders. Every dot in the figure represents one single company. An overview of the ETS companies in Flanders with the size of the dots representing the amount of CO_{2eq} emissions that are verified per company is provided in Figure 6. In Figure 7 the ETS companies and respective verified CO_{2eq} emissions for the Netherlands are shown.

---

[5] http://www.biogas-renewable-energy.info/biogas_composition.html

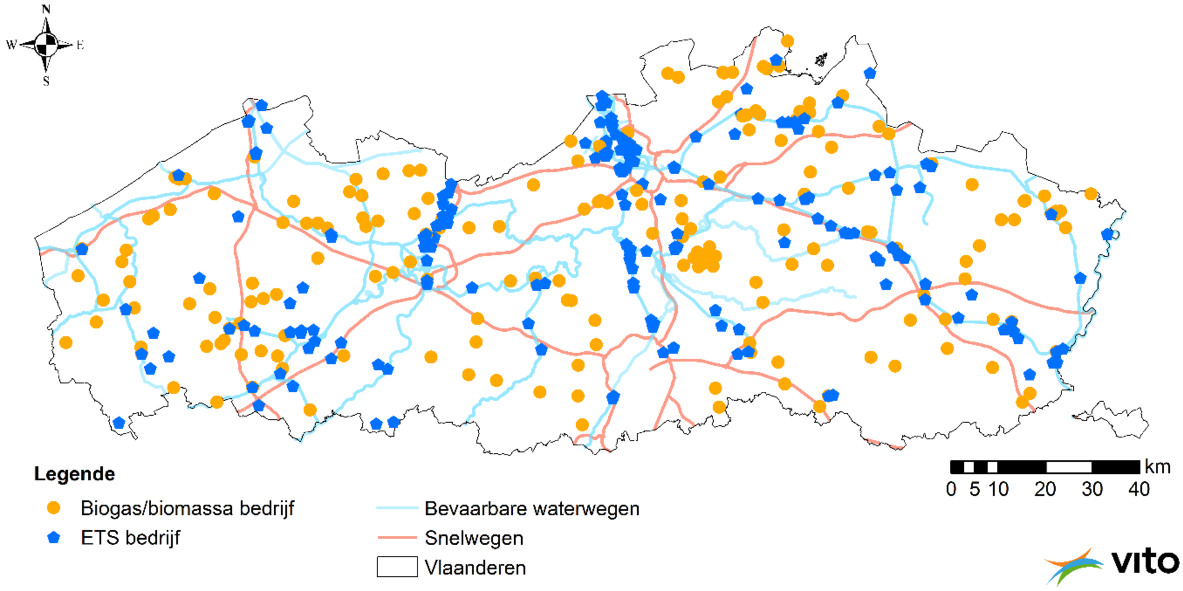


Figure 5: ETS and biogas/biomass companies in Flanders

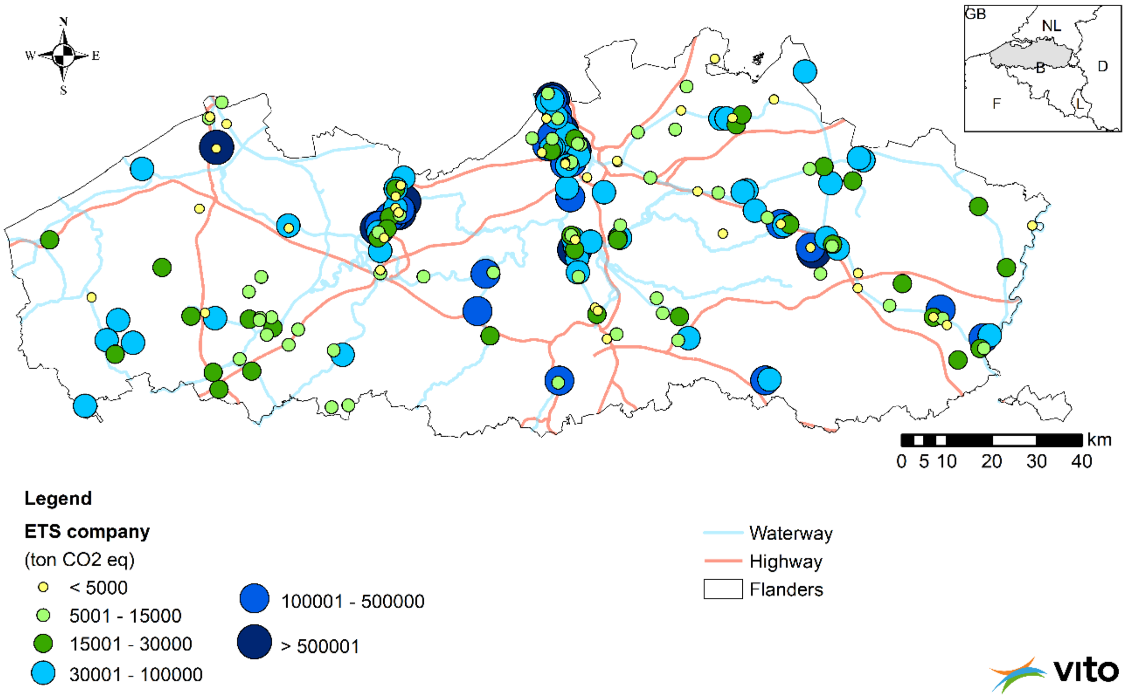


Figure 6: Emissions (in ton CO_{2eq}) ETS companies in Flanders

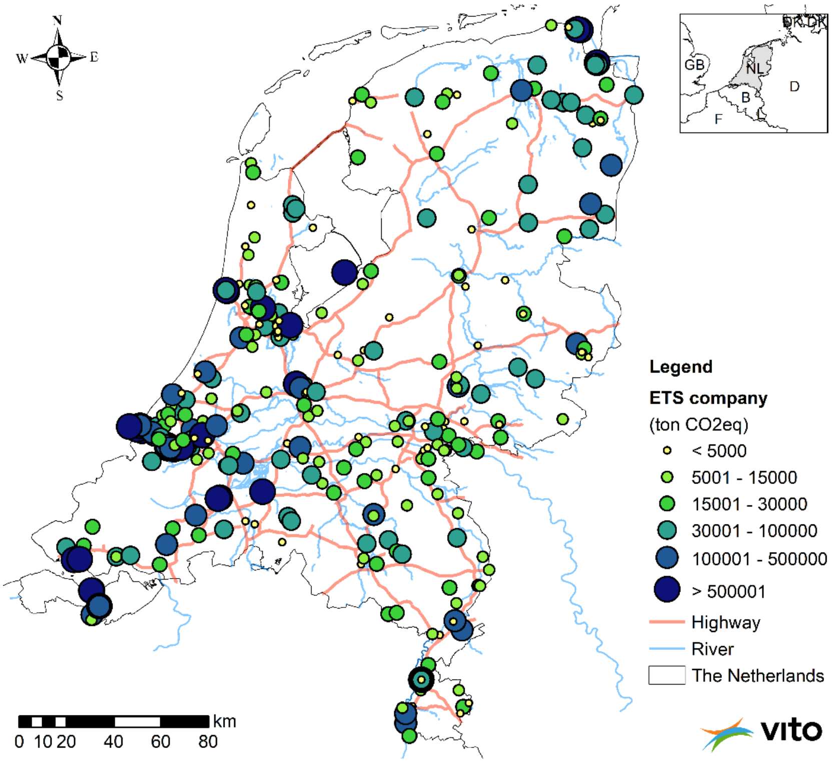


Figure 7: Emissions (in ton CO_{2eq}) ETS companies in the Netherlands

The emissions per company vary widely from almost 5 million ton per year to nearly zero. Therefore, we made a graph for the ETS companies in Flanders with the percentage of companies that falls within a specified category of total CO_{2eq} emissions (see Figure 8). It can be seen that over 75% of the ETS companies have CO_{2eq} emissions below 100,000 ton per year. According to Oei et al. (2014) a minimum of 100,000 ton CO_2 needs to be captured to justify the investment. Note that this study is focused on CCS projects and that this minimum amount can be different for CCU purposes.

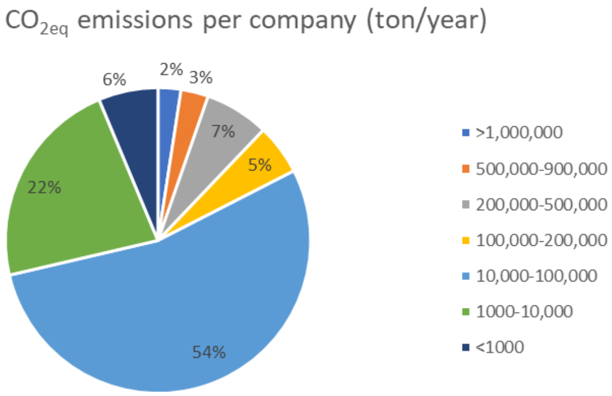


Figure 8: Share of companies in Flanders according to CO_{2eq} emissions

We used the ETS companies as a proxy to identify the companies with the largest emissions. The emissions for the ETS companies are expressed as CO_{2eq}, whereas we are mostly interested in the CO_2 emissions alone. However, note that not all types of gases are taken into account within the ETS system and that in the majority of the cases the mentioned CO_{2eq} will correspond to the CO_2 emissions (see Chapter 4).

In Flanders emissions from industry to the atmosphere are registered via an ‘integraal milieujaarverslag (IMJV)’ per company. Only companies with emissions above the threshold value have an obligation to register their emissions. The ‘Vlaamse Milieu Maatschappij (VMM)’ recently reported the result of these registrations in the publication ‘Lozingen in de lucht – 2000-2016’. To have an indication of the CO_2 emissions per company, we made use of this information. In 2016 the total CO_2 emissions of the individually registered companies amounted to over 31 million ton. In Table 4 an overview is provided of the sectors in Flanders with the largest CO_2 emissions. In the table we also added an indication of the total emissions of CO, NO_x, SO_x, N_2O, CH_4, and NH_3. From the table it can be seen that refineries and iron and steel industry have the highest emissions per company. This is also clear from the list of the 20 highest emitters in Flanders which are provided in Table 5. In the iron and steel industry the amount of CO emissions is also very high.

Table 4: Number of companies and emissions per sector in Flanders (VMM, 2016)

Sector	**#**	**CO_2 (kton)**	**CO (kton)**	**SO_x (kton)**	**NO_x (kton)**	**N_2O (kton)**	**CH_4 (kton)**	**NH_3 (kton)**
Refineries	4	5228	1.27	9.89	3.98	0.15	0.09	0.0005
Electricity production	16	11,340	0.96	0.76	3.37	0.10	0.44	0.01
Iron and steel industry	2	4328	149	5.75	5.89	0	1.14	0.03
Chemical industry	71	8368	1.54	2.14	8.08	2.98	0.30	0.61

Table 5: Top 20 emitters in Flanders (ETS, 2016; VMM, 2016)

ETS (company level)	**VMM (emission point level)**
Electrabel – Centrale knippegroen	Electrabel – Centrale Knippegroen
Arcelor Mittal Gent	E.ON Generation Belgium – Centrale Langerlo
Total Raffinaderij Antwerpen	Electrabel – Centrale Rodenhuize
BASF Antwerpen	Arcelor Mittal Gent – installatie 1
Esso Raffinaderij Antwerpen	Centrale Zandvliet Power (BASF)
T-Power	Total Raffinaderij Antwerpen
Centrale Zandvliet Power	EDF Luminus – Site Ringvaart
Total Olefins Antwerp	Esso Raffinaderij Antwerpen
Electrabel – Centrale Herdersbrug	Esso Raffinaderij Antwerpen
EDF Luminus – Site Ringvaart	Total Olefins Antwerp
Evonik Degussa Antwerpen	Evonik Degussa Antwerpen – Oxeno Antwerpen
Electrabel – Centrale Rodenhuize	Electrabel – Centrale Herdersbrug
Essent Energie België	Electrabel – Centrale Herdersbrug
Indepent Belgian Refinery	Total Olefins Antwerp
BP Chembel	Borealis Kallo
Air Liquide – Jupiter 2	Total Raffinaderij Antwerpen
E.ON Generation Belgium – Centrale Langerlo	BP Chembel
Air Liquide – Jupiter 1	A&S energie
Borealis Kallo	Air Liquide Large Industry – Jupiter 1
Electrabel – Centrale Lanxess Rubber	Electrabel – Centrale Lanxess Rubber

2.3. CO_2 CAPTURE – PURIFICATION – TRANSPORT

In the previous section we described the different CO_2 emitters and the emission potential that is available. One should keep in mind that CO_2 is not available for free as it should be captured, purified and, depending on the site location, also transported. Some studies even state that the capture cost amount to 70-80% of the total cost of a full CCS system (i.e. capture, transport and storage) (Leung, Caramanna, & Maroto-Valer, 2014). In case the plant is situated in an isolated location, the cost for capture and transport will not be justified, also when the volume is small, the economic feasibility will be low. Both capture and transport are in general only interesting if large volumes can be processed. Note for example that CO_2 capture in the cement industry will be less complex and expensive compared to CO_2 capture at an oil refinery. This is due to the fact that an oil refinery has a large number of smaller emission points, whereas a cement facility typically only has two emission points. Another industry that is often overlooked for CO_2 capture is pulp and paper. The location of this industry is often isolated from heavy industry, as they are located close to densely forested areas. The largest pulp and paper facilities in Europe are located in Finland, Sweden, Spain and Portugal with CO_2 emissions over 1 million ton annually. CO_2 capture from this industry is only interesting if the capture and transport cost is significantly reduced, or when the CO_2 can be used locally.

Depending on the technology flue gases can directly be used or should be concentrated. However, the majority of the processes will need concentrated CO_2 streams. Concentrated CO_2 streams are described in section 2.2. In case no concentrated stream is available, one needs to add a capture plant that concentrates the CO_2 emissions. Even if diluted CO_2 streams can be used, a form of purification can still be needed, however, this can be a low cost gas-cleaning system (Brinckerhoff, 2011). For example, algae or some of the mineralization processes can use diluted CO_2 from point sources, whereas other processes need concentrated CO_2 (Scott et al., 2010). However, biological systems such as algae growth systems have certain requirements concerning the amount of impurities that can be tolerated. Thus, although the CO_2 should not be concentrated, it needs to be purified depending on the source. The development of CCU options or robust catalyst systems that can cope with diluted CO_2 streams, having some impurities is put forward as one of the action points by the SET implementation plan.

The price a CO_2 processor should pay will only be lower than the costs of capture and transport in case a CO_2 emitting company otherwise needs to pay a penalty for emitting the CO_2. This means that in case one wants to receive the CO_2 for a low price or even for free, the penalty should be higher than the cost for capture and transport (Bennett et al., 2014).

In the next paragraphs we will first provide more detail on the CO_2 capture and purification options and costs and second give a brief overview of transportation costs.

2.3.1. CO_2 CAPTURE, CONCENTRATION AND PURIFICATION

In literature the CO_2 capture cost and the CO_2 avoided cost are used interchangeably, although a difference exists between both. In studies the calculation method is not always fully transparent which makes direct comparison between studies more difficult. The CO_2 capture cost is the cost, both operational and capital expenditures, to capture CO_2, divided by the total amount of CO_2 captured. The CO_2 avoided cost is the cost of CO_2 captured, divided by the CO_2 emissions that are avoided compared to the reference plant. Depending on the goal of the study, one of both can be chosen. For example, if you want to have an idea of the environmental impact, it is better to use the cost of CO_2 avoided instead of the cost of CO_2 captured.

Different technologies exists for carbon capture and purification (i.e. separation). Capture technologies are typically categorized as pre-combustion, oxyfuel combustion and post-combustion processes. A schematic overview of the different CO_2 capture categories is provided in Figure 9. For capture technologies it is typically assumed that efficiencies range between 85% and 90%. Examples of separation technologies are chemical absorption (e.g. amine scrubbing, ammonia scrubbing, amino acid salts, Ca-looping technology and alkali carbonate scrubbing), physical absorption (e.g. solvents or ionic liquids), adsorption (e.g. metal organic frameworks, activated carbon, molecular sieves or zeolites), membrane technologies, cryogenic distillation, enzyme-based systems and hydrate based separation. An overview of advantages and disadvantages of the different capture technologies was made by Ghaib and Ben-Fares (2018) and Leung et al. (2014).

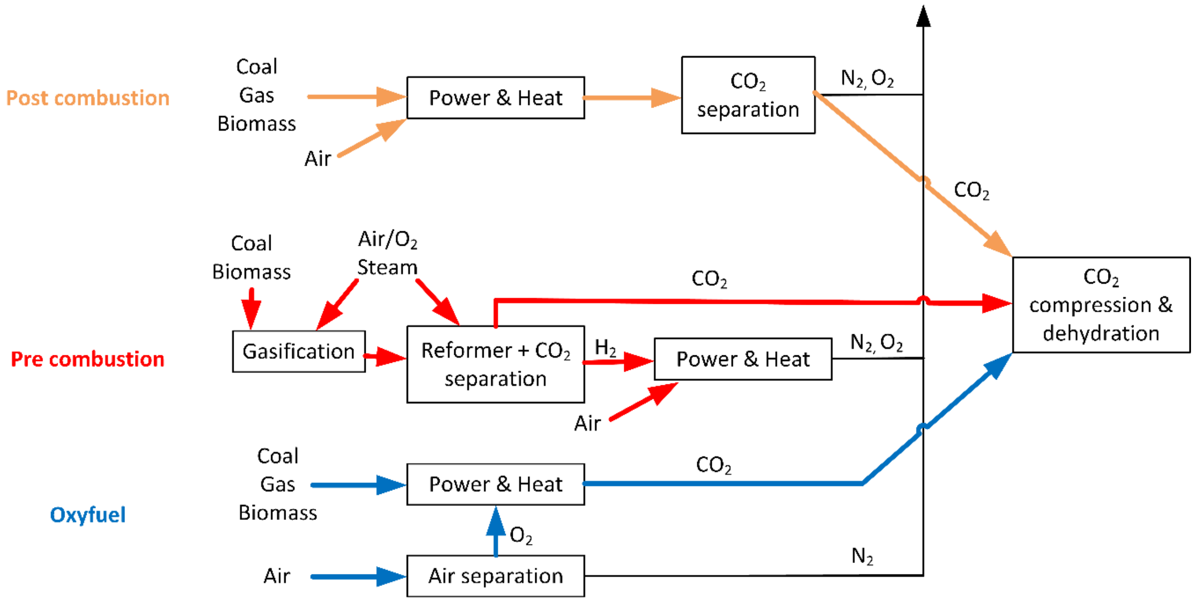


Figure 9: Overview of CO_2 capture technologies
Based on (Metz, Davidson, De Coninck, Loos, & Meyer, 2005; Moazzem, Rasul, & Khan, 2012)

→ Capture technologies

Post combustion processes remove the CO_2 after combustion. These are especially interesting for retrofitting existing power plants. The major challenge is the energy penalty and associated cost because of the low CO_2 concentrations in the flue gases. A concentration of over 95% is needed, whereas the concentration in the flue gases is typically below 15% (Leung et al., 2014).

In pre combustion processes the fuel is pretreated using a gasification and steam reforming step resulting in H_2 and CO_2 (Leung et al., 2014).

In the oxyfuel combustion, O_2 is used instead of air to reduce the amount of nitrogen in the exhaust gas. MacDowell et al. (2010) state that the oxyfuel combustion process is interesting because it produces a gas that is mainly composed of CO_2, H_2O, particulates, and SO_2. Since H_2O can be removed by condensation and the particulates and SO_2 by electrostatic precipitation and desulphurization, a pure CO_2 streams results which is suitable for compression, transport and storage. In this process a fuel is combusted in a mixture of pure O_2 (i.e. >95% purity) and CO_2 (80-98%). The major challenge is the energy intensive air separation unit (Leung et al., 2014).

Some industrial processes, such as natural gas processing or ethanol production, generate a high purity CO_2 stream as intrinsic part of the process. These gases are vented if not captured. In literature one speaks about inherent separation.

→ Separation processes

Chemical absorption is the preferred and most developed method for capturing carbon from gas streams with low CO_2 concentration (3-20%) and low to moderate partial pressures of CO_2 (Dimitriou et al., 2015; Ghaib & Ben-Fares, 2018). Atsonios et al. (2016) state that monoethanolamine scrubbing (MEA) (i.e. post-combustion chemical absorption technique) is the most competitive and ready to apply technology. MEA is also identified as the most suitable technology to capture CO_2 from a gas stream by Hunt, Sin, Marriott, and Clark (2010). In the amine-based CO_2 capture technology a CO_2 rich gas stream is brought in contact with an aqueous amine solution. Water soluble salts are formed from the reaction between the amine solvent and the CO_2. A large solvent consumption is expected, i.e. 0.35 to 2 kg per ton of CO_2 captured. Another disadvantage, and probably the biggest disadvantage, is the susceptibility of amines to thermal and oxidative degradation. The presence of O_2, SO_x and CO_2 degrades the amines. Also, the CO_2 stream is produced at low pressure which is not interesting for transport and storage. This means additional costs have to be made for compression. Typically the solvent regeneration process takes place at 120°C and 2 bar. The energy demand is estimated between 330 and 340 kWh per ton CO_2 recovered. Nevertheless, the technology has the advantage that it is expected that it would easily be retrofitted to the back end of existing power stations. (Khoo & Tan, 2006; MacDowell et al., 2010). The CO_2 removal efficiency of the MEA system is 70-90%. The Global CCS Institute report the heat requirements for solvent regeneration and energy requirement for cycling the solvent between two treatment stages and other auxiliary power uses (e.g. blowers to move low pressure gas around the plant) as the main technical challenges.

Compared to the above mentioned chemical absorption processes, the physical solvent-based processes have lower energy requirements. Energy demands range between 160 and 180 kWh per ton CO_2 recovered (Khoo & Tan, 2006). The biggest difference is that physical-solvent based processes use weak physical bonds and, therefore, use pressure swing adsorption (PSA) or temperature swing adsorption (TSA) to release the CO_2. These processes are preferred for gas streams with high partial pressures over 3.5 bar or high overall pressures (Metz et al., 2005). Sorbents are selected based on large specific surface area, high selectivity and high regeneration ability and often molecular sieves, activated carbon, zeolites, calcium oxides, hydrotalcites and lithium zirconate are used. PSA is often used for power plants and has a typical efficiency of over 85%. TSA results in a CO_2 purity of 95% (Leung et al., 2014).

Carbonate looping is a capture technology that is mainly interesting as a post combustion process in the cement industry. To get a concentrated CO_2 stream temperatures of 900 to 950 °C are required. As a consequence the energy requirements are high, although heat can be recuperated from the hot CaO and CO_2 stream. As such the energy requirements can be minimized. Also interesting is that the exhausted CaO can be used as a feedstock for the cement industry, i.e. as an alternative for fresh limestone. Other disadvantages are sintering, attrition and chemical deactivation due to a competing chemical reaction with SO_2. Carbonate looping is much cheaper than MEA because of the cheap sorbent that is used in carbonate looping compared to MEA (MacDowell et al., 2010).

An overview of some capture technologies according to their working ranges over CO_2 concentrations is provided in Figure 10.

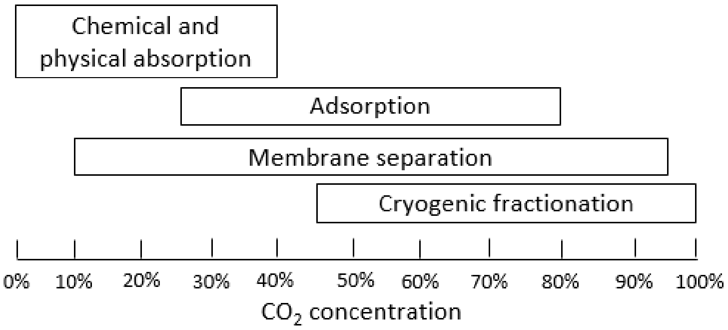


Figure 10: Working range CO_2 capture technologies
Based on Nova Institute (2018)

→ Direct Air Capture (DAC)

Atmospheric CO_2 concentrations are globally around 400 ppm (monthly average). Many of the technologies to capture CO_2 from the atmosphere are still in development. The technologies for 'Direct Air Capture' (DAC) are much more expensive than the technologies for capture from point sources and on top they require large amounts of energy. Energy is used for air transportation and sorbent regeneration. The minimal theoretically needed energy is about 3.4 times higher compared to point sources with a 10% CO_2 concentration (David W Keith, Ha-Duong, & Stolaroff, 2006). However, DAC can become interesting in the future if other CO_2 sources start to decrease due to the use of low carbon technologies. Funding is mainly provided for capturing CO_2 from point sources. According to a study by Frost & Sullivan (2015), atmospheric CO_2 removal is mainly investigated in North-America, followed by Europe. They conclude that mandatory regulations need to be introduced that require industrial involvement in future technology development. At the moment mainly spin offs from universities exist. According to the report the global carbon capture and sequestration from point sources market is expected to grow at a compound average growth rate (CAGR) of 25% and will reach a market size of $6.8 billion by 2019. They assume that the greatest development will take place in the Asia Pacific region as they expect that industrial development will be greatest in that region and that there will be pressure on this region to adopt CCS technologies.

→ Capture cost

The capture costs are influenced by the CO_2 concentration and the size of the plant. In general the costs are lower if a higher CO_2 concentration is available and the capture plant is larger. In case the CO_2 needs to be purified and toxic or hazardous chemicals needs to be removed, the cost further increases (Naims, 2016). If the CO_2 stream is more concentrated, this also implies that a smaller volume needs to be treated and as a consequence, the energy requirements are lower. This positively influences both the economic feasibility and environmental impact. Also important is the pressure, the higher the CO_2 partial pressure, the more economically interesting the separation process.

In a document from the global CCS institute it is reported that circa 500 million ton of low cost, high concentration CO_2 is available per year as a by-product of mainly natural gas processing and fertilizer plants. An additional 18,000 million ton CO_2 is available at a higher cost from power, steel and cement plants. Low cost CO_2 has a price below 15 euro per ton, whereas high cost has a price between 35 and 75 euro per ton (Brinckerhoff, 2011). The same values are reported by the International Energy Agency (IEA).

The estimated costs for CO_2 capture that can be found in literature vary largely between different sources, but also depending on the CO_2 emitting process. An overview of CO_2 emissions, concentrations, partial pressure and estimated capture cost per process is provided in Table 6. For coal-fired power plants the avoided cost are estimated between 34 and 68 euro per ton CO_2. Note that the avoided costs are higher than the capture costs. The capture costs are closer to 20 to 40 euro per ton CO_2. A cost of 47 euro per ton CO_2 in 2012 which will be lowered to 25 euro per ton CO_2 in 2020 is estimated by the Global CCS institute for power generation installations. Whereas they estimate the cost from cement industry to be 155 euro per ton CO_2 avoided and only 16 euro per ton CO_2 avoided if from natural gas processing. Also House et al. (2011) mention a lower price for CO_2 from natural gas-fired power plants, i.e. the capture cost would be in the range of 18 to 35 euro per ton CO_2. A specific example is the cost for CO_2 capture with an amine scrubber, which is estimated at 44 euro per ton CO_2 (Atsonios et al., 2016). The authors use this cost based on the IEA report in which one can find an average post-combustion capture cost of 20 euro per ton for the CAPEX and 24 euro per ton for the OPEX. In the paper of Oei et al. (2014) the operation cost per ton CO_2 varies between 16 and 47 euro depending on the source. The investment costs range between 116 and 275 euro per ton CO_2. Capture costs from point sources range from as low as 15 to over 160 euro per ton.

As already mentioned, CO_2 capture from ambient air is more expensive compared with capture from point sources and prices range from 200 to 1000 euro per ton. House et al. (2011) estimate the cost for air capture in the order of 700 euro per ton CO_2. Based on literature, the authors find a range for air capture processes between 72 and 144 euro per ton CO_2. Other authors find a range from 150 to 750 euro per ton CO_2 (Boot-Handford et al., 2014; Sanz-Perez, Murdock, Didas, & Jones, 2016). A recent study describes a direct air capture process with a levelized cost of ca. 75 to 195 euro per ton CO_2. The process requires 5.25 GJ of gas and 366 kWh of electricity per ton CO_2 captured in case the CO_2 is delivered at 150 bar (David W. Keith, Holmes, Angelo, & Heidel, 2018). Another company is Climeworks in Switzerland that target a cost of less than approximately 80 euro per ton CO_2 for large scale installations on the long term, currently their capture cost amounts to approximately 500 euro per ton CO_2.

Bulk prices for CO_2 are low and are expected to remain low (i.e. 3-15 USD/metric ton from ammonia plants in the US) (Brinckerhoff, 2011).

Table 6: CO_2 emissions, concentrations, capture cost and partial pressure per CO_2 source
Based on (Assen et al., 2016; Leeson et al., 2017; Leung et al., 2014; Naims, 2016; Oei et al., 2014)

Sector	CO_2 source	Global CO_2 emissions (Mt/year)	CO_2 concentration in exhaust gas (vol%)	CO_2 capture cost (€/ton)	CO_2 partial pressure (bar)[6]
Biomass processes	Fermentation	18-200	15-100	10	
	Biogas upgrading		~100		
	Biogas		19-38		
	Bioethanol		100		
Power generation	Natural gas	146-2288	3-10	30-63	
	Petroleum	750	3-8		
	Coal	9000	10-15	32-46	
Industrial processes	Cement	2000	14-33	17-68	
	Iron and steel	900-1000	15-35	16-120	
	Ethylene oxide	10-15	30-100	15-63	3
	Oil refineries	850-900	3-13	90-160	
	LNG sweetening	25-30			
	Ammonia	120-240	~100	16-33	5
	Ethene and other petrochemical processes	155			
	Hydrogen production	54	70-90	30-40	3-5
	Natural gas production	50	5-100	10-30	0.5-44
	Aluminum production	8	<1	75-97	
	Pulp and Paper		7-20	58	
Other	Air		0.04	600-1000	

---

[6] CarbonNext project

2.3.2. CO_2 TRANSPORT

In the study of Jarvis and Samsatli (2018) it is stated that the economic and environmental impacts of transport technologies will be key. Only with direct air capture transport costs can be avoided as the technology can be located near the processing facility. Although point sources are widely distributed in the landscape, as can be seen from the maps with CO_2 emitters in Flanders and the Netherlands, typically large stationary clusters exists e.g. in the harbors. These clusters provide opportunities to create a transport network of CO_2 to storage sites or shared transport (Leeson et al., 2017). Furthermore, in these areas CO_2 users are often also located, implying that also transport distances are shortened.

Depending on the distance and volume, other transport methods are preferred. Pipelines are often preferred for high volumes of CO_2 over long distances or when the CO_2 needs to be transported for several years (e.g. in the case of power plants). For shorter lifetimes, road or rail tankers can be more cost competitive.

Pipelines typically have a temperature between 13°C and 44 °C and a pressure of 85 to 150 bar (Leung et al., 2014). Jarvis and Samsatli (2018) advice for CO_2 pipelines to work at 100-150 bar and 5-30°C. Impurities in the CO_2 stream can influence the boundaries of the pressure and temperature. Water concentrations over 50 ppm can cause corrosion and hydrates can affect the operation of the valves and compressors. Important is that if a network of pipelines is formed, that all sources need to produce a stream with the same quality (Leung et al., 2014). The costs of a pipeline from 1000 km decrease from 6 to 3.7 euro per ton with a respective CO_2 mass flow of 25 million ton to 200 million ton per year (Chandel, Pratson, & Williams, 2010). Atsonios et al. (2016) take a transport cost of 9.23 euro per ton CO_2 into account in case a pipeline network is used. Other authors estimate the CAPEX at 175,000-4,122,000 euro per km and the OPEX at 4,400-105,000 euro per km. In the paper of Oei et al. (2014) the transport costs are estimated between 2 and 20 euro per ton CO_2 depending on the network settings. The capital costs range between 0.08 and 0.15 euro per ton CO_2 and kilometer of pipeline. These values are in the same range as mentioned in the report of the Zero Emissions Platform (2011). The costs of CO_2 transport largely increase with increasing distance. Using existing gas pipelines is not as straightforward as it needs to be checked if the pipelines can be exposed to CO_2 fluxes for a long period in terms of corrosion and if brittle fractures do not happen due to sharp cooling in case of a supercritical CO_2 leak (Rabindran, Cote, & Winning, 2011). For transport by truck the CO_2 is liquified, typically at 17 bar and -30°C. The cost is estimated at 0.22 euro per ton per km (Kuramochi, Ramírez, Turkenburg, & Faaij, 2013). For storage costs, estimation can also be found in the paper of Atsonios et al. (2016). CO_2 storage costs in liquid form are between 4.46 to 13.86 euro per ton CO_2.

Oei et al. (2014) developed a scalable mixed integer, multiperiod, welfare optimizing network model for Europe, i.e. CCTS-Mod., to determine a cost minimizing strategy on whether to purchase CO_2 certificates or to abate the CO_2 through investments in a carbon capture, transport and storage infrastructure. Based on their analysis, the authors conclude that with CO_2 prices higher than 50 euro per ton, carbon capture, transport and storage contributes to the decarbonization of the industrial sectors (i.e. cement and iron and steel industry) in Europe, whereas for the power sector, a CO_2 certificate price over 75 euro per ton is needed.

Taking into account that the minimal amount of CO_2 to make the capture economically interesting should be 100,000 ton per year (Oei et al., 2014) and assuming that an installation runs 365 days a year and 24 hours a day, the minimal hourly CO_2 flow should approximately be 35 ton.

2.4. ELECTRICITY AND HYDROGEN MARKET

Using renewable energy for the electricity provision of CCU processes is not only necessary from an environmental point of view, but provides also advantages for grid stabilization and long-term, large-scale, seasonal storage (Bushuyev et al., 2018). Also the use of green hydrogen is a prerequisite for CCU processes to have an environmental advantage over conventional production routes.

Electricity is an important cost factor for CCU processes. Electricity price is composed of the cost for electricity production, as well as of network costs, VAT and other taxes and levies. In Table 7 we provide an overview of the electricity cost in 2017 for Belgium and the Netherlands according to Eurostat data. In 2017 the electricity price in Belgium ranged between ca. 70 and 260 euro per MWh and in the Netherlands between ca. 65 and 195 euro per MWh depending on the total annual consumption.

Table 7: Electricity prices for non-household consumers in €$_{2017}$/kWh
Eurostat: nrg_pc_205

Consumption (MWh)	Price component	Belgium	The Netherlands
<20	Incl. all taxes and levies	0.259	0.195
	Energy and supply	0.067	0.060
	Network costs	0.093	0.053
	Taxes, fees, levies and charges	0.097	0.071
20-500	Incl. all taxes and levies	0.188	0.139
	Energy and supply	0.054	0.049
	Network costs	0.056	0.025
	Taxes, fees, levies and charges	0.077	0.066
500-2000	Incl. all taxes and levies	0.134	0.096
	Energy and supply	0.047	0.042
	Network costs	0.025	0.019
	Taxes, fees, levies and charges	0.059	0.035
2000-20,000	Incl. all taxes and levies	0.111	0.093
	Energy and supply	0.045	0.040
	Network costs	0.018	0.020
	Taxes, fees, levies and charges	0.047	0.033
20,000-70,000	Incl. all taxes and levies	0.086	0.069
	Energy and supply	0.042	0.039
	Network costs	0.010	0.013
	Taxes, fees, levies and charges	0.034	0.017
70,000-150,000	Incl. all taxes and levies	0.072	0.064
	Energy and supply	0.041	0.038
	Network costs	0.005	0.012
	Taxes, fees, levies and charges	0.024	0.014
>150,000	Incl. all taxes and levies	0.070	0.066
	Energy and supply	0.041	0.039
	Network costs	0.000	0.014
	Taxes, fees, levies and charges	0.013	0.013

In a recent report ‘Het potentieel voor groene waterstof in Vlaanderen – Een routekaart’ (2018) the potential of hydrogen in Flanders is described. In the report an estimation is made of the amount of hydrogen that might be used in industry for its decarbonization in combination with the use of captured CO_2. In 2030 the technical potential is estimated at 61 kiloton H_2 requiring 1.9 GW of renewable energy. This potential is estimated to increase to 481 kiloton H_2 by 2050, requiring 14.5 GW of renewable energy. It is clear that the needed amount of renewable energy is larger than the estimated potential of renewable energy in Flanders. Furthermore, the authors state that it is an underestimation of the real technical potential of H_2 use in the chemical industry. To realize the technical potential, some important economic boundary conditions have to be met. The price of green hydrogen should be in the range of 2 to 4 euro per kg to be competitive for the chemical industry. With the current investment costs this is hard to realize, however, investment costs are decreasing. For green H_2 production also the electricity cost is important and is too high at the moment, especially if the distribution costs and taxes need to be paid. At the moment the cost of H_2 production using water-based electrolysis is not yet competitive (Van Dael et al., 2018). The most cost-effective production route is via steam reforming of natural gas. However, this can change if gas prices increase sharply. Experts expect water-based electrolysis will become competitive in the future. Currently, hydrogen from electrolysis costs between 2.6 and 3.8 euro per kg and it is expected that this cost will be lowered to 2 euro per kg. With these prices for hydrogen, the CO_2 abatement cost ranges between 46 and 157 euro per ton for the current options of methanol, ethanol and Fischer-Tropsch hydrocarbons (Metabolic, 2017). Note that for H_2 production using water electrolysis, the yearly operating hours are important due to the high investment costs. Minimally 4000 hours per year are necessary (Bazzanella & Ausfelder, 2017). Important is that the environmental footprint will be lower than the current production routes in case renewable energy is used.

2.5. END-PRODUCTS

CO_2 is directly used in various industries and for various purposes such as the food industry, extractants, refrigerants, inert agents, cement curing, fire suppression, and enhanced fuel recovery. A large variety end-products are possible with CCU-based processes. However, many authors claim that focus should first be on fuel production as the fuel consumption market is much larger than the chemical market. One should take into account that the margins in the bulk markets such as fuels are much smaller compared to high value chemicals. Furthermore, it should be taken into account that high investment costs are needed if one focusses directly on bulk markets. Also, large amounts of renewable energy will have to be available to make sure that the environmental impact is improved. For these reasons, smaller, high-value markets might be more interesting to focus on in the beginning.

Current annual global CO_2 utilization for chemicals is in the order of 200 million ton (Aresta, Dibenedetto, & Angelini, 2013; Mac Dowell, Fennell, Shah, & Maitland, 2017). It is expected that even with new chemicals or polymers, the amount of CO_2 used will not grow over 300 to 500 million ton per year (Aresta et al., 2013). Other studies mention an upper limit of 700 million ton per year for chemicals (Mac Dowell et al., 2017; Song, 2006). The CO_2 use in fuels is much larger. In the study of Snoeckx and Bogaerts (2017) they say that the fuels market is 12 to 14 times larger than the chemical market. This is also in accordance with other studies in which they mention a CO_2 use up to 2 gigaton annually on a global scale (Quadrelli, Centi, Duplan, & Perathoner, 2011). In the report of Brinckerhoff (2011) the global non-captive CO_2 demand is estimated to be only 80 million ton per year and 50 million ton of it is for enhanced oil recovery. The potential for CO_2 utilization in Europe, based on the current chemical industry, is estimated at 500 million ton annually (Assen et al., 2016).

The largest markets for CO_2 demand are enhanced oil recovery, enhanced coal bed methane recovery, mineralization processes, and liquid fuels. Other potentially interesting markets are urea yield boosting, beverage carbonation, food processing, preservation and packaging, and polymer processing.

Depending on the industry and whether we look at the current or future potential CO_2 use, the numbers differ largely (Brinckerhoff, 2011; Naims, 2016):

- Enhanced oil recovery (EOR): Currently between 25 and 300 million ton of CO_2 per year, future potential can be up to 300 million ton annually;
- Urea: 30-130 million ton CO_2 per year;
- Beverage industry: 8 million ton CO_2 in 2011 and can potentially grow till 14 million ton per year. This CO_2 needs to have a high purity;
- Pharmaceutical industry: up to 1 million ton CO_2 per year;
- Water treatment: up to 5 million ton CO_2 per year;
- Fine and high added-value chemicals: <0.01 million ton CO_2 per year;
- Bulk chemicals (e.g. methanol): 1-2.5 million ton CO_2 per year, however for renewable methanol or formic acid estimations of more than 300 million ton per year are available;
- Basic petrochemicals (e.g. ethylene or polypropylene): 1.5-4.5 million ton CO_2 per year;

An overview of production rates, CO_2 use and prices for different products are provided in Table 8. A more detailed description of the methanol, syngas, and formic acid market is provided in the next paragraphs.

Table 8: Production rates, CO_2 use in compounds and price
Based on (Bennett et al., 2014; Brinckerhoff, 2011; Bushuyev et al., 2018; Mac Dowell et al., 2017; Metabolic, 2017; Naims, 2016) and ICIS

Compound	**Global Production (Mton/year)**	**Global CO_2 Use (Mton/year)**	**CO_2 use (ton/ton product)**	**Production trend (% per year)**	**Price (€/ton)**
Inorganic carbonates	200-250	50-70	0.25-0.28	Growing (8)	
Carbonates	0.2-2	0.005-0.5	0.5-0.75	Growing (300)	
Polycarbonates	4-5	0.01-1	0.2	Growing (8)	
Carbamates	5-6	1		Growing (4)	
Polyurethanes	8-10	0.5		Growing (8)	
Acrylates	3	1.5		Growing (7)	
Urea	180-190	112-132	0.73-0.75	Growing (5)	200
Methanol	50-80	8-10	1.37-1.49	Growing (7)	300-350
Formic Acid	0.6-1	0.8	0.96	Growing (4)	510-1020
Ethylene	140		3.13	Growing (7)	900-1100
Propanol					1100
Syngas			1.57	Growing (9)	650
Acetic anhydride	2.5				1063
VAM	6.5				1000-1400
Propionic acid	0.5				2210
MMA	4.5				1300-3000
Adipic acid	3				2400
DMC	0.5				748
Ethanol	70		1.91	Growing (7)	600-750*

Compound	Global Production (Mton/year)	Global CO_2 Use (Mton/year)	CO_2 use (ton/ton product)	Production trend (% per year)	Price (€/ton)
Lactic acid	0.9				
Butyric acid	0.8				
Acetic acid	5-15		1.47	Growing	595-900
DME	9-20	3-5		Growing (10)	357-650
FA	21-27	3.5-5	0.16-2	Growing (7)	298-1000
Acetylene				Growing (3)	1600
MTBE	10			Uncertain	550-750
Propylene				Growing (7)	900-1000
2-Phenyllactic acid	Specialty chemical				10000
1-Phenylethanol					3000-5000
Acetophenone					3000-5000
Benzilic acid					5000-10,000
Benzhydrol					5000-10,000
Benzophenone					5000-10,000
Mandelic acid					5000-10,000
Benzyl alcohol					2000-3000
Benzaldehyde					3000-5000
2-(Furan-2-yl)-2-hydroxyacetic acid	Not produced commercially				>10,000
Furfural	0.2-0.3			Growing	1200-1500

VAM = Vinyl acetate monomer
MMA = Methyl methacrylate
DMC = Dimethyl carbonate
DME = Dimethyl ether
FA = Formaldehyde
MTBE = Methyl tert-butyl ether
* Industrial price, can be up to 850 euro per ton if fuel grade.

2.5.1. METHANOL MARKET

Globally the methanol market generates annually over 50 billion dollar in economic activity and creates over 90,000 jobs worldwide[7]. The global production capacity is estimated at 110 million tons. The global demand is about 60-90 million ton according to Marc Alvarado (2016) and it is expected that this market demand will further grow over the next five years with 7% annually, other studies mention a demand increase of only 1 to 3% annually (Metabolic, 2017). According to IEA the demand would raise to minimally 171 million ton in 2050 (van der Hoeven, Kobayashi, & Diercks, 2013). In Europe the demand is 7.5 million tons (i.e. ca. 10% of the global demand) and production is only 2.3 million ton per year. This implies that most methanol is imported in Europe (Metabolic, 2017). China is expected to have a demand share of 61%. The increase in market size will be dependent on the future use of methanol in markets such as fuel additives, olefins and aromatics. Therefore, it is also expected that the production capacity in China will further grow, whereas the European production capacity is expected to be constant. An average methanol plant produces 440,000 ton per year (Pérez-Fortes, Schöneberger, Boulamanti, & Tzimas, 2016).

---

[7] https://www.methanol.org/the-methanol-industry/

Traditionally methanol is synthesized from syngas using a Fischer-Tropsch system in the presence of heterogeneous catalysts at elevated pressures (50-250 bar) and moderate temperatures (200-350°C). Syngas is, in Europe, mainly produced from natural gas and residual fuel oil, whereas in the Middle East natural gas is the most often used feedstock. In China mainly coal-based production takes place. Feedstock cost make up as much as 90% of the total cost and, for that reason, a low cost feedstock is key to improve the economics of methanol production. Taking into account that the price of natural gas is highly fluctuating, this also influences the current methanol production process (Wernicke, Plass, & Schmidt, 2014). Another production pathway is based on biomass to create bio-methanol. The production is very similar to the conventional methanol production, via gasification of the biomass (Bazzanella & Ausfelder, 2017). Carbon Recycling International (CRI) already demonstrates methanol synthesis using CO_2 and H_2 as feedstock, with an annual production capacity of more than 5 million liter (i.e. ca. 4 kiloton). H_2 is produced via geothermal energy and CO_2 is captured from a nearby electricity plant. Another pilot plant produces 100 ton per year. This plant is owned by Mitsui Chemicals Inc.. In this plant CO_2 from point sources is used and H_2 from water photolysis (Pérez-Fortes, Schöneberger, Boulamanti, & Tzimas, 2016).

Energy consumption for methanol production from natural gas is lower than using the waste gas route, mainly due to H_2 production, i.e. 2 MJ/kg methanol compared to 3.52 MJ/kg in case of steam methane reforming and 17.9 MJ/kg in case of electrolysis use to produce hydrogen (Metabolic, 2017).

Methanol can be an attractive market as the market is large and the technologies are well developed (Metabolic, 2017). Approximately 60% is used in the chemical sector, the rest is used in fuel applications. Of the chemicals more than half is used for the production of formaldehyde. Other chemicals that are produced from methanol are acetic acid, methyl tertbutyl ether, dimethyl ether, olefins and polymers. It is expected that methanol will increasingly be used as a liquid fuel in emerging economies. In China and the USA the concept of a 'methanol economy' of 'liquid sunshine' is also been put forward. The market price of methanol can vary between 300 and 450 euro per ton. In November 2018 the price in Europe as reported by Methanex is 428 euro per ton. In the past, the methanol price was highly fluctuating. An overview of the prices on the European market reported by Methanex over the past years is provided in Figure 11. Some experts also indicate the potential of receiving a green premium which can further increase the price up to 600 to 800 euro per ton.

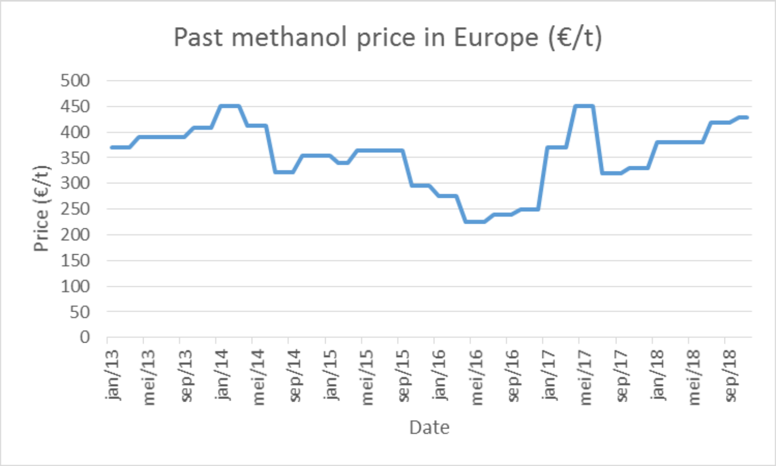


Figure 11: Methanex' methanol contract price in Europe
(Methanol monthly average regional posted contract price history, 2018)

2.5.2. SYNGAS MARKET

Syngas or synthesis gas is an intermediate in the chemical industry that is used to synthesize fuels, e.g. diesel and gasoline, and other chemicals via the Fischer-Tropsch process using specific catalyst and operating conditions. It can be used as an intermediate for the generation of e.g. ammonia or methanol. It is a gas mixture that mainly consists of CO and H_2, and often contains significant portions of CO_2 and H_2O. The composition is dependent on the production process, and can be adapted to the needs of the end-product. Currently syngas is mainly produced using steam and dry reforming of natural gas or methane in Fischer-Tropsch synthesis. Ratios between H_2 and CO vary between 3:1 and 1:1 for the production processes of steam reforming and dry reforming, respectively.

According to Pei, Korom, Ling, and Nasah (2016), the cost for syngas production from natural gas is mainly dependent on the natural gas price, and varies between $24.46-$90.09 per thousand cubic meters, while the cost for syngas produced from underground coal gasification varies between $37.27-$39.80 per thousand cubic meters (Pei et al., 2016).

2.5.3. FORMIC ACID MARKET

Formic acid is currently a small market with a demand of less than 1 million ton per year in 2015. In 2012 the global production was 620 kiloton (Sean M Jarvis & Sheila Samsatli, 2018). Expectations are that the demand will further grow with on average between 3.8 and 4.9% on a global scale (Sean M. Jarvis & Sheila Samsatli, 2018; Pérez-Fortes, Schöneberger, Boulamanti, Harrison, & Tzimas, 2016; Van Wesemael, 2018). The formic acid market is expected to grow even faster by 2030 (Brinckerhoff, 2011). This growth is expected because of the diversity of end-uses, i.e. formic acid can both be used as a chemical feedstock and a fuel. Some authors even state that the market will grow till 5 to 24 million ton. The growing market is also expected because of a decrease in price. Currently the production of formic acid is relatively expensive (Agarwal, Zhai, Hill, & Sridhar, 2011).

The majority of the global consumption of formic acid is situated in the Asia Pacific region and in Western Europe (Afshar, 2014). Consumption takes place in the feed industry as a silage additive or preservative and the leather and textile industry for tanning and dyeing (Hietala et al., 2016). In Europe it is also used as an antibacterial agent as the use of non-prescribed feed antibiotics are banned. Currently the use as a fuel is still limited, however, interest is growing. Formic acid can be an interesting hydrogen carrier as it is easier to store (i.e. it can store 580 times more H_2 than the same volume of hydrogen gas) and transport (Agarwal et al., 2011; Hendriks, Noothout, Zakkour, & Cook, 2013; Hietala et al., 2016; Pérez-Fortes, Schöneberger, Boulamanti, Harrison, et al., 2016). It can also be used to replace mineral acids such as HCl and H_2SO_4 in steel pickling or it can be used in the production of formate salts which are used as airport de- and anti-icing agents in mainly Europe. An airport uses typically ca. 2000 ton of formate solution with a 50% concentration (Agarwal et al., 2011).

Several production routes are available. (1) Methanol carbonylation with CO in the liquid phase at 45 bar and 80°C towards methylformate, in the second step the hydrolysis of methyl formate takes place with the removal of methanol and methyl formate by high pressure distillation to give ca. 85% formic acid content, followed by distillation at slightly below atmospheric pressure to produce higher formic acid concentrations. (2) In another process aqueous formic acid is extracted with a formic acid ester. (3) It is also produced as a byproduct of polyhydric alcohol manufacturing, butane oxidation to acetic acid and of the oxidation of cyclohexane to adipic acid. (4) Furthermore, formic acid occurs naturally in ants, bees and wasps (Afshar, 2014). The production scale of one plant is typically around 10,000 ton per year (Pérez-Fortes & Tzimas, 2016).

The production is mainly based in Europe with plants from BASF in Germany, Eastman in Finland and a plant in the UK which was owned by BP. Another plant is owned by BASF in China. In the BASF process, formats are converted which synthesis formic acid from methylformate hydrolysis in which methyl formate is produced from CO and water.

The price for formic acid is dependent on the active ingredient content and the purity. The market price of formic acid (85 wt%) on the European market amounted to 510-600 euro per ton in 2014. BASF regularly increases the price (Afshar, 2014; Hietala et al., 2016; Pérez-Fortes, Schöneberger, Boulamanti, Harrison, et al., 2016; Rieser, Hernandez, & Barry, 2018). In China the price amounts to 770 euro per ton in 2018 for 94% formic acid.

CHAPTER 3 SUSTAINABILITY ASPECTS

Often capturing and using CO_2 for the production of a variety of products is linked with a positive environmental impact. Life Cycle Assessment (LCA) is considered as a suitable metric for the quantification of the environmental impacts. von der Assen, Voll, Peters, and Bardow (2014) provided, based on their tutorial review, some key learning points for the LCA of CCU: (1) an LCA can be performed at an early development stage and should be mandatory for CCU, (2) LCA cannot determine the absolute environmental impact but should be used to determine the hot spots, (3) an LCA for CCU always needs to include the CO_2 source and the production of energetic feedstocks (e.g. H_2), (4) all (co-)products need to be included and (5) the amount of utilized CO_2 is not per se equal to the amount of avoided CO_2 emissions. The CO_2 that is utilized is often reemitted at a later point in time. For that reason it is not possible to just aggregate the used volumes of CO_2 as an indicator for its environmental impact. A detailed assessment is needed for every CCU technology compared to its conventional counterpart to calculate the real carbon footprint (Naims, 2016). The need for a standardized LCA assessment for CCU technologies was also identified by the European Commission and therefore, Zimmermann et al. (2018) made some suggestions for LCA to improve transparency and comparability.

Two aspects that are important when speaking about the potential of CCU in climate mitigation change, i.e. the amount of CO_2 that can be sequestered and the time over which it can be sequestered.

First, the amount of CO_2 that can be sequestered is to a large part dependent on the market potential of the targeted products. According to a recent study by Mac Dowell et al. (2017) CCU will not account for more than 1% of the mitigation challenge. The reason for this is the mismatch between the scale of CO_2 production and the scale of utilization options allowing long-term sequestration. Current total global anthropogenic emissions are over 35 gigaton CO_2 per year. According to studies, the maximum utilization of CO_2 for chemical purposes is 650 to 700 million ton per year on a global scale. Taking into account that only 25% of the products are really sequestering CO_2 for a significant duration, the total potential of CCU chemicals for climate change mitigation is less than 1% (Aresta et al., 2013; Mac Dowell et al., 2017). However, it has to be remembered that by using captured CO_2, the alternative, often fossil-based, feedstock is replaced and that also the emissions of using this fossil-based feedstock are avoided.

Second, depending on the product the sequestration time differs. Carbonates typically have a longer lifetime, especially when used in the construction industry, i.e. the carbon is sequestered for hundreds to thousands of years. But although mineralization is an interesting path for long term CO_2 capture and the potential demand for affordable construction material is large, the question remains whether carbonate products are available in such volumes and whether they could find a viable market in the low-cost construction materials sector. Chemicals and polymers have a short to long lifetime depending on the end-products for which these are used (Brinckerhoff, 2011). Plastics have an average lifetime of 8 to 14 years, inclusive recycling before disposal. The lifetime of fertilizers and fuels is even less than a year. For these reasons it is important to take into account the substitution effects as the displaced system can have higher emissions than the CCU system (Bennett et al., 2014).

The conversion of CO_2 into liquid fuels can reduce emissions relative to a baseline, however, this will not be a significant contribution to the CO_2 mitigation challenge seeing the almost immediate release of the captured CO_2 to the atmosphere (Mac Dowell et al., 2017). Other authors even state that the conversion of CO_2 into energy rich compounds using fossil carbon is 'non-sense' as more CO_2 is emitted than converted (Aresta et al., 2013).

The production of CO_2-based chemicals (methane, methanol, ethylene and formic acid) is not always carbon neutral or beneficial. In the research of Bennett et al. (2014) only the production of formic acid has a lower carbon footprint compared to the other chemicals considered. This can be explained by the fact that most products have the energy content on a per carbon basis that is close to the fuels used to produce the electricity with a generating efficiency lower than 50%. The authors note that the emissions are mainly related to the electricity generation step. As a consequence, they conclude that reducing CO_2 emissions through CO_2 utilization is only possible if the electricity is from renewable sources. In general it needs to be taken into account what the energy efficiency is of a process to determine whether the CCU process is more environmental sustainable than the fossil-based route. Both the capture and conversion process require energy (von der Assen et al., 2014). In CCU technologies, also hydrogen is often an important element. In order to be sustainable, hydrogen needs to be produced using renewable energy. However, producing hydrogen at a large scale on a variable basis, to make use of lower energy prices, is economically less interesting and makes the use of hydrogen expensive.

CHAPTER 4 LEGAL ASPECTS

In this chapter we will discuss some important legal aspects on a European level that have an influence on the further development of the CCU sector in the region Flanders – the Netherlands.

For CCU the emission trading system (ETS) in Europe is of interest. This system is introduced to reduce greenhouse gas emissions and as such combat climate change. We briefly describe this system in the first subsection.

For CCU fuels the Renewable Energy Directive is important. A summary of the main changes in the revised Renewable Energy Directive (RED II) can be found below. The RED II is not definitive yet, however, no major changes are expected on this version. Other policies that can be of interest or the CO_2 emission standards and the Clean Vehicle Directive. The Clean Vehicle Directive is about public fleet procurement. We will not discuss the latter two regulations within this report.

4.1. EU ETS

The ETS system in Europe covers 45% of EU's greenhouse gas emissions and limits emissions from over 11,000 heavy energy-using installations and airlines. Several sectors are covered by the ETS system for CO_2 emissions such as power and heat generation, oil refineries, steel and iron sector, aluminum, metal, cement, lime, glass, ceramics, pulp and paper, acids and bulk organic chemicals. Also the aviation sector is included. Next to CO_2 also N_2O and PFCs of a limited number of sectors are covered by ETS.

The ETS system works according to a cap and trade principle, which means that a maximum amount of greenhouse gases is allowed to be emitted by the installations that are included within the system. The cap for 2013 from fixed installations was set at ca. 2 billion allowances. This maximum amount is reduced over time with 2.2% per year as of 2021 (i.e. ca. 48 million emission allowances), currently the annual rate is 1.74% (i.e. ca. 38 million emission allowances). Installations that are covered by the system either receive or buy emission allowances and these allowances can be traded with one another. A company has to make sure that it has sufficient allowances to cover its emissions. In case they do not have sufficient allowances, a fine of 100 euro per ton CO_{2eq} is imposed. The fine increases with inflation. If they have more allowances than needed, they can sell these allowances to other companies. As such, greenhouse gas emissions are reduced where it costs the least to do so.

Currently the ETS is in the third phase. Early 2018 the framework was already revised for the next trading period, i.e. fourth phase (2021-2030). Due to market conditions, the emissions were reduced at a faster rate than expected, resulting in a surplus of allowances and as a consequence low market prices around 3 to 5 euro per ton CO_2. Therefore, it was decided to postpone the auction of 900 million allowances until 2019-2020. In January 2019 a market stability reserve will be started in which these 900 million allowances will be included. On top, unallocated allowances will also be transferred to this reserve. Because of this action the CO_2 price increased and in October 2018 the average price per ton CO_2 amounted to 17.5 euro on the EEX trade market (see below).

Due to the decreasing amount of allowances, it is expected that the price will further increase to 11-53 euro per ton CO2 in 2030 and 85 to 264 euro per ton by 2050[8].

Part of the allowances are allocated for free. The system of free allocation will be extended in time, although it has been revised to make sure that focus is on those sectors with the highest risk of relocating their production outside of the EU (i.e. carbon leakage). Another change that was made in phase 3 is that in the past the free allocation was based on historical greenhouse gas emissions, whereas this is now done based on benchmarks (see below). Measures are taken to make sure that the total number of free allocations will be further reduced. The sectors with the highest risk to just move their activities to other countries where the carbon constraints are less strict, get 100% of the allowances for free. These sectors are listed in the commission decision of 27 October 2014 (2014/746/EU). For other sectors the free allocation will be phased out after 2026 from maximum 30% to 0% by 2030. The total amount of allowances that is expected to be allocated for free over the period 2021-2030 is over 6 billion. Note that the power sector does not get any allowances for free, also installations for the capture, transport or storage of CO_2 do not get free allowances.

The benchmark is based on the average greenhouse gas emissions of the best performing 10% of the installations in the EU producing the product. In case an installation meets the benchmark, the allowances that are provided, cover the emissions. Otherwise, installations need to choose one of the following options or combine them: (i) reduce the emissions or (ii) buy allowances from other companies or via auctions. In principle, the benchmark is calculated based on the product rather than the input to make sure that the greenhouse gas emissions savings are as large as possible and to make sure that the energy savings within the full production process are as high as possible.

In case of waste gases, the free allocation is done to the producer of the waste gas if it is produced within the boundaries of a product benchmark and to the consumer if it is produced outside of the boundaries of this product benchmark. Allocation related to the production of waste gases is only done for the emissions that are additional to the reference fuel natural gas. Remaining emissions can be allocated to the consumption of it, depending on the use. The question whether emissions that are used for CCU purposes are exempt from the ETS system, is also raised. This question might be easy to answer in case of a permanent or long term storage of the emissions, e.g. mineralization. However, in case the emissions are used to produce e.g. fuels or plastics, this question is more difficult to answer. Especially because the transport sector is for example outside of the ETS system and therefore, a carbon leak would result from it.

The allowances that are not allocated for free, are auctioned. The share of allowances that are auctioned is increasing. In 2013 more than 40% was auctioned and this share is expected to increase to more than 50% by 2020. From 2021 on, the share of auctioned allowances should minimally be 57%. Auctions are preferred as the polluter should pay principle is put into practice. The two auction platforms that are in place or the European Energy Exchange (EEX) and the ICE Futures Europe. The ICE acts as the UK platform. The total revenues for the EU from these auctions amounted to 3.6 billion euro and the majority of this money is used for climate and energy related purposes. At least 50% of the revenues from the auctions need to be spent on activities that positively influence the greenhouse gas emission balance, e.g. actions that reduce the emission of greenhouse gases by e.g. energy efficiency measures, the capture and storage of CO_2 or lowering the emissions of public transport. In Flanders these revenues are used for the climate policy plan (i.e. “Vlaams Klimaatbeleidsplan”).

---

[8] EC (2014), Impact Assessment accompanying the document: A policy framework for climate and energy in the period from 2020 up to 2030.

Another 400 million allowances are reserved within an innovation fund to support innovation of low-carbon technologies such as CCU and CCS. Another 50 million allowances from the market stability reserve will be used for the innovation fund if not allocated. This innovation fund extends the existing support under the NER300 program. Objective and transparent criteria will be used. Maximum 60% of the costs can be subsidized of which 40% should not be dependent on the verified avoidance of greenhouse gas emissions. For none of the projects, the subsidies can be more than 15% of the total amount of allowances that is reserved for this purpose.

4.2. RENEWABLE ENERGY DIRECTIVE II (RED II)

The Renewable Energy Directive is being revised. The information below comes from the version of June 21, 2018.

The following two definitions are important for CCU fuels:

- ***Renewable liquid and gaseous transport fuels of non-biological origin***: liquid or gaseous fuels which are used in transport other than biofuels whose energy content comes from renewable energy sources other than biomass.
- ***Recycled carbon fuels***: liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin which are not suited for material recovery in line with Article 4 of Directive 2008/98/EC and waste processing gases and exhaust gases of non-renewable origin which are produced as an unavoidable and not intentional consequence of the production process in industrial installations.

In the RED II article 25 ‘Mainstreaming renewable energy in the transport sector’ is most important for CCU fuels, or e-fuels. In the article it is stated that each Member State sets an obligation on fuel suppliers to ensure a share of minimally 14% by 2030 of renewable energy supplied for final consumption in the transport sector. It is mentioned that the Member States may decide to include the contribution of recycled carbon fuels to reach this minimum share. However, this is not obliged, so the Member States can decide themselves. The share of advanced biofuels and biogas is minimally 3.5% by 2030. In the annex a list of input sources that are accepted for the production of advanced biofuels is published. For advanced biofuels a minimum share is provided, whereas for the first generation of biofuels and bioliquids a maximum share is stated. The total allowed share is limited to 7%, however, the share can increase with maximum 1% compared to the share in 2020.

Important is that for the calculation of the share of renewable energy in the transport sector, the renewable liquid and gaseous transport fuels of non-biological origin (i.e. ReFuNoBio) are also taken into account when these are used as intermediate product for the production of conventional fuels.

If electricity is used for road vehicles, the contribution of renewable electricity is considered to be 4 times its energy content. When used for rail transport, a factor of 1.5 will be used. For advanced biofuels a factor of 2 can be taken into account for the energy content. With exception of fuels produced from food or feed crops, the contribution of fuels supplied in the aviation and maritime sector are considered to be 1.2 times their energy content. One should note that the share of renewable electricity is calculated based on the share of electricity from renewable energy sources in the grid of the Member State as measured 2 years before the year in question, unless a direct connection is used. For the production of ReFuNoBio, Member States can decided to allow that renewable electricity connected to the grid is fully counted if evidence is provided, e.g. guarantee of origin or power purchase agreement. The commission will work on a common European methodology to comply with the requirements by December 2021.

It is not exactly clear how recycled carbon fuels are taken into account to calculate their share for the REDII. Note that in case renewable energy is used for the recycled carbon fuels, that they will fall under the categories of ReFuNoBio or advanced biofuels depending on the origin of the renewable electricity.

For recycled carbon fuels, the minimum threshold for greenhouse gas emission savings need to be set by the commission at the latest by January 2021. In the document it is mentioned that they will also ensure that no credit for avoided emissions is given for CO_2 whose capture already received an emission credit under other legal provisions. This means that the methodology will also be influenced by decisions taken within the ETS system. For renewable liquid and gaseous transport fuels of non-biological origin the savings shall be minimally 70% as of January 1, 2021.

Note the important sentence in the definition of the recycled carbon fuels: '… which are produced as an unavoidable and not intentional consequence of the production process…'. For many industries one has to search for solutions to lower the emissions and as a consequence, some emissions might be avoided in the future. It is not clear how this will be taken into account.

In conclusion, the RED II mentions three important things for CCU fuels/e-fuels. The first aspect is related to the use of renewable energy. For CCU fuels it is possible to use electricity from the grid and still be able to prove that you are using 100% of renewable electricity by e.g. guarantees of origin. However, in that case such a system to prove that you are using 100% of renewable electricity needs to be in place. The second aspect is the source of CO_2. Although in the first draft of the revised RED only CO_2 of direct air capture was mentioned, this is now broadened to industrial point sources as well. However, it is not mandatory and member states can decide themselves whether they allow this. This means that this aspect is still quite uncertain. The third aspect is that it is not clear yet how the greenhouse gas emission savings will be calculated and what the minimal savings need to be.

CHAPTER 5 PUBLIC PERCEPTION AND ACCEPTANCE

Purely technical, environmental or economic benefits do not guarantee success of innovative products and technologies. Indeed, the question ‘how do potential customers perceive these products and technologies’ is also important (van Heek, Arning, & Ziefle, 2017a). Studies on the public perception and acceptance of CCU are mainly performed in the UK and Germany (Jones, Olfe-Kräutlein, Naims, & Armstrong, 2017; Perdan, Jones, & Azapagic, 2017; van Heek et al., 2017a; van Heek, Arning, & Ziefle, 2017b).

According to the studies, the majority of the general public is not aware of CCU (Perdan et al., 2017). Despite that, in general studies show an overall support for CCU technologies, but, this support is strongly dependent on people’s self-professed lack of knowledge on the technology, questions concerning the techno-economic feasibility and uncertainty about the societal consequences. One should also keep in mind that information does not necessarily correspond to knowledge as users might not trust and believe this information. Therefore, strategies have to be developed so that users feel well informed. This is especially important because from a study by van Heek et al. (2017b) it was concluded that a strong link exists between the perceived knowledge and risk perception. Also the study of Perdan et al. (2017) concluded that CCU was more seen as an effective technology to combat climate change by respondents with a prior awareness compared with those without prior awareness. Interesting was that the more informed respondents were also more likely to express safety concerns. It is known that the opinion of uninformed respondents are weak and unstable (Jones, Radford, Armstrong, & Styring, 2014). But it is also known that especially uninformed opinions can be shaped by relevant actors and therefore it is good to gain insight into public perception as early as possible so that future communication strategies can be defined (Perdan et al., 2017).

van Heek et al. (2017a) examined, using a qualitative study, the acceptance of several plastic products and analyzed laypersons’ perceptions and needs compared to attitudes and perspectives of scientific experts. They concluded that a large difference exists between laypersons and experts and that especially laypersons had some concerns about negative health effects. Especially for this reason a communication strategy has to be well designed. For laypersons it is not clear that the CO_2 used in a product can only be released after combustion and that the CO_2 cannot ‘just’ escape from the product. The authors suggest to put focus on the advantages in terms of fossil resource savings by e.g. using a simple and easily understandable energy efficiency label, cfr. the European Union energy label.

Often a disconnection exists between the developers and governmental research programs context on what drives CCU. For example, developers point to the fairly limited contribution that CCU can make to climate change mitigation, whereas this is often used as the context in research programs (Jones et al., 2017). This is probably the case because governmental organizations often link CCU with CCS and as already mentioned in the introduction of this report, both have a link, however, have different basic motivations and logics. Jones et al. (2017) performed a research on the social acceptance of CCU. In their study they used the ‘triangle of social acceptance’ from Wüstenhagen, Wolsink, and Bürer (2007) as the three levels of acceptance that are then taken into account. Based on their review, the authors suggested a research agenda for future research about socio-political acceptance, market acceptance and community acceptance.

The 'Diffusion Theory' of Rogers (Figure 12) can be used to explore the factors that affect the market acceptance of CCU (Jones et al., 2017). At the moment only a limited number of products are available on the market and therefore, consumers are still in the 'knowledge stage' of the diffusion theory model. Therefore, the perception is shaped by the characteristics of the socio-economic system the consumer is part of, the communication behavior and a consumers' individual attitude. Gaining more knowledge about CCU can provide a basis for adoption, however, this is strongly dependent on the values, beliefs and attitude of the consumer. Once a consumer is more knowledgeable, he or she needs to be persuaded. Important is that this stage is strongly influenced by the characteristics that are communicated to the consumer (Rogers, 1995). Also note the conclusion of van Heek et al. (2017a) concerning the communication strategy and which aspects to put forward.

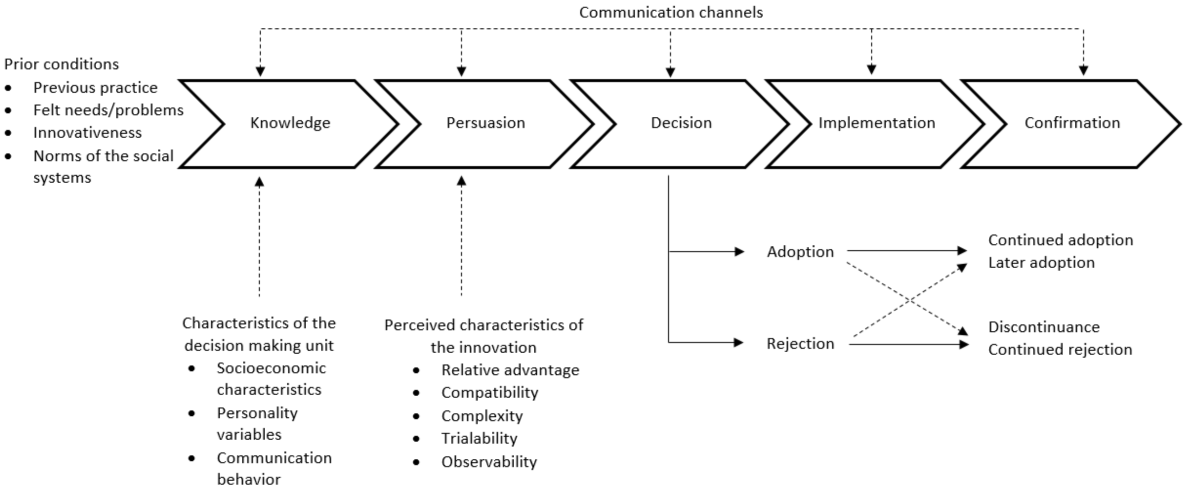


Figure 12: Diffusion Theory of Rogers (Rogers, 1995)

In the CarbonNext project, the researchers from the University of Sheffield provide guidelines for a communication strategy concerning CCU. The first thing they advise is to make sure that your communication strategy fits the audience you target and that you take into account their background and reason for interest in CCU. Second, they state that your communication should not only differ depending on your audience, but also on your product. It is best to have a communication strategy for each specific product. Third, one has to make sure that it is clearly communicated that carbon from waste CO_2 is used and not from fossil fuels. Furthermore, as a fourth recommendation, the researchers mention that it should be made clear that the CO_2 used in a product is only released after combustion. Fifth, it needs to be explained that the CCU product, directly replaces the conventional product. The only difference is that it is manufactured differently. Therefore, they also give the recommendation to clearly explain the product properties and whether these might even be improved compared to the conventional product. The seventh recommendation they give is to clearly explain the carbon footprint. Finally, it must be clear that CCU is not a replacement for CCS. Both CCU and CCS might contribute to the reduction of CO_2 emissions, however, CCU is mainly focused on creating added value to CO_2 by using it as a carbon source for the creation of new products.

Concerning the different audiences or stakeholders you can make a distinction between academia/research, industry (both small and large scale), policy makers and the general public. You need research to make sure that technologies are developed on a laboratory scale. Industry will be involved to first demonstrate the different processes on a pilot scale and later in large demonstration projects to result in market implementation. You need both research and industry to make sure that sufficient budget is foreseen for R&D funding and that regulation supports the development of CCU processes (i.e. lobbying). And finally you need policy makers to translate the requests of the research and industry into the right conditions to facilitate the developments.

CHAPTER 6 CONCLUSION

CO_2 is already used in large amounts in industry, however, the potential CO_2 supply is much larger than the demand. Especially on a short term, CO_2 conversion to chemicals will not have a big impact on reducing global CO_2 concentrations, although it will impact the amount of additional CO_2 emissions. CCU has other important advantages that explain the huge interest in it, e.g. providing feedstock security and greening of conventional products or even to produce new products and materials. It is probably not the question if conventional CO_2 will be replaced, but rather when this will happen.

Although it seems that the commercialization of CCU technologies could produce a considerable amount of benefits, there are still various challenges and risks that need to be overcome before large-scale implementation can be achieved. Most risks are linked to the perceived environmental impact and technological risks. The main technological challenge originate from the high thermodynamic stability of CO_2, which requires high energy levels to overcome (Müller, Mokrushina, & Arlt, 2014)(Müller, Mokrushina, & Arlt, 2014)(Müller, Mokrushina, & Arlt, 2014)(Müller, Mokrushina, & Arlt, 2014). To manage this issue, catalysts such as zinc (Zn) and cobalt (Co) are being used, although this can form an obstacle considering the limited performance and lifetime of many catalysts and the fact that they are often sourced from geopolitically unstable regions, which can possibly cause supply security issues. Researchers are putting more and more attention to finding catalyst based on earth abundant materials. Other risks include the high costs associated with CO_2 capture and the overall poor economic viability, due to the low price of the end products in case of bulk applications, the large dependence on (renewable) hydrogen and the limited sequestration time. Therefore, we believe that focus will first be put on small-scale applications producing high-value chemicals and that later on, bulk products will be added.

For the further development of CCU technologies it is important to have a clear, transparent and uniform methodology to assess the techno-economic and environmental performance. This methodology should also integrate both assessments to allow for the combined optimization of both impacts. Furthermore, it is important to perform these assessments from low TRL on. This is important to steer technical developments towards market introduction and to allow researchers and technology developers to clearly communicate about their technology. This will also allow to identify, combined with the technical specifications, for each specific case study (i.e. CO_2 source, location, targeted end-product, …), which CCU technology might be most promising.

REFERENCES

Afshar, A. A. N. (2014). *Chemical Profile: Formic Acid*. Retrieved from http://chemplan.biz

Agarwal, A. S., Zhai, Y., Hill, D., & Sridhar, N. (2011). The electrochemical reduction of carbon dioxide to formate/formic acid: engineering and economic feasibility. *ChemSusChem, 4*(9), 1301-1310.

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science, 354*(6309), 182-183.

Aresta, M., Dibenedetto, A., & Angelini, A. (2013). The changing paradigm in CO 2 utilization. *Journal of CO2 Utilization, 3*, 65-73.

Armstrong, K., & Styring, P. (2015). Assessing the potential of utilization and storage strategies for post-combustion CO2 emissions reduction. *Frontiers in Energy Research, 3*, 8.

Assen, N. v. d., Müller, L. J., Steingrube, A., Voll, P., & Bardow, A. (2016). Selecting CO2 sources for CO2 utilization by environmental-merit-order curves. *Environmental science & technology, 50*(3), 1093-1101.

Atsonios, K., Panopoulos, K. D., & Kakaras, E. (2016). Investigation of technical and economic aspects for methanol production through CO2 hydrogenation. *international journal of hydrogen energy, 41*(4), 2202-2214. doi:http://dx.doi.org/10.1016/j.ijhydene.2015.12.074

Bazzanella, A., & Ausfelder, F. (2017). *Low carbon energy and feedstock for the European chemical industry*: DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie eV.

Bennett, S. J., Schroeder, D. J., & McCoy, S. T. (2014). Towards a framework for discussing and assessing CO2 utilisation in a climate context. *Energy Procedia, 63*, 7976-7992.

Boot-Handford, M. E., Abanades, J. C., Anthony, E. J., Blunt, M. J., Brandani, S., Mac Dowell, N., . . . Hallett, J. P. (2014). Carbon capture and storage update. *Energy & Environmental Science, 7*(1), 130-189.

Brinckerhoff, P. (2011). Accelerating the uptake of CCS: industrial use of captured carbon dioxide. *Global CCS Institute*, 260.

Bushuyev, O. S., De Luna, P., Dinh, C. T., Tao, L., Saur, G., van de Lagemaat, J., . . . Sargent, E. H. (2018). What Should We Make with CO 2 and How Can We Make It? *Joule*.

Centi, G., & Perathoner, S. (2011). CO2-based energy vectors for the storage of solar energy. *Greenhouse Gases: Science and Technology, 1*(1), 21-35.

Chandel, M. K., Pratson, L. F., & Williams, E. (2010). Potential economies of scale in CO2 transport through use of a trunk pipeline. *Energy Conversion and Management, 51*(12), 2825-2834.

de Pee, A., Pinner, D., Roelofsen, O., Somers, K., Speelman, E., & Witteveen, M. (2018). *Decarbonization of industrial sectors: the next frontier*. Retrieved from

Dimitriou, I., García-Gutiérrez, P., Elder, R. H., Cuéllar-Franca, R. M., Azapagic, A., & Allen, R. W. (2015). Carbon dioxide utilisation for production of transport fuels: process and economic analysis. *Energy & Environmental Science, 8*(6), 1775-1789.

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., . . . Nakicenovic, N. (2014). Betting on negative emissions. *Nature Climate Change, 4*(10), 850.

Ghaib, K., & Ben-Fares, F.-Z. (2018). Power-to-Methane: A state-of-the-art review. *Renewable and Sustainable Energy Reviews, 81*, 433-446.

Hendriks, C., Noothout, P., Zakkour, P., & Cook, G. (2013). Implications of the Reuse of Captured CO2 for European Climate Action Policies. *ECOFYS Netherlabds BV*.

Hietala, J., Vuori, A., Johnsson, P., Pollari, I., Reutemann, W., & Kieczka, H. (2016). Formic Acid. In *Ullmann's Encyclopedia of Industrial Chemistry* (Vol. 23).

House, K. Z., Baclig, A. C., Ranjan, M., van Nierop, E. A., Wilcox, J., & Herzog, H. J. (2011). Economic and energetic analysis of capturing CO2 from ambient air. *Proceedings of the National Academy of Sciences, 108*(51), 20428-20433.

Hunt, A. J., Sin, E. H., Marriott, R., & Clark, J. H. (2010). Generation, capture, and utilization of industrial carbon dioxide. *ChemSusChem: Chemistry & Sustainability Energy & Materials, 3*(3), 306-322.

Jarvis, S. M., & Samsatli, S. (2018). Technologies and infrastructures underpinning future CO2 value chains: A comprehensive review and comparative analysis. *Renewable and Sustainable Energy Reviews, 85*, 46-68.

Jarvis, S. M., & Samsatli, S. (2018). Technologies and infrastructures underpinning future CO 2 value chains: A comprehensive review and comparative analysis. *Renewable and Sustainable Energy Reviews, 85*, 46-68.

Jones, C. R., Olfe-Kräutlein, B., Naims, H., & Armstrong, K. (2017). The social acceptance of carbon dioxide utilisation: a review and research agenda. *Frontiers in Energy Research, 5*, 11.

Jones, C. R., Radford, R. L., Armstrong, K., & Styring, P. (2014). What a waste! Assessing public perceptions of Carbon Dioxide Utilisation technology. *Journal of CO2 Utilization, 7*, 51-54.

Keith, D. W., Ha-Duong, M., & Stolaroff, J. K. (2006). Climate strategy with CO 2 capture from the air. *Climatic Change, 74*(1-3), 17-45.

Keith, D. W., Holmes, G., Angelo, D. S., & Heidel, K. (2018). A Process for Capturing CO2 from the Atmosphere. *Joule*.

Khoo, H. H., & Tan, R. B. (2006). Life cycle investigation of CO2 recovery and sequestration. *Environmental science & technology, 40*(12), 4016-4024.

Kuramochi, T., Ramírez, A., Turkenburg, W., & Faaij, A. (2013). Techno-economic prospects for CO2 capture from distributed energy systems. *Renewable and Sustainable Energy Reviews, 19*, 328-347.

Leeson, D., Mac Dowell, N., Shah, N., Petit, C., & Fennell, P. (2017). A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *International Journal of Greenhouse Gas Control, 61*, 71-84.

Leung, D. Y. C., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews, 39*, 426-443. doi:https://doi.org/10.1016/j.rser.2014.07.093

Mac Dowell, N., Fennell, P. S., Shah, N., & Maitland, G. C. (2017). The role of CO2 capture and utilization in mitigating climate change. *Nature Climate Change, 7*(4), 243-249.

MacDowell, N., Florin, N., Buchard, A., Hallett, J., Galindo, A., Jackson, G., . . . Fennell, P. (2010). An overview of CO 2 capture technologies. *Energy & Environmental Science, 3*(11), 1645-1669.

Metabolic. (2017). *Coresym - Carbon monoxide reuse through industrial symbiosis between steel and chemical industries*. Retrieved from Amsterdam:

Methanol monthly average regional posted contract price history. (2018). Retrieved from https://www.methanex.com/sites/default/files/methanol-price/MxAvgPrice_Oct%2031%2C%202018.pdf

Metz, B., Davidson, O., De Coninck, H., Loos, M., & Meyer, L. (2005). IPCC, 2005: IPCC special report on carbon dioxide capture and storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. *Cambridge, United Kingdom and New York, NY, USA, 442*.

Moazzem, S., Rasul, M., & Khan, M. (2012). A review on technologies for reducing CO2 emission from coal fired power plants. In *Thermal Power Plants*: InTech.

Müller, K., Mokrushina, L., & Arlt, W. (2014). Thermodynamic Constraints for the Utilization of CO2. *Chemie Ingenieur Technik, 86*(4), 497-503. doi:10.1002/cite.201300152

Naims, H. (2016). Economics of carbon dioxide capture and utilization—a supply and demand perspective. *Environmental Science and Pollution Research, 23*(22), 22226-22241.

Oei, P.-Y., Herold, J., & Mendelevitch, R. (2014). Modeling a carbon capture, transport, and storage infrastructure for Europe. *Environmental Modeling & Assessment, 19*(6), 515-531.

Pei, P., Korom, S. F., Ling, K., & Nasah, J. (2016). Cost comparison of syngas production from natural gas conversion and underground coal gasification. *Mitigation and adaptation strategies for global change, 21*(4), 629-643.

Perdan, S., Jones, C. R., & Azapagic, A. (2017). Public awareness and acceptance of carbon capture and utilisation in the UK. *Sustainable Production and Consumption, 10*, 74-84.

Pérez-Fortes, M., Schöneberger, J. C., Boulamanti, A., Harrison, G., & Tzimas, E. (2016). Formic acid synthesis using CO2 as raw material: Techno-economic and environmental evaluation and market potential. *international journal of hydrogen energy, 41*(37), 16444-16462.

Pérez-Fortes, M., Schöneberger, J. C., Boulamanti, A., & Tzimas, E. (2016). Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment. *Applied energy, 161*, 718-732. doi:https://doi.org/10.1016/j.apenergy.2015.07.067

Pérez-Fortes, M., & Tzimas, E. (2016). Techno-economic and environmental evaluation of CO2 utilisation for fuel production. *Publications Office of the European Union, Luxembourg*.

Quadrelli, E. A., Centi, G., Duplan, J. L., & Perathoner, S. (2011). Carbon Dioxide Recycling: Emerging Large-Scale Technologies with Industrial Potential. *ChemSusChem, 4*(9), 1194-1215.

Rabindran, P., Cote, H., & Winning, I. G. (2011). *Integrity management approach to reuse of oil and gas pipelines for CO2 transportation.* Paper presented at the Proceedings of the 6th Pipeline Technology Conference. Hannover Messe, Hannover, Germany.

Rieser, K.-P., Hernandez, A., & Barry, R. (2018). Trade News. Retrieved from https://www.basf.com/us/en/company/news-and-media/news-releases

Rogers, E. M. (1995). Diffusion of Innovations: modifications of a model for telecommunications. In *Die Diffusion von Innovationen in der Telekommunikation* (pp. 25-38): Springer.

Sanz-Perez, E. S., Murdock, C. R., Didas, S. A., & Jones, C. W. (2016). Direct capture of CO2 from ambient air. *Chemical reviews, 116*(19), 11840-11876.

Scott, S. A., Davey, M. P., Dennis, J. S., Horst, I., Howe, C. J., Lea-Smith, D. J., & Smith, A. G. (2010). Biodiesel from algae: challenges and prospects. *Current Opinion in Biotechnology, 21*(3), 277-286.

Snoeckx, R., & Bogaerts, A. (2017). Plasma technology–a novel solution for CO 2 conversion? *Chemical Society Reviews, 46*(19), 5805-5863.

Song, C. (2006). Global challenges and strategies for control, conversion and utilization of CO 2 for sustainable development involving energy, catalysis, adsorption and chemical processing. *Catalysis today, 115*(1), 2-32.

Van Dael, M., Kreps, S., Virag, A., Kessels, K., Remans, K., Thomas, D., & De Wilde, F. (2018). Techno-economic assessment of a microbial power-to-gas plant–Case study in Belgium. *Applied energy, 215*, 416-425.

van der Hoeven, M., Kobayashi, Y., & Diercks, R. (2013). Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes. *International Energy Agency: Paris*, 56.

van Heek, J., Arning, K., & Ziefle, M. (2017a). Differences between laypersons and experts in perceptions and acceptance of CO2-utilization for plastics production. *Energy Procedia, 114*, 7212-7223.

van Heek, J., Arning, K., & Ziefle, M. (2017b). Reduce, reuse, recycle: Acceptance of CO 2-utilization for plastic products. *Energy policy, 105*, 53-66.

Van Wesemael, V. (2018). *Koolstofafvang en -hergebruik: Een marktstudie en techno-economische analyse.* Universiteit Antwerpen,

von der Assen, N., Voll, P., Peters, M., & Bardow, A. (2014). Life cycle assessment of CO 2 capture and utilization: a tutorial review. *Chemical Society Reviews, 43*(23), 7982-7994.

Wernicke, H.-J., Plass, L., & Schmidt, F. (2014). Methanol generation. In *Methanol: the basic chemical and energy feedstock of the future* (pp. 51-301): Springer.

Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. *Energy policy, 35*(5), 2683-2691.

Zimmermann, A., Wunderlich, J., Buchner, G., Müller, L., Armstrong, K., Michailos, S., . . . Stokes, G. (2018). *Techno-Economic Assessment & Life-Cycle Assessment Guidelines for CO2 Utilization* (1916463908). Retrieved from