THE BREAKTHROUGH OF CCS/CCU:
AN ANALYSIS OF DRIVERS AND HURDLES

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Stamnummer/ Student number : 01103422
Promotor/ Supervisor: Prof. dr. Steven De Meester
Co-promotor/ Co-supervisor: Prof. dr. Korneel Rabaey

Masterproef voorgedragen tot het bekomen van de graad van:
Master’s dissertation submitted to obtain the degree of:

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Vertrouwelijkheidsclausule/CONFIDENTIALITY AGREEMENT

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Naam student/name student: JOHANNA HAERENS

Handtekening/signature
"The fact is that no species has ever had such wholesale control over everything on earth, living or dead, as we now have. That lays upon us, whether we like it or not, an awesome responsibility. In our hands now lies not only our own future, but that of all other living creatures with whom we share the earth."

- Sir David Attenborough
Abstract

Carbon capture and storage (CCS) consists of capturing CO₂ from point sources and storing it; carbon capture and utilisation (CCU) captures CO₂ as well, but uses it as a feedstock to make new products. Both processes prevent carbon dioxide from directly reaching the atmosphere, and can thus be seen as ways to mitigate climate change. Even though many of these technologies have been proven to be possible, implementation in industry on a large scale has not yet occurred.

The objective of this study is twofold: (1) to detect why industrial actors have not yet applied carbon capture and storage (CCS) or carbon capture and utilisation (CCU) technologies on a large scale (hurdles) and which actions could change the current situation (drivers), and (2) to evaluate the effectiveness of possible economic incentives that can stimulate the upscaling of CCS and CCU technologies. To achieve this objective, both a qualitative and quantitative analysis are carried out.

The qualitative analysis is discussed within the theoretical framework of the multi-level perspective (MLP), a theory on the co-evolution of society and technology. To find the hurdles and drivers (or, lock-in mechanisms and sociotechnical regime cracks, as they are called within MLP research) to upscaling CCS/CCU technologies in industry, experts from four sectors are interviewed. During these in-depth interviews, we detected that the largest hurdle to upscaling is the lack of economic performance of the CCS/CCU technologies. We further discussed possible economic incentives with the interviewees. These incentives are further used as the basis for the quantitative analysis, in which their effectiveness to stimulate upscaling is evaluated. We deal with the oil price and three market-based policy instruments from the European Union: The European Emissions Trading System (EU-ETS), subsidies to stimulate cost decrease and a carbon tax. From our analyses, it is clear that interference by policymakers will be necessary for upscaling CCS/CCU technologies in industry, since the required increase in the oil price is much higher than the anticipated increase. First, to stimulate the learning effect and thus, a faster decrease in costs, subsidies provide a good option. Second, after a cost decrease, a carbon tax can stimulate buying behaviour towards more sustainable products, and this way, push industry in the right direction. And third, it is clear that EU-ETS in its current form will not provide an incentive for CCS, and certainly not for CCU.
PROLOGUE

When I was confronted with the surprised expressions at the faculty student administration, I realised that writing a master’s dissertation at a different faculty than your own is not common practice. For me, however, deciding to do so was a logical decision. My aim was to write a master’s thesis on a topic that I was passionate about, something I could not seem to find at my own faculty. Fortunately, I soon came across what I was looking for at the faculty of bioscience engineering.

I hereby would like to thank the people without whom this study would not have been possible.

What initially started as a case study of one company, turned into multiple interviews in four different sectors, and this is thanks to the enthusiasm and kindness of people involved with the topic. I would therefore first like to thank everyone who was willing to cooperate in this study. Second, I would like to thank my mom, who, no matter what, is always proud of what I accomplish, but also never afraid to give her unvarnished opinion. Her academic experience has given me unfair advantage, which I was happy to exploit. Third, I would to thank my partner in everything and my voice of reason, Andreas, who makes sure I put things in perspective and unconditionally has my back. And fourth, I would like to thank my three roommates, whose doors were always open to listen to my complaints, who distracted me when I needed it most, but most importantly, who did not judge me when I went into the kitchen for my fifth cup of coffee.

But most of all, I would like to thank the two people who have guided me through this study. Professor Korneel Rabaey, my co-supervisor, welcomed me with open arms at the faculty of bioscience engineering and enthused me over a subject I initially knew nothing about. He provided feedback and connected me to the right people, among whom my supervisor, professor Steven De Meester. However, the term supervisor does not really seem fitting here, since professor De Meester was nothing short of a mentor. I would like to express my sincerest gratitude for his support and guidance, and I feel privileged to have been his “hobby project” during this course of this study.
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<tbody>
<tr>
<td>BAT</td>
<td>Best Available Technology</td>
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<tr>
<td>BAU</td>
<td>Business As Usual</td>
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<tr>
<td>bbl</td>
<td>Barrel, volume measure for crude oil</td>
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<td>CAPEX</td>
<td>Capital Expenditure</td>
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<td>CCS</td>
<td>Carbon Capture and Storage</td>
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<td>CCU</td>
<td>Carbon Capture and Utilisation</td>
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<tr>
<td>CDM</td>
<td>Clean Development Mechanism</td>
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<tr>
<td>CER</td>
<td>Certified Emissions Reduction</td>
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<tr>
<td>CO</td>
<td>Carbon Monoxide</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
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<tr>
<td>COP</td>
<td>Conference of the Parties</td>
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<tr>
<td>CRI</td>
<td>Carbon Recycling International</td>
</tr>
<tr>
<td>CSR</td>
<td>Corporate Social Responsibility</td>
</tr>
<tr>
<td>DME</td>
<td>Dimethyl Ether</td>
</tr>
<tr>
<td>ECBM</td>
<td>Enhanced Coal-Bed Methane Recovery</td>
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<td>EGR</td>
<td>Enhanced Gas Recovery</td>
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<tr>
<td>EOR</td>
<td>Enhanced Oil Recovery</td>
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<tr>
<td>ERU</td>
<td>Emission Reduction Units</td>
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<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>EU ETS</td>
<td>European Union Emissions Trading System</td>
</tr>
<tr>
<td>EUA</td>
<td>European Allowance</td>
</tr>
<tr>
<td>FOAK</td>
<td>First-of-a-kind</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
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<td>GHG</td>
<td>Greenhouse Gas</td>
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<td>GO</td>
<td>Guarantee of Origin</td>
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<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
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<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>IGCC</td>
<td>Integrated Gasification Combined Cycle</td>
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<tr>
<td>JI</td>
<td>Joint Implementation Project</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt Hour</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
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<tr>
<td>LCOE</td>
<td>Levelised Costs of Electricity</td>
</tr>
<tr>
<td>MEA</td>
<td>Monoethanolamine</td>
</tr>
<tr>
<td>MLP</td>
<td>Multi-Level Perspective</td>
</tr>
<tr>
<td>MMBtu</td>
<td>Million British Thermal Units (BTU)</td>
</tr>
<tr>
<td>MO</td>
<td>Metal Oxides</td>
</tr>
<tr>
<td>NGCC</td>
<td>Natural Gas Combined Cycle</td>
</tr>
<tr>
<td>OOIP</td>
<td>Original Oil in Place</td>
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<tr>
<td>OPEX</td>
<td>Operating Expenditure</td>
</tr>
<tr>
<td>OS</td>
<td>Oil Shale</td>
</tr>
<tr>
<td>PC</td>
<td>Pulverised Coal</td>
</tr>
<tr>
<td>PCC</td>
<td>Precipitated Calcium Carbonate</td>
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<tr>
<td>PPP</td>
<td>Polyether carbonate polyols</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RED</td>
<td>Renewable Energy Directive</td>
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<tr>
<td>SCCS</td>
<td>Scottish Carbon Capture and Storage</td>
</tr>
<tr>
<td>SCPC</td>
<td>Supercritical Pulverized Coal</td>
</tr>
<tr>
<td>SRCCS</td>
<td>Special Report on Carbon Capture and Storage (IPCC, 2005)</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
<tr>
<td>ZEP</td>
<td>Zero Emissions Platform</td>
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1 INTRODUCTION

A sunk costs is a classic economic term and indicates a cost that has been incurred and cannot be recovered. According to micro-economic theory, these costs should not influence a company’s decisions, since there is nothing that can be done about them. One can interpret these sunk costs in a more philosophical sense: what’s done is done and there is no way change it. It’s better look at the future and try to optimise it. Climate change can be approached in a similar manner. The damage that has been caused is done and there is no way to recover it. We can, however, look at the future and do everything in our power to make sure that we do not aggravate the situation.

Therefore, slowly but steadily, our society is shifting towards a more sustainable way of living. One of the main action points is to reduce greenhouse gas emissions, such as CO₂, for example by using solar energy instead of fossil energy. This way, processes that produce harmful emissions are avoided. But what to do with products, such as steel and cement, for which carbon dioxide emissions are intrinsically part of their production process? For these processes, no sustainable alternatives exist. Moreover, it will still take a long time before fossil power plants are history. Consequently, an alternative way to prevent harmful emissions from reaching the atmosphere, is by capturing the CO₂. The idea of capturing carbon dioxide is not new, but has only recently been considered as a way to mitigate climate change. There are two possibilities: one can either capture CO₂ and store it (carbon capture and storage, CCS), or capture CO₂ and convert it into a product (carbon capture and utilisation, CCU).

In this study, we will deal with different aspects of CCS/CCU. The outline is as follows: in the literature review (§2), we discuss global warming, the international interventions to combat global warming and the currently existing CCS and CCU technologies. Next, after explaining our objectives (§3) and used methods (§4), we will report and discuss the results of a qualitative (§5.1) and quantitative analysis (§5.2) on CCS/CCU. In the last part, we conclude and give some perspectives for the future (§6).
2 LITERATURE

2.1 CARBON DIOXIDE AND GLOBAL WARMING

The chemical element carbon serves as a basis of power supply, of technology and is a component of numerous products we create and consume. Aside from the benefits carbon brings to our modern lives, it also harms the planet. The production of energy from fossil fuels (oil, gas and coal) and the manufacturing of products that contain carbon eventually lead to the emission of carbon dioxide into our atmosphere (Martens et al., 2016). The atmospheric CO$_2$ today amounts to 3000 Gt and the anthropogenic sources can be subdivided into CO$_2$ point sources and atmospheric CO$_2$. Worldwide, there are more than 7,500 “large” point sources ($\geq$0.1 Mt CO$_2$/y) and 79% of their CO$_2$ emissions originate from fossil-fuelled power plants, which make them the main greenhouse gas contributors (Haszeldine, 2009; Martens et al., 2016; Von Der Assen, Müller, Steingrube, Voll, & Bardow, 2016).

Carbon dioxide (CO$_2$) is one of the notorious gases known as greenhouse gases (GHGs), the main contributors of the greenhouse effect, also known as global warming. The greenhouse effect is a natural phenomenon and was discovered in 1824 by the French physicist Joseph Fourier (Black, 2013). The sun radiates different wavelengths of energy into our solar system. About 30% of the solar radiation that reaches the earth’s atmosphere is immediately reflected back into space; oceans, land and atmosphere absorb the remaining 70%. Certain atmospheric gases, such as water vapour, carbon dioxide, methane and nitrous oxide, let this direct solar radiation pass through, but capture the infrared radiation that is reemitted by the heated surface of the earth, which results in higher temperatures. These gases are vital to life on earth as they act like a blanket that ensures an average temperature of 15°C instead of -18°C, thus making our planet habitable. As the atmospheric concentrations of these greenhouse gases have risen significantly due to human activities since the beginning of the industrial revolution, more infrared radiation is trapped with a gradual increase in the earth’s surface temperature as a result (Dincer, 2000; Eurostat, 2016b; Lallanila, 2016). At the same time, a surface the size of Italy is deforested every year, thereby destroying the earth’s largest natural buffer against global warming. The average temperature on earth since 1880 has increased by 0.8°C and two thirds of the warming has taken place since 1975 (NASA, 2016). Fourteen out of the fifteen hottest years on record have occurred since the year 2000 (Jackson et al., 2016). All this
can be seen in Figure 1 (NASA, 2016). Growing ocean acidification, extreme weather events and enormous natural and societal impacts are other expected results of global warming (Lallanila, 2016). Today, it seems that most people in developed countries accept climate change as real and relevant. Nevertheless, there appears to be confusion about the role of CO₂ where it comes from and which effect it can have, not just on the climate, but also on human health (Orange, Dohle, & Siegrist, 2014).

2.2 INTERNATIONAL INTERVENTIONS TO COMBAT GLOBAL WARMING

The Canadian steam engineer Guy Stewart Callendar published the first paper on the relationship between global warming and anthropogenic CO₂ emissions in 1938. At that time, only a handful of people believed in “The Callendar Effect”, as global warming was called; most scientists could – and some still do – not believe that the human race had the ability to pose an impact on something as immense as the climate (Applegate, 2013). It would take more than half a century before this positive correlation became widespread knowledge and world leaders recognised that action needed to be taken.

2.2.1 The Kyoto Protocol

In the first Intergovernmental Panel on Climate Change (IPCC) Assessment Report, published in 1990, the problem of climate change was proclaimed on an international level. Two years later, the United Nations Framework Convention on Climate Change (UNFCCC) was negotiated at “the Earth Summit”, with the objective “to stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic
interference with the climate system” (United Nations, 1992). Stemming from the UNFCCC, the Kyoto Protocol is agreed by 192 parties on the third Conference of the Parties (COP) in Kyoto in 1997. Thirty-seven industrialised countries plus the European community pledged to reduce their greenhouse gas emissions by an average of 5.2% compared to their 1990 level by 2008-2012. No targets were set for over 100 developing countries, including India and China, based on the fact that these countries only contributed a relatively small share to the century-long build-up of CO₂. The United States (USA), one of the largest emitters, did not ratify the treaty (Black, 2013; King, Richards, & Tydesley, 2011; United Nations, 2014; Van Langenhove & Walgraeve, 2014).

In order to turn these country-specific targets into reality, the Kyoto Protocol includes several mechanisms: the Clean Development Mechanism (CDM), Joint Implementation Projects (JI) and International Emissions Trading. CDM is a mechanism for industrialised countries to support developing countries to become more sustainable. By investing in projects in developing countries, industrialised countries receive Certified Emissions Reductions (CERs), which lowers their Kyoto CO₂ reduction targets. For instance, The Netherlands finances projects in Latin-American countries to develop renewable energy sources, for which they receive CERs. A JI is a project financed by industrialised countries to reduce carbon dioxide emissions in other industrialised countries. The Netherlands invested in durable energy projects, waste management, biomass installations and reforestation in Eastern-Europe and New-Zealand and thus received “Emission Reduction Units” (ERUs), cutting down their own Kyoto targets. The last mechanism is Emissions Trading, a system where participants can trade tonnes of CO₂-equivalents. Each country is allowed a certain amount of emission units and countries that have an excess (assigned, but unused) can sell them to countries that exceed their cap (UNFCCC, 2014; Van Langenhove & Walgraewe, 2014).

In 2005, the treaty took effect and at the COP in Copenhagen in 2009, the parties stated their determination to limit global warming to 2°C between now and 2100 (“Why 2°C?,” 2015). In 2012, the “Doha Amendment”, or second commitment of the Kyoto Protocol, started for the period 2012-2020. Several countries, such as Canada, Japan and Russia, however, have withdrawn their support for the second commitment (Rosen, 2015). At the COP21 in Paris in December 2015, the Parties made the “first-ever universal, legally binding global climate deal” (European Commission, 2015c). On the 4th of November 2016, less than one year after signing
it, the Paris climate deal came into force, turning it into a “diplomatic miracle”. The two largest polluters, China and the USA, were some of the first countries to sign the deal (Minten, 2016).

Before the 2012 deadline, some countries and regions were well on track to meet their Kyoto goals. Other countries, however, were not. In addition, all the efforts of reducing greenhouse gases were more than nullified by the increasing emissions of the USA and China, the world’s largest emitters (Henson, 2011). The result is that between the nineties and 2012 the global CO\textsubscript{2} emissions rose to 145% of their 1990 level (Global Carbon Atlas, 2015). These disappointing results were not the only reason why the Kyoto Protocol endured heavy criticism. In the article “Time to ditch Kyoto”, Prins and Rayner (2007) discuss why they believe that “the Kyoto Protocol was always the wrong tool for the job”. In their opinion, it has not only failed because of its lack of success slowing global warming, but also because it has stifled discussion of alternative policy approaches to combat climate change (Prins & Rayner, 2007). In the paper “The wrong solution at the right time”, Rosen (2015) argues that the Kyoto Protocol is a case of institutional design failure, which has cost the global community something that cannot be replaced: time. The author reasons that it was the right moment to act, but because of a lack of compliance, efficiency and effectiveness in the design of the protocol, only dismal progress has been made in almost two decades. Moreover, all of the design flaws are extended for the 2012-2020 period in the Doha Amendment (Rosen, 2015). Both papers argue that Kyoto has led to a path-dependent structure which is extremely difficult to unlock (Prins & Rayner, 2007; Rosen, 2015).

2.2.2 The European Union

Aside from complying with the Kyoto targets, the European Union (EU) launched the Climate and Energy package, which sets three climate and energy targets for the year 2020 for all member states. By 2020, the EU aspires for a 20% cut (compared to 1990) in greenhouse gas emissions, 20% renewable energy and a 20% improvement in energy efficiency. The main instruments to accomplish the first target are the EU Emissions Trading System (EU-ETS) and the Effort Sharing Decision (ESD). The former sets a single EU-wide cap for power stations, industrial plants and the aviation industry which allows economic actors to trade emissions among themselves. The latter sets GHG emission targets for sectors not included in the EU-ETS, such as transport, building, agriculture and waste. These non-ETS sectors are expected to reduce their emissions by 10% in 2020 compared to 2005 levels. The European Union had
cut 22.9% of man-made GHG emissions by 2014 compared to 1990. There is nevertheless a large variety in accomplishment between the member states of the EU, as can be seen in Figure 2. The best performers are situated in Eastern Europe (Lithuania, Romania, Latvia), cutting their emissions in half, and the worst performers situated in Southern Europe (Malta, Cyprus, Spain), with emissions still increasing. Belgium performs just below the European average (European Commission, 2016b; Eurostat, 2016a).

The goal of EU-ETS is simple: it is a cap-and-trade scheme in which a fixed number of permits to emit carbon are allocated to firms and these can be traded between them. If a company exceeds its allowed emission, it must purchase allowances from others and vice versa. Due to the scarcity of allowances, companies in the ETS sectors should be induced to lower their emissions. However, because the recession has reduced industrial demand for the permits and because too many allowances were given out in the first place, there is a huge overcapacity, which resulted in a very low carbon price (~ €5 in the third quarter of 2016) (Swartz, 2013).

Other stimuli for sustainable technologies can be found in Horizon 2020 and NER300. Horizon 2020 is a research and innovation programme, of which a part of the funding is dedicated to upscaling environmentally sound technologies. It has nearly 80 billion euros of funding available for the period 2014-2020 (European Commission, n.d.). NER300 is a funding programme for innovative low carbon energy demonstration projects. It focuses
specifically on environmentally safe carbon capture and storage and innovative renewable energy technologies. The funding programme is called NER300 because it is funded from the sale of 300 million EU emission allowances (EUA) from the New Entrants’ Reserve of the EU emissions trading system (European Commission, 2014). Currently, governments in OECD countries still grant more subsidies to coal, oil and gas than to the fight against global warming. Not only do these subsidies undermine global efforts to mitigate climate change, they also aggravate local pollution problems. This money would be better spent in strategic investments that benefit society as a whole (OECD, 2015).

2.2.3 The tragedy of the commons

“Freedom in a commons brings ruin to all.” – Garett Hardin (1968)

Garret Hardin (1968) gives a possible explanation for the difficulty to make different nations comply with the Kyoto Protocol, European or other initiatives in his historic paper “The Tragedy of the Commons”. By commons the author means a “common pool” or “open access resource” and gives the metaphor of an open pasture with a cattle herder as a rational decision maker. The herder receives direct benefits from each cow he raises, but only bears a fraction of the cost of overgrazing: his rational response is therefore to add more and more animals. Since every herder makes the same rational decision about this open pasture, the result of this acting out of self-interest is that there is no grass left to graze and thus “brings ruin to all” (Engel & Saleska, 2005; Hardin, 1968). Hardin himself mentions that the Tragedy of the Commons reappears in the problem of pollution and many scholars over the years have linked environmental and ecological issues to his thesis. The problem of climate change is an excellent application of the commons problem, where the atmosphere is the open pasture and the different nations are the cattle herders. No nation has an incentive to reduce its emissions because this will only decrease their own benefits – e.g. economic benefits from burning fossil fuels – without tangibly preventing the problem of global warming. The standard economic solution would be to either privatize the commons or to subject the use of the commons to a centralized governing authority, where the Kyoto Protocol is a mixture of both (Engel & Saleska, 2005).
2.2.4 Hope for the future

Historically, increasing GHG emissions and economic growth went hand in hand. The richer the country, the more people had access to electricity and transportation, and thus the more GHGs were emitted. In periods where the emissions growth staggered, it was always related to economic downturns, such as the sudden decline of 9.3% of CO₂-emissions in 2009 in the EU-27 (Eurostat, 2011). Nonetheless, in 2014 the tables started to turn on this tight positive correlation. Even though the global gross domestic product (GDP) grew at a stable rate of 3.3 – 3.4% per year during 2012, 2013 and 2014, there was little or no emissions growth: 0.6% in 2014 compared to an average of 2.4% in the previous decade, making scientists believe that a peak in emissions will be reached soon (Jackson et al., 2016; Yeo & Evans, 2016). Figure 3 shows the decline in emissions intensity (CO₂/GDP) (Jackson et al., 2016). This slower growth in GHG emissions is attributed to a decrease in coal consumption in China, combined with below-average growth in global demand for oil and natural gas and an on-going expansion in renewable energy, such as wind and solar capacities (Jackson et al., 2016). Many innovations and movements, some of which will be discussed in the present study, contribute on a much smaller scale to the mitigation of GHG emissions. However, the more of these innovations emerge, the larger the impact will be. It’s important to keep in mind that no single technology will provide all of the emission reductions needed to achieve stabilization, but that a portfolio of mitigation measures will be needed (IPCC, 2005).

Figure 3 - Global CO₂ emissions from fossil-fuel use and industry since 1990 and emissions intensity CO₂/GDP. Retrieved from Jackson et al. (2016).
2.3 CARBON CAPTURE: SOLUTIONS BEYOND AVOIDING CO₂

Even though the tide is slowly changing and carbon dioxide emissions are decreasing, processes that produce CO₂ will continue to exist. In order not to let climate change exceed its limits, this unavoidable carbon dioxide must be prevented from reaching the atmosphere. The present study focuses on Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) as ways to do just that. First, we will elaborate on the capturing of CO₂ in general, as this process is of interest for both storage and utilisation. Next, we will look at CCS and CCU. Both CCS and CCU capture CO₂ emissions to prevent its release into the atmosphere but they differ in the destination of the captured CO₂. For CCS, carbon dioxide is captured and stored for a long time at a certain location (geological storage, enhanced oil recovery or mineralisation), while for CCU, carbon dioxide is converted into commercial products (Cuéllar-Franca & Azapagic, 2015). An overview of the options can be found in Figure 4 (Bruhn, Naims, & Olfe-Kräutlein, 2016).

Figure 4 - Overview of CCS and CCU. Retrieved and adapted from Bruhn et al. (2016).
2.3.1 Capturing carbon dioxide

Before the carbon dioxide can either be stored or converted into products, it needs to be captured by separating it from other gases in the industrial waste gas streams. There is no one-size-fits-all technology because of the variety of industrial processes emitting CO$_2$. Generally, there exist three possible configurations for CO$_2$ capture: post-conversion capture, pre-conversion\(^1\) capture and oxy-fuel combustion capture. These can be seen schematically in Figure 5 (Cuéllar-Franca & Azapagic, 2015; IPCC, 2005). Post-conversion capture separates the CO$_2$ from waste gas streams after the conversion of the carbon source. This can be achieved using absorption in solvents or adsorption by solid sorbents. Absorption by monoethanolamine (MEA) is the most common method. This method is however not

\(^1\) Post-conversion capture and pre-conversion capture are referred to as post-combustion capture and pre-combustion capture, respectively, in the context of power plants (Cuéllar-Franca & Azapagic, 2015). Since this study does not only discuss power plants, the broader term is used. However, most literature focuses on power plants.
economically viable for all industries because of a high heat consumption. Pre-conversion capture involves capturing CO$_2$ that is generated as a side product of an intermediate reaction of a conversion process. The carbon dioxide is separated using physical or chemical absorption before the second phase of conversion process. An example is the separation of CO$_2$ from hydrogen in an integrated gasification combined cycle (IGCC) power plant. As in the case of post-conversion capture, pre-conversion capture also incurs a large energy penalty. The penalty is however lower for the physical sorbents as they are regenerated by reducing pressure instead of by heat, as is the case for chemical sorbents. Oxy-fuel combustion burns coal or gas in denitrified air to result in flue gas with high CO$_2$ concentrations and water. For this method, there is no need for chemicals, but pure oxygen is expensive and the environmental impacts are high because of the energy intensive air-separation processes (Cuéllar-Franca & Azapagic, 2015; Haszeldine, 2009). Variations inside these technologies are possible, with the specifics depending on the industry.

Every capture method requires substantial amounts of energy, resulting in indirect CO$_2$ emissions and other environmental impacts if no sustainable energy sources are used (von der Assen et al., 2016). This explains why the operational expenditure of capture is so high. Moreover, large capital expenditures are required for installing the necessary capture infrastructure. The prices for industrial equipment rose significantly in the past decade, due to the high industrial growth and demand in Asia, especially China (Rubin, Davison, & Herzog, 2015). The capture step thus takes up the largest fraction of the costs (Naims, 2016). An elaborate techno-economic comparative assessment of these capture methods in the iron and steel, cement, petrochemical and refineries industry can be found in Kuramochi et al. (2012). Most literature, however, focuses on fuel combustion plants: their ubiquity and large production volumes of CO$_2$ make them the best source for CO$_2$, according to Kosowski & Kuk (2016). A detailed cost overview of the capture methods for different fuel combustion plants is given in Rubin et al. (2016), in which a comparison is made between the current costs to the costs mentioned in the SRCCS in 2005 (Rubin et al., 2015). Naims (2016) combines recent techno-economic literature to draw up a table with a benchmark capture cost (based on the Best Available Technology (BAT)) and capture rate for different sources of CO$_2$. An adapted version can be found in Table 1. The cost of capturing CO$_2$ is generally calculated as follows (Naims, 2016):
\[ \text{cost of CO}_2 \text{ captured} \left( \frac{\text{€}}{\text{tCO}_2} \right) = \frac{\text{additional costs of CO}_2 \text{ capture (€)}}{\text{amount of CO}_2 \text{ captured (tCO}_2)} = \frac{\text{costs}_{\text{capture \ plant (€)}} - \text{costs}_{\text{reference \ plant (€)}}}{\text{amount of CO}_2 \text{ captured (tCO}_2)} \]

Table 1 - Global emissions, benchmark capture costs (€2014/t CO\textsubscript{2}) and estimated capture rate for different sources of CO\textsubscript{2}. Retrieved and adapted from Naims (2016).

<table>
<thead>
<tr>
<th>CO\textsubscript{2} emitting source</th>
<th>Global emissions (Mt CO\textsubscript{2}/year)</th>
<th>Benchmark capture cost (€2014/t CO\textsubscript{2})</th>
<th>Estimated capture rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal to power</td>
<td>9031</td>
<td>34</td>
<td>85</td>
</tr>
<tr>
<td>Natural gas to power</td>
<td>2288</td>
<td>63</td>
<td>85</td>
</tr>
<tr>
<td>Cement production</td>
<td>2000</td>
<td>68</td>
<td>85</td>
</tr>
<tr>
<td>Iron and steel production</td>
<td>1000</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Refineries</td>
<td>850</td>
<td>99</td>
<td>40</td>
</tr>
<tr>
<td>Petroleum to power</td>
<td>765</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Ethylene production</td>
<td>260</td>
<td>63</td>
<td>90</td>
</tr>
<tr>
<td>Ammonia production</td>
<td>150</td>
<td>33</td>
<td>85</td>
</tr>
<tr>
<td>Bioenergy</td>
<td>73</td>
<td>26</td>
<td>90</td>
</tr>
<tr>
<td>Waste combustion</td>
<td>60</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Hydrogen production</td>
<td>54</td>
<td>30</td>
<td>85</td>
</tr>
<tr>
<td>Natural gas production</td>
<td>50</td>
<td>30</td>
<td>85</td>
</tr>
<tr>
<td>Fermentation of Biomass</td>
<td>18</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Aluminium production</td>
<td>8</td>
<td>75</td>
<td>85</td>
</tr>
</tbody>
</table>

2.3.2 Carbon Capture and Storage (CCS)

The Intergovernmental Panel on Climate Change (IPCC) defined carbon capture and storage (CCS) in its Special Report (SRCCS) of 2005 as follows:

“Carbon dioxide (CO\textsubscript{2}) capture and storage (CCS) is a process consisting of the separation of CO\textsubscript{2} from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere.” (IPCC, 2005)

CCS thus integrates four elements: CO\textsubscript{2} capture, compression of the CO\textsubscript{2} from a gas to a liquid or a denser gas, transportation of pressurized CO\textsubscript{2} from the point of capture to the storage locations and isolation from the atmosphere by storage (Benson et al., 2008).

The contribution of CCS is anticipated to be about 20\% of required emission reductions over the next century, based on worldwide assessments (IPCC, 2005, 2007). Several authors refer to geological storage as a “temporary, but necessary” method to mitigate climate change.
If we can store CO$_2$ underground, it can buy us extra time to research and develop more durable solutions, such as renewable energy. In fact, Benson et al. (2008) argue that CCS cannot be excluded from the emission reduction options because of three main reasons: (1) the cost of the overall emission reduction actions will be greater, (2) it will not be possible to sufficiently reduce emissions without CCS, and (3) excluding CCS as a mitigation option would hinder international negotiations, since many parts of the world depend enormously on fossil fuels (Benson et al., 2008). The authors further state that key conditions need to be met if CCS is to become part of the solution to mitigate climate change, the most crucial one being that the volumes of CO$_2$ captured and stored are sufficiently large to make a difference (Benson et al., 2008). At the moment, there are 15 large-scale CCS-projects worldwide, accounting for about 40 Mt of CO$_2$ every year (Global CCS Institute, 2015).

According to the SRCCS of the IPCC (2005), the net reduction of emissions to the atmosphere through CCS depends on (1) the fraction of CO$_2$ captured, (2) the increased CO$_2$ production resulting from loss in overall efficiency of power plants or industrial processes due to the additional energy required, (3) transport and storage, (4) any leakage from transport and (5) the fraction of CO$_2$ retained in storage over the long term. A power plant with CCS could reduce CO$_2$ emissions to the atmosphere by approximately 80-90% compared to a plant without CCS (IPCC, 2005). The optimal degree of emission reduction will further depend on trade-offs between the amount of emissions reduced, the cost of capture and the age of the facility on

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**Figure 6** - Total LCOE for CO$_2$ capture, transport and geological storage based on recent studies of current technology for new power plants. Values in EUR/MWh. Data retrieved and adapted from Rubin et al. (2015).
which it is deployed. It may for instance be more advantageous in the short-term to use a lower cost technology that captures 50% of the emissions from existing coal-fired power plants in China than to strive for larger emission reductions only applicable in particular industries (Benson et al., 2008). A comparison of the levelised costs of electricity (LCOE) for a reference plant, a plant with geological storage and with EOR for different types of power plants can be found in Figure 6.

In the following paragraphs, three CCS categories will be discussed: geological storage, enhanced oil recovery (EOR) and mineral carbonation. One could debate on whether EOR should be considered a form of CCU instead of CCS. In our opinion, following the definition of the IPCC, CO₂ is only transported and stored and therefore EOR belongs to the category of carbon capture and storage. Figure 7, retrieved from IPCC (2005), clearly visualises some of the different methods for storing CO₂. In this figure, mineral carbonation is not included.

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**Figure 7 - Methods for storing CO₂ in deep underground geological formations (IPCC, 2005)**

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2 “The LCOE reflect the minimum price at which electricity has to be sold to ensure that the investment made pays off.” (Visser & Held, 2014)

3 NGCC = Natural Gas Combined Cycle; SCPC = Supercritical Pulverized Coal; IGCC = Integrated Gasification Combined Cycle
2.3.2.1 Storage below sea level

The first discussed CCS technology consist of capturing CO₂ from point sources at power plants or industrial installations, compressing it, transporting it and injecting it into geological formations, and has been demonstrated successfully in Norway at the Sleipner gas field since 1996 (Benson et al., 2008). CO₂ can either be stored as a compressed gas, a liquid or in a supercritical state in various designated locations, where a difference is made between geological and ocean storage. In the geological case, the CO₂ is stored at depths of 800-1000 metres in geological formations such as depleted oil and gas reservoirs, deep saline aquifers and coal bed formations. In the case of ocean storage, captured CO₂ is injected directly into the deep ocean (at depths greater than 1000 m). In contrast to geological storage, ocean storage still has not been tested on a large scale, even though it has been studied for over 25 years (Cuéllar-Franca & Azapagic, 2015; European Commission, 2012). There are concerns about unknown biological impacts, high costs, impermanence of ocean storage and concerns regarding public acceptance. This resulted in a decrease in interest and investment over the 2000’s (Benson et al., 2008), and the international research community no longer pursues ocean storage as an active option (Rubin et al., 2015). Considering this, we will not further consider the ocean storage option.

Storing CO₂ deep underground is the most mature CCS option because it can rely on experience from the oil and gas sector, and can be implemented by applying known technology developed for this purpose (Benson et al., 2008; Cuéllar-Franca & Azapagic, 2015; IPCC, 2005). Even though the individual component technologies required for capture, transport and storage are well-understood and some even technologically mature, the largest challenge for CCS deployment remains the integration of component technologies into large-scale demonstration projects (IEA, 2013), especially for industrial applications of CCS (Cuéllar-Franca & Azapagic, 2015). Aside from this challenge, public perception also plays a large part in this mitigation option being deployed on a significant scale. The idea of storing CO₂ underground has encountered resistance (for instance in Barendrecht in The Netherlands (Feenstra, Mikunda, & Brunsting, 2010)), because some see it as “sweeping dirt under the carpet” or think of it as too risky (Martens et al., 2016). Potential risks are e.g. CO₂ leaking and alteration of groundwater chemistry (Global CCS Institute, 2015). The risks associated with geological storage are generally assumed to be similar to those of existing activities, such as oil and gas production, natural gas storage, and acid gas injection, and are thus supposed to be
manageable (Benson et al., 2008). Nonetheless, it is necessary to provide adequate and unbiased information to the general public, because many misconceptions exist today concerning geological storage and the behaviour of CO₂ in the reservoir (Orange et al., 2014).

The European Union implemented CCS in its Climate and Energy Package as an option to reduce its long-term emissions reduction goal. It is seen as one of the few options to reduce unavoidable emissions from industrial processes, such as the production of steel, on a sufficiently large scale. A legal framework, the “CCS Directive” was set up to ensure safety and to minimize risks and any negative effects (European Commission, 2012). Even though the European Union is providing support, currently there are no large-scale CCS projects operational in the European Union (aan de Brugh, 2016). In the United Kingdom a pioneering competition was launched for a 1 billion GBP investment in CCS, but the government pulled out in November 2015, six months before it was due to be awarded (Carrington, 2015). The argument for doing so was that CCS did not fit into the “areas of spending that will achieve the best economic returns while delivering on the commitments to invest 100 billion GBP in infrastructure by the end of the Parliament” (The Energy and Climate Change Committee, 2016). Today, however, the UK is again relocating money towards CCS projects (Macalister, 2016).

2.3.2.2 Enhanced oil recovery

A second CCS technology is active in the oil and gas sector, where a specific division focuses on producing more oil from a given discovered field after it has already gone through the primary and secondary production phase (a “reluctant” or “depleted” reservoir). Not many oil companies take part in these activities, because it is expensive and the monetary returns are slower. Exploring new fields leads to much quicker rewards and is thus a more attractive option. After the primary and secondary phase, with still 50-70% of the oil remaining in the reservoir, one can choose to produce more oil in a tertiary recovery phase by injecting heat, chemicals and/or gases into the oilfields. These techniques are heaped together as enhanced oil recovery (EOR) of which carbon dioxide flooding (CO₂-EOR) is one of the most proven methods. When almost pure (at least 95%) carbon dioxide is injected into a depleted reservoir, it mixes with the oil, swells it and makes it lighter, resulting in the oil getting detached from rock surfaces. The oil can thus flow more freely within the reservoir, so that it can be collected. This all leads to a high oil recovery potential; best practices generally recover 5-15% of the
original oil in place (OOIP) using this method. Usually the carbon dioxide and water are separated from the oil when it reaches the surface, so that it can be re-injected for further EOR (CSLF Task Force, 2013; Melzer, 2012; Suebsiri, Wilsan, & Tontiwachwuthikul, 2006; Verma, 2015). Similarly, carbon dioxide can be used to extract natural gas from unmineable coal deposits, a method called enhanced coal-bed methane recovery (ECBM), or from gas fields, denoted enhanced gas recovery (EGR). These two “enhanced hydrocarbon recovery” options are not commercially available yet, and we therefore focus on the more mature enhanced oil recovery (Cuéllar-Franca & Azapagic, 2015; Hendriks, Noothout, Zakkour, & Cook, 2013). One should keep in mind, however, that the main objective of EOR is to maximise oil production and that the storage of CO₂ happens incidentally. Using EOR as a method to store anthropogenic CO₂ and mitigate climate change, would mean a complete shift in approach, posing new challenges on the stakeholders involved (Cooney, Littlefield, Marriott, & Skone, 2015; CSLF Task Force, 2013). An overview of CO₂-EOR is given in Figure 8 (PennEnergy, 2014).

The first large-scale testing of CO₂-EOR took place in the 1970’s in the Permian Base (Texas and New-Mexico, USA). The use of carbon dioxide flooding to enhance oil production has been increasing ever since and is today widely used in the USA and Canada. In Europe, this technique has not been installed (yet), but CO₂-EOR options in the North Sea are being
explored by SCCS (Scottish Carbon Capture and Storage) (Littlecott, Scott, & Haszeldine, 2014).

The injected CO$_2$ can originate from three different sources: (1) natural hydrocarbon gas reservoirs containing CO$_2$ as an impurity, (2) natural CO$_2$ reservoirs and (3) industrial or anthropogenic sources. In all three cases, the gas needs processing in order to bring the CO$_2$ concentration to the right level (90-98%) (Verma, 2015). The main source of CO$_2$ used today is naturally occurring CO$_2$, because of its low cost and wide availability (Cuéllar-Franca & Azapagic, 2015). Currently, about 45 Mt of naturally stored CO$_2$ is used annually for EOR or EGR. This results in higher total emissions than using CO$_2$ that was emitted anyway, e.g. by an industrial plant (Naims, 2016). Whether the oil and gas industry will make a switch to anthropogenic sources, will depend on the costs and the incentives to do so (Cuéllar-Franca & Azapagic, 2015).

Even though the monetary benefits of CO$_2$-EOR do not occur as quickly as gas/oil drilling and exploration, they are eventually continuous and substantial. CO$_2$-EOR leads to long-term returns; to prove this point, Melzer (2012) indicates that the first 1970’s CO$_2$ flooding projects (SACROC and Crossett, both in the Permian Base in Texas, USA) are still under operation today and produce nearly one million barrels of oil per year. Forty years after the reservoir was denoted as “depleted”, it still creates revenues, taxes and employment and stores carbon dioxide at the same time (Melzer, 2012). These economic benefits of enhanced oil recovery can offset some of the capture and storage costs, making this CCS option possibly cost-effective.

Several studies have been conducted to estimate the emissions associated with producing oil from anthropogenic CO$_2$. The results are often promising: EOR projects could store significant amounts of CO$_2$ and thereby reduce the greenhouse gas impacts of power generation and oil production. Nonetheless, most life cycle analyses do not consider the fact that, when the produced oil later is combusted for electricity production, it again results in emissions, decreasing the potential benefits on the environment significantly. If we do include all the lifecycle stages of CO$_2$, as has been done by Jaramillo et al. (2009), we can see that the net emissions are positive, meaning that eventually more CO$_2$ is emitted than stored in the reservoir. However, when comparing these emissions to current electricity production, the net emissions can be up to 60% lower (Jaramillo, Griffin, & McCoy, 2009). EOR might not be the most durable way of storing CO$_2$, but it is a way of producing electricity with lower
environmental impact and, moreover, could be a way to create confidence around storage of CO₂ in a cost-effective way. This could unblock the road to geological storage, which can effectively have an impact on climate change.

2.3.2.3 Mineral carbonation

In the third CCS option, CO₂ reacts with metal oxides (MO, M is a divalent metal), resulting in the formation carbonates and heat release (Cuéllar-Franca & Azapagic, 2015), according to the following chemical reaction (IPCC, 2005).

\[
\text{MO + CO}_2 \rightarrow \text{MCO}_3 + \text{heat}
\]

This is a natural process which permanently fixates CO₂ in a solid mineral phase (Martens et al., 2016). There is a difference between in-situ and ex-situ carbonation. The former is similar to geological storage, since CO₂ is injected into silicate-rich geological formations or alkaline aquifers, resulting in carbonates. The latter carbonates natural minerals or industrial residues, such as slag from steel production or fly ash, and requires an additional energy input. Ex-situ mineral carbonation can either lead to carbonates without economic value that need to be disposed, or to commercial products. This second ex-situ option will be discussed infra, in the section on carbon capture and utilisation (§2.3.3.4). Two unique features make mineral carbonation an attractive CO₂-capture option. First, metal bearing materials are available in abundance and second, carbon dioxide, once stored, virtually cannot escape the carbonate. This makes monitoring after storage, as is required for geological storage, unnecessary (IPCC, 2005).

Ex-situ mineral carbonation involves the above-ground carbonation of either natural minerals or industrial alkaline wastes. This can be achieved using industrial chemical processes, as seen in Figure 9. When using natural minerals such as olivine, wollastonite or serpentine (Sanna, Uibu, Caramanna, Kuusik, & Maroto-Valer, 2014), this process consists of a pre-treatment (mining, crushing and milling of rocks) and a sequestration process, the former resulting in a significant energy penalty (Gerdemann, O’Connor, Dahlin, Penner, & Rush, 2007). The end product is a relatively pure carbonate, which can be disposed of without environmental consequences. The most obvious location for this purpose is the mine site (IPCC, 2005). As can be seen in Figure 9, another option of ex-situ mineral carbonation is using industrial waste.
The availability at low costs near energy and industrial sites, the low degree of pre-treatment and less energy-intensive conditions make using solid industrial residues preferable over natural minerals (Olajire, 2013). Some carbonates can be turned into commercial products (e.g., construction products), which will be discussed in the segment on carbon capture and utilisation (section 2.3.3.4).

We will not discuss in-situ mineral carbonation in detail, because of its similarity to geological storage (see supra, §2.3.2.1) (Olajire, 2013). We would, however, like to refer to one recent success story: the CarbFix Project⁴ in Iceland. In this project, carbon dioxide of a geothermal power plant was injected into basaltic rocks of 400 and 800 metres deep. After two years, about 95% of the injected CO₂ had disappeared: it had reacted with the volcanic rock to form carbonate minerals, much faster than predicted and at a relatively low cost (17 USD/t CO₂)⁵. These results demonstrate that the safe long-term storage of anthropogenic CO₂ emissions

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⁴ Details can be found on https://www.or.is/carbfix-project.
⁵ This low cost is due to the fact that they don’t incur the capture costs.
through mineralisation can be far faster than previously stated. When the carbon dioxide was not separated from impurities like H2S, similar results were obtained, lowering the costs significantly (Matter et al., 2016). In other types of rock, such as sandstone, the carbonation reaction can take centuries, making basalt or ultramafic rock preferable. Moreover, on the earth’s surface very large basalt volumes are available. The Columbia River basalts in the USA alone have a total estimated capacity to sequester over 100 Gt of CO₂, about 1% of 2014’s global CO₂ emissions (Olajire, 2013).

![Figure 10 - Geological cross-section of the CarbFix injection site. Retrieved from Matter et al. (2016).](image-url)
2.3.3 Carbon Capture and Utilisation (CCU)

Recovery and utilisation of carbon dioxide has been around since long before climate change was public knowledge. Between 1869 and 1922, three major processes were developed: the synthesis of salicylic acid, the Solvay process, and the conversion of ammonia and CO\textsubscript{2} in urea (Aresta, Dibenedetto, & Angelini, 2013). Carbon capture and utilisation differs from carbon capture and storage in the destination of the captured CO\textsubscript{2}. Instead of transporting the CO\textsubscript{2} to a particular location for long-term storage, it is used as a raw material and transformed into value-added products and services (Cuéllar-Franca & Azapagic, 2015; Hendriks et al., 2013). This way, CO\textsubscript{2} emissions are reduced via two major effects: (1) a direct effect, through consuming CO\textsubscript{2} and thereby avoiding its release in the atmosphere and (2) an indirect effect, through substituting emission intensive products. The indirect effect may have a larger positive impact on the environment than the direct one (Bruhn et al., 2016; Zimmermann & Kant, 2015). Hence, carbon capture and utilisation has the potential to reduce both CO\textsubscript{2} emissions and fossil resource depletion, while creating commercial products and thus, business opportunities. This overall CO\textsubscript{2} emissions reduction potential is however limited by the market potential of these CO\textsubscript{2}-based products. Notable examples of industrial use of CO\textsubscript{2} include the production of urea (~70 Mt CO\textsubscript{2} per year), inorganic carbonates and pigments (~30 Mt CO\textsubscript{2} per year), methanol (~6 Mt CO\textsubscript{2} per year), salicylic acid (~20 kt CO\textsubscript{2} per year) and propylene carbonate (a few kt CO\textsubscript{2} per year) (Jajesniak, Eldin, Omar, & Wong, 2014). Moreover, since CO\textsubscript{2} is a relatively inert molecule, most of the current industrial uses of CO\textsubscript{2} are highly energy-intensive, requiring steep levels of energy (“The Carbon Challenge”) for capture and conversion (Jajesniak et al., 2014). If this necessary energy comes from fossil fuels, the whole process is counterproductive (X. Lim, 2015). It is thus important to look at the overall life cycle of a product (von der Assen, Voll, Peters, & Bardow, 2014). One must note that, compared to CCS, CCU does not allow for long-term storage of CO\textsubscript{2}. The CO\textsubscript{2} incorporated in the products will be emitted into the atmosphere after a certain time, depending on the product’s lifetime. This can be days or weeks (e.g. liquid fuels), years (e.g. polymers) or even decades to centuries (e.g. cement) (Bruhn et al., 2016). One thus cannot avoid that CO\textsubscript{2} is emitted into the atmosphere,
but producing products without emitting CO₂ and using CO₂ that would otherwise be emitted, will result in a net reduction. Figure 11 illustrates all emissions in the CCU process.

It is important to remember that carbon capture and utilisation will not be a total solution to the carbon dioxide problem, though it can make a substantial difference. If currently known processes were to be deployed in the most efficient way and at the greatest possible scale, they could directly use about 300 million tonnes of CO₂ per year, indirectly reducing CO₂ emissions by around one 1 Gt per year. This is about 5% of the total net emissions (X. Lim, 2015; Naims, 2016). CCU should be encouraged complementary to other mitigation technologies and can thus unfold its potential in creating local circular economy solutions (Naims, 2016). The potential of CCU on a regional level in Europe was published in a recent study. The results are mapped and can be found in Figure 12, where (a) presents the CO₂ availability and (b) the potential for the utilisation of CO₂, based on nine selected receiving processes (Patricio, Angelis-Dimakis, Castillo-Castillo, Kalmykova, & Rosado, 2017). The regions in North Rhine-Westphalia (Germany), the Antwerp Province and East Flanders (Belgium), Cataluña (Spain)
and Śląskie (Poland) are the most promising in terms of CO₂ availability and CO₂ potential. All these regions have significant industrial or port activities (Patricio et al., 2017).

Figure 12 - Map for matching (a) CO₂ availability and (b) potential for CO₂ utilization on a regional level. Retrieved from Patricio et al., (2017).
Naims (2016) draws up a table with the possibilities/applications for CO₂, divided into three categories: direct utilisation, materials and fuels (Naims, 2016). We added a fourth category to this division: splitting materials into chemicals and products from mineral carbonation. This results in the following sections: first, we will briefly discuss direct utilisation. Secondly, we will look at converting carbon dioxide into fuels, which can be achieved via a chemical or a microbiological pathway. Further, we will examine CO₂ to chemicals, which can be marketed as such or can be converted into products. And lastly, we will treat mineral carbonation – again – but now from a different perspective: the carbonation process is used to make CO₂-based products, such as construction materials. Our goal is to take a closer look at the different options that exist in each subdivision of carbon capture and utilisation, without entering into detail about the chemistry or biology behind the processes.

2.3.3.1 Direct Utilisation

The first CCU option is the direct utilisation of CO₂. Pure carbon dioxide is currently used directly in various applications. In the food industry, CO₂ is used to carbonate beverages and in food processing, preservation and packaging. Furthermore, CO₂ can be used to decaffeinate coffee: the most common method is to bathe the steamed coffee beans in compressed carbon dioxide, which then removes the caffeine without eliminating the flavour (Coffee Review, 2016; Global CCS Institute, 2011). For the food and beverages market, an extremely high purity level is required (Global CCS Institute, 2011; Naims, 2016). Some other direct application possibilities are the provision of CO₂ to greenhouses to maximise the plant growth rate, the use of CO₂ as a refrigerant gas in large industrial air conditioning and refrigeration systems, in fire extinguishers, dry fabric cleaning, etc. (Global CCS Institute, 2011; Styring, Jansen, de Coninck, Reith, & Armstrong, 2011). In the pharmaceutical industry, CO₂ can be used as a respiratory stimulant or as an intermediate in the synthesis of drugs. Most of these applications are restricted to sources producing CO₂ waste streams of high purity, such as ammonia production (Cuéllar-Franca & Azapagic, 2015). Moreover, the CO₂ sequestration capabilities of these markets are rather low (~11 Mt CO₂ for the food and beverage industry and ~6 Mt CO₂ as an industrial gas (Naims, 2016)), which explains why most literature does not even mention this category of CCU.
As a second CCU possibility, the conversion of CO\(_2\) to fuel is treated. We follow Centi and Perathoner (2009) and define three possible chemical methods to turn carbon dioxide into fuels. The first one, hydrogenation of CO\(_2\), is a method where two molecular actors, carbon dioxide and hydrogen (H\(_2\)) are brought together to produce large volumes of chemicals such as methanol, dimethyl ether (DME) and ethanol, which can all be used as fuels (Klankermayer & Leitner, 2015). The main concern for this method is the availability of hydrogen. H\(_2\) can be produced through water electrolysis, but this requires a lot of (renewable) energy, increasing the cost significantly (Centi & Perathoner, 2009). The average manufacturing cost of hydrogen, produced by alkaline water electrolysis and operated with wind power, corresponds to 5.22 €/kg (Otto, Grube, Schiebahn, & Stolten, 2015). Another possibility is to extract hydrogen gas from fossil fuels (1.22 €/kg (Otto et al., 2015)). To give an idea: the production cost of methanol using conventional fossil-based methods is today about 0.08 €/kg, whereas it can be produced at a cost of 0.3 €/kg in the best possible scenario using CO\(_2\) and water electrolysis (Aresta, Dibenedetto, & Angelini, 2014). One possibility is to produce hydrogen out of water using excess (renewable) electricity, outside the peak hours, as a way to “store energy”. The produced hydrogen can thus later be used to make new fuels or chemicals (Aresta et al., 2014), a process called power-to-liquid, in case of liquid fuels, or power-to-gas, in case of methane. In case of liquid fuels, DME is the first derivative of methanol, a fuel that has a high potential as alternative to conventional diesel and as a supplement to liquefied petroleum gas (LPG) (Pontzen, Liebner, Gronemann, Rothaemel, & Ahlers, 2011). Another fuel is ethanol, which has several advantages over methanol as a product of CO\(_2\) hydrogenation, mainly because of its safer handling and transport and its better compatibility to gasoline. Other hydrocarbon fuels can be produced using a hydrogenation reaction, but require a more intensive use of resources (energy, H\(_2\), more reaction steps, etc.) and are thus a less favourable option. Examples are hydrogenation to methane via a Sabatier reaction or the production of light alkanes (Centi & Perathoner, 2009). These will not be discussed in detail.

The second chemical method to convert CO\(_2\) to fuels is through a reaction with hydrocarbons. The most relevant reaction is the reforming of methane with carbon dioxide to produce syngas, a combination of H\(_2\) and carbon monoxide (CO). Syngas can then be used in a Fischer-Tropsch
reaction to produce synthetic fuels (hydrocarbons and alcohols). This process is called "dry reforming", and has the following reaction:

\[ \text{CO}_2 + \text{CH}_4 \rightarrow 2 \text{H}_2 + 2 \text{CO} \] (Martens et al., 2016)

On the one hand, this reaction has the advantage that two of the principal gases responsible for the greenhouse effect are used and thus, not released into the atmosphere. On the other hand, this is a strongly endothermic reaction, requiring temperatures above 700°C. Another disadvantage is that the catalysts (mostly based on nickel) can be deactivated by sintering and coking. Technologies to overcome this issue have been developed, but are not commercially available yet (Centi & Perathoner, 2009; Martens et al., 2016; Park, Chang, & Lee, 2004).

Photo- and electrochemical/catalytic conversion of CO\(_2\) is the last possibility, where the use of solar energy is used to directly or indirectly reduce carbon dioxide (Centi & Perathoner, 2009). Photochemical reduction of CO\(_2\) is a reproduction of nature’s photosynthesis process. Sunlight, water and CO\(_2\) are combined over a catalyst to reduce CO\(_2\) to CO and convert it into other interesting organic compounds. A barrier to this methodology is the efficiency of the catalyst necessary for the reaction vs. the cost of the materials used for synthesis, making large-scale application economically unviable for now (Hu, Guild, & Suib, 2013). In electrochemical valorisation of CO\(_2\), renewable electrical energy is supplied to establish a potential between two electrodes. This way, CO\(_2\) can be transformed into CO and value-added chemicals, such as methanol, under mild conditions (Albo, Alvarez-Guerra, Castano, & Irabien, 2015).

After years of extensive research, there are several companies that were able to chemically produce fuels from carbon dioxide. The current leader is without a doubt Carbon Recycling International (CRI)\(^6\), an Icelandic company producing methanol based on carbon dioxide and hydrogen, using geothermal energy to split water into hydrogen and oxygen. This methanol is then sold to the market, were it is used to blend with gasoline and to produce biodiesel. The CRI-plant releases 90% less CO\(_2\) compared to the production of the same amount of energy from fossil fuels and its annual production of methanol has mounted up to about 5 million litres. If larger volumes are used, the excess e-methanol will be exported to Europe (Carbon

\(^6\) More information on http://carbonrecycling.is/
Recycling International, 2016; Grahn, Taljegård, Ehnberg, & Karlsson, 2014; Martens et al., 2016). SunFire\textsuperscript{7}, a German company, was able to produce “e-diesel” in collaboration with Audi. This production process is similar to what we discussed and can be seen in Figure 13. The German Minister of Education and Research drove from Dresden to Berlin in her Audi powered by this CO\textsubscript{2}-based fuel in the Spring of 2015 to prove its effectiveness (Wetzel, 2015).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{power_to_liquids.png}
\caption{Power-to-liquids as executed by Sunfire GmbH. Renewable energy is used to produce hydrogen via water electrolysis. H\textsubscript{2} and CO\textsubscript{2} are then combined to produce syngas, which is later converted to fuels. Retrieved from Sunfire (2016).}
\end{figure}

2.3.3.2 Biological route

Biological carbon mitigation involves CO\textsubscript{2} uptake by living organisms, which can be photosynthetic or electrosynthetic. Photosynthetic microorganisms use solar energy to convert CO\textsubscript{2} into organic carbon, creating a significant amount of biomass (Cheah et al., 2016). These organisms already convert around 100 Gt of carbon into biomass annually, using highly sophisticated natural mechanisms for carbon fixation and utilisation. This resource has remained largely untapped and could potentially be a disruptive technology in CCU (Jajesniak et al., 2014). In the process of natural photosynthesis, terrestrial plants use solar energy to convert CO\textsubscript{2} and water to glucose molecules during their growth. This leads to biosequestration and massive biomass production at the same time. This biomass can later be fermented into various biofuels, such as bioethanol and biobutanol, or to other products. The solid residue is anaerobically digested, so that biogas (CO\textsubscript{2} and CH\textsubscript{4}) is produced (Cheah et al.,

\textsuperscript{7} More information on http://www.sunfire.de/en/applications/fu
Similarly, microalgae can be used to convert CO₂ into fuels. The interest towards this route is due to microalgae’s higher photosynthetic efficiency in converting CO₂, high biomass productivity and valuable fuel and non-fuel co-products. The photosynthetic efficiency⁸ of microalgae is in the range of 3-8%, whereas that of terrestrial plants is 0.5% on average. Microalgae can biologically fix CO₂ from flue gas, without having to separate it. This makes microalgal biorefineries potentially more economic. These microalgae can then serve as feedstock for the fermentation of CO₂ to biofuels, including biodiesel, fermentative bioethanol and biobutanol (Cheah et al., 2016). The cultivation of algae takes place in open-pond systems or in (semi-) closed bioreactors to which water, nutrients and CO₂ are supplied, which needs to be mixed continuously (Styring et al., 2011). Issues concerning biomass-based production are the requirements of arable land, water and nutrients. Furthermore, the primary production depends on photosynthesis, a CO₂ fixation method characterized by its relatively low energy efficiency (Verbeeck & Rabaey, 2014).

Harnessing the molecular mechanisms of non-photosynthetic organisms that can utilise CO₂ directly for the production of energy-dense liquid fuels (“electrofuels”) is an interesting pathway to study (Hawkins, McTernan, Lian, Kelly, & Adams, 2013). This field of research is called microbial electrosynthesis and addresses the use of microorganisms as catalysts in cathodes to achieve electricity driven synthesis of chemicals and fuels (Rabaey, Johnstone, Wise, Read, & Rozendal, 2010). Various carbon fixing microorganisms in different life forms can carry out the microbiological reduction of CO₂, using electrons derived from water as an abundant, inexpensive source of reductant (Cheah et al., 2016; Nevin, Woodard, & Franks, 2010). CO₂ and hydrogen, produced with renewable energy, is then fermented by microbes into alcohols, such as ethanol. These can later be blended with gasoline or serve as an energy source on their own (Irfan, 2012; Nevin et al., 2010; Wills, 2014). Microbial electrosynthesis differs significantly from photosynthesis; carbon and electron flow is directed primarily to the formation of multicarbon products, rather than to the production of biomass. Only one step is necessary, whereas after the photosynthetic biomass production, biomass still needs to be converted into biofuels, requiring extensive additional processing. When a photovoltaic system is used as an electricity source, microbial electrosynthesis operates indirectly under the

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⁸ Photosynthetic efficiency can be defined as the percentage of total available light that is converted into chemical energy. Retrieved from http://www.encyclo.co.uk/meaning-of-Photosynthetic%20efficiency.
influence of the sun; yet, this photovoltaic technology is much more effective in capturing solar energy than photosynthesis. Microbial electrosynthesis can thus also be seen as a biological way to store renewable energy (Nevin et al., 2010). The main challenges to this technology are (1) the microbial physiology, efficiency, specificity, and reaction rate and (2) the minimization of internal losses of the engineering and materials (Rosenbaum & Franks, 2014).

Lastly, CO₂ can be sequestered by anaerobic bacteria for metabolism under specific conditions. This process is enabled by the catalytic activity of certain enzymes that are present in anaerobic CO₂-sequestering organisms (e.g. Archaea). The end products of this anaerobic fermentation process are chemicals, such as alcohols and biogas, which can be used as fuels or as raw materials to other products. For these metabolism processes, the operational parameters (pressure, temperature, hydraulic retention time, etc.) are of extreme importance (Venkata Mohan, Modestra, Amulya, Butti, & Velvizhi, 2016). A commercial application of this anaerobic technology can be found in LanzaTech, a company founded in New-Zealand. They have discovered a microbe that ferments waste gas so that it can be converted into ethanol. Currently, it successfully operates two plants at steel mills in China, where commercial operation has begun in 2015. Ethanol produced this way, cuts the carbon footprint of petroleum gas by 60-80% (Wills, 2014).

2.3.3.3 CO₂ to Materials: Chemicals

Carbon dioxide can, as a third option, be utilised as a feedstock to chemically or biologically produce chemicals (Cuéllar-Franca & Azapagic, 2015). Both the basic chemistry and biology to produce these chemicals are similar to what we discussed supra (§2.3.3.2), which we therefore will not repeat. The conversion of CO₂ to materials is still limited to few applications on a modest scale, except for urea synthesis, accounting for approximately 130 Mt CO₂ per year. Aside from that, only a marginal amount of CO₂ is utilised to produce several speciality chemicals. The estimated demand for these chemicals varies between 115 Mt and 180 Mt CO₂ per year, depending on the source. To compare, the estimated large-scale potential for fuel production is approximately 2 Gt CO₂ per year (Naims, 2016).

Following Quadrelli et al. (2011), there are five general types of chemicals that can be produced chemically using CO₂. Other categorisations are of course possible as well. In this section, we did not include chemicals that can be used both as fuel and as commodity, such as methanol
and ethanol, as they have been discussed *supra* (§2.3.3.2.1). The first chemical of the categorisation of Quadrelli et al. (2011) is urea, the largest-volume industrial example of converting CO₂ into value-added products. Urea is used for fertilizers and polymer synthesis. Acrylates, lactones and carboxylic acids form the second group of possible chemicals. An example for this group is sodium acrylate, a key basic intermediate for the large market of polyacrylates, an absorbing material used in diapers. Third, monomeric carbonates are identified, for instance ethylene carbonate, used as organic solvent in pharmaceutical and cosmetic preparations, and as electrolyte in lithium-ion batteries. The production process using CO₂ is a less toxic route as well as reduces the CO₂ emissions sevenfold, compared to the conventional method based on glycol (Naims, 2016). Similarly, Asahi Kasei Chemicals produces around 660,000 tonnes of polycarbonates per year by replacing the toxic chemical phosgene with CO₂ (X. Lim, 2015; Ukuoka, Ojo, Achiya, Minaka, & Asegawa, 2007). Fourth, isocyanates can be synthesised from an amine and CO₂ using certain catalysts. And last, many functional polymers can incorporate CO₂. An industrial application of CO₂ to polymers is polyether carbonate polyols (PPP) (Quadrelli, Centi, Duplan, & Perathoner, 2011). PPP could substitute conventional polyether polyols, of which the global production was 8 Mt per year in 2012. These CO₂-based polyols have a reducing impact on global warming of 11-19% and on fossil resource depletion of 13-16% (von der Assen et al., 2014). The estimated market and near-term market potential for different types of chemicals can be seen in Table 2, based on Naims (2016). According to Otto et al. (2015), formic acid, oxalic acid and formaldehyde are the most interesting bulk chemicals (polymers and fuels are not considered) to produce. Their reactions represent useful CO₂ utilisation options with high potential for future technical, ecological and economic analysis (Otto et al., 2015).

**Table 2 - Current and estimated near-term markets of CO₂ utilisation. Retrieved and adapted from Naims (2016).**

<table>
<thead>
<tr>
<th>Product/application</th>
<th>Current est. volumes</th>
<th>Near-term est. volumes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO₂</td>
<td>Product CO₂</td>
</tr>
<tr>
<td>Materials: chemicals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urea</td>
<td>117515</td>
<td>142400</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>114000</td>
<td>155000</td>
</tr>
<tr>
<td>PC (polycarbonates)</td>
<td>3500</td>
<td>21000</td>
</tr>
<tr>
<td>Carbonates</td>
<td>10</td>
<td>4000</td>
</tr>
<tr>
<td>Acrylates</td>
<td>5</td>
<td>200</td>
</tr>
<tr>
<td>Carbamates</td>
<td>0</td>
<td>5300</td>
</tr>
<tr>
<td>Formic acid</td>
<td>0</td>
<td>600</td>
</tr>
<tr>
<td>PUR (polyurethanes)</td>
<td>0</td>
<td>8000</td>
</tr>
</tbody>
</table>
Because of the multitude of CO₂-utilizing microorganisms available, the ability to genetically modify microorganisms and the use of protein engineering, there is an array of biological CO₂-based products. Aside from the biofuels and bioalcohols treated supra (§2.3.3.2.2), some bacteria are capable of producing bioplastics and other products, such as complex biopolymers (e.g. proteins). For instance, CO₂ can be reduced biologically to form PHB, a thermoplastic with thermal and mechanical properties comparable to those of petrochemically-derived polypropylene (Jajesniak et al., 2014).

2.3.3.4 CO₂ to Materials via mineral carbonation

Aside from just storing CO₂, ex-situ mineral carbonation can, as a fourth CCU technology, use carbon dioxide for the production of materials, mostly in combination with industrial residues. The carbonation reaction and general information is the same as explained supra (§2.3.2.3). Steel and blast furnace slags, cement kiln dust and waste cement, fly ashes, municipal waste incineration ash, mining wastes and asbestos are all examples of industrial residues rich in magnesium or calcium. These left-overs have a CO₂ fixation potential and can be turned into commercial products when reacting with CO₂. An illustration is the production of cement and building materials out of stainless steel slag (Quadrelli et al., 2011; Van Driessche, 2015), as is done by Carbstone Innovation NV⁹, a Belgium-based company. The storage capacity of these applications is limited (Mt) when compared to the amount of CO₂ to be stored (Gt/year) (Gerdemann et al., 2007) and the technologies still need to demonstrate commercial viability on a large scale, but can be interesting for nations like Belgium, that lack geological storage (Sanna et al., 2014). One problem is that the costs of producing these products is still higher than producing similar products in the conventional way. As for the industrial residue carbonation, steelmaking slag is a good option to carbonate. Even though still expensive (77 €/t CO₂ avoided), the maximum CO₂ storage capacity is 0.40 kg CO₂/kg slag on average and CO₂ improves the characteristics of the slag (Bobicki, Liu, Xu, & Zeng, 2012; Sanna et al., 2014). Waste cement and CKD storage capacities are somewhat lower, respectively 0.20 and 0.24 kg CO₂/kg slag on average and costs are about 136-323 USD per tonne CaCO₃ produced.

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⁹ More information on Carbstone Innovation NV on https://www.carbstoneinnovation.be/
Another good performer is oil shale (OS) ash, with a large storage capacity (0.46 kg CO$_2$/kg OS ash) (Bobicki et al., 2012). More industrial residue possibilities are discussed elaborately in Sanna et al. (2014), Bobicki et al. (2012) and Lim et al. (2010), for instance precipitated calcium carbonate (PCC), used in the production of paper, paint, rubber and plastics (M. Lim, Han, Ahn, & You, 2010). This last method had a net global warming potential (GWP) value of -0.3 tonne CO$_2$ equivalent per tonne calcium carbonate produced (Teir, Kotiranta, Pakarinen, & Mattila, 2016).

2.4 CONCLUDING REMARKS

This literature study started with the effects of carbon dioxide on the environment and the international interventions that are currently present to combat climate change. Because not all carbon dioxide can be avoided, there is a need to prevent these emissions from reaching the atmosphere. The literature research is therefore continued by an explanation of the currently existing carbon capture technologies to mitigate climate change. After expanding on the general capture aspect, three CCS and four CCU categories are discussed extensively.

In relation to CCS/CCU technologies, some conclusions can be drawn from this literature review. First, we can conclude that there are many possibilities to store and utilise carbon dioxide, something that was not too long ago – especially for CCU – considered as ludicrous. Second, carbon capture technologies, even though promising, will not have the magnitude of impact on climate change that we need: the annual amount of carbon dioxide emissions are simply too large for storage or to meet the demand of CO$_2$-based products. CCS/CCU technologies should therefore become part of a portfolio of climate change mitigation options. Third, from the literature it was clear that we are in an interesting era for carbon capture. Even though the idea of storing CO$_2$ has been around for decades, it has only been researched thoroughly during the last fifteen years. CCU is an even more recent research topic: as the reader may have noticed, most of the papers on carbon capture and utilisation employed supra (§2.3.3) were published in 2012 or later. Therefore, the majority of the available literature consists of scientific publications that deal with technical specificities, generally without paying much attention to the CO$_2$ reduction potential or potential profitability of these processes. Furthermore, attempts to quantify the potential net benefits (e.g. by means of an LCA) for CCU are still limited, and most of them are based on context-specific and thus potentially unrepresentative case studies (Hendriks et al., 2013). And lastly, interest for CCS/CCU has
grown in the last couple of years. Nonetheless, to this date, there are only a few large-scale projects in operation. What the hurdles are that prevent this from happening, could not be deduced from the studying existing literature. Therefore, the hurdles and drivers to the upscaling of CCS/CCU technologies will be the subject of the remainder of this study.
3 OBJECTIVES

The objective of this master’s dissertation is twofold:

1. To detect why industrial actors have not yet applied carbon capture and storage or carbon capture and utilisation technologies on a large scale (hurdles) and which actions could change the current situation (drivers).
2. To evaluate the effectiveness of possible economic incentives that can stimulate the upscaling of the CCS and CCU technologies in industry.

To achieve the first part of the objective, a qualitative analysis is performed. This qualitative analysis is carried out in the context of a theoretical framework, the multi-level perspective (MLP), which looks at technology in its context and emphasises the co-evolution of society and technology. To find the hurdles and drivers (or, lock-in mechanisms and sociotechnical regime cracks, as they are called in the MLP) for the technology niches of CCS and CCU, four in-depth interviews with experts from industry are conducted. Each interviewee is currently employed in a function that is closely related to the topic of CCS/CCU and works in a different, though highly emitting sector. The idea of capturing CO₂ emissions has appealed to these companies for several years, but no large-scale investments have been made (yet). The interviews were directed at finding the hurdles and drivers that are considered in their decision-making process.

To reach the second part of the objective, the qualitative analysis is followed by a quantitative analysis. Here, four possible economic incentives to stimulate the upscaling of CCS and CCU technologies are evaluated. The first incentive is related to the price of fossil resources, and the other three are market-based policy instruments of the European Union. Due to a lack of data, our methods to assess the effectiveness of these economic incentives are restricted to an application of relevant literature and simplified calculations. The methods do however prove to be valuable in providing a better insight.
4 MATERIALS AND METHODS

4.1 QUALITATIVE ANALYSIS

For the qualitative analysis, we made use of the multi-level perspective (MLP), a theory on how society changes and develops. It looks at technology in its context and emphasises the co-evolution of technology and society. It therefore uses insights from evolutionary economics, sociology of technology, history of technology and innovation studies to provide a perspective on system innovations. Because the methods used in the qualitative analysis are based on the MLP, we will explain the essentials of this theory here and link it to CCS/CCU. A schematic illustration of the MLP, in which we highlighted the most important parts for our case, can be found in Figure 14.

The MLP has three analytical and heuristic levels to understand system innovations. First, at the micro-level, there are technological niches where radical innovations emerge, which initially act as unstable sociotechnical configurations with low performance and high costs. These niches are incubation rooms, protecting the innovations against mainstream market selection; they are carried and developed by small networks of dedicated actors, often outsiders or fringe actors. Niches are important, because they provide locations for learning processes, which occur at many dimensions: technology, user preferences, regulation, symbolic meaning, infrastructure, and production systems, until they are developed enough to challenge the current regime (Geels, 2005; Geels & Schot, 2007). We see CCS/CCU and other renewable, low-carbon technologies as technological niches in the transition towards low-carbon industry. The most promising technologies in the CCS niche and CCU niche were treated in the literature review supra (§2.3) and are listed here in Table 3.

<table>
<thead>
<tr>
<th>Niche CCS</th>
<th>Niche CCU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological storage (§2.3.2.1)</td>
<td>CO₂ to fuels (§2.3.3.2)</td>
</tr>
<tr>
<td>Enhanced Oil Recovery (§2.3.2.2)</td>
<td>CO₂ to chemicals (§2.3.3.3)</td>
</tr>
<tr>
<td>Mineral carbonation (§2.3.2.3)</td>
<td>Mineral carbonation (§2.3.3.4)</td>
</tr>
</tbody>
</table>
Second, the sociotechnical landscape at the macro-level refers to the aspects of the wider exogeneous environment, which is beyond the direct influence of niche and regime actors (macro-economics, deep cultural patterns, macro-political developments), but do affect sociotechnical development. The changes at the landscape level usually take place slowly through an interaction of stabilising and destabilising landscape pressures (Geels, 2005, 2012; Geels & Schot, 2007). In our context, destabilising landscape pressures come from the concerns surrounding climate change: global warming is a real threat to our planet’s wellbeing.
and everything that lives on it. Moreover, industry is generally seen as a scapegoat for this problem, which pushes it to look for solutions to improve its image and become more future-oriented. This opens up so-called “windows of opportunities”. Conversely, stabilising pressures, such as our fossil-dependent energy system and the fact the societal thinking is permeated by short-termism, slow this change down.

Lastly, sociotechnical regimes form the meso-level in the MLP, which consist of three interlinked dimensions: (1) network of actors and social groups, (2) formal, normative and cognitive rules that guide the activities of actors, and (3) material and technical elements. The existing socio-technical regimes are characterised by stabilising lock-in mechanisms on all three dimensions, which result in path dependencies and preserving the status quo. The only innovation that still occurs is of an incremental nature. Cracks in the regimes can make them weaker over time (Geels, 2005, 2012; Geels & Schot, 2007). It is these lock-in mechanisms and cracks in the sociotechnical regime that will serve as our focus in the qualitative analysis. We will further refer to them as hurdles and drivers, respectively. Before the interviews, we identified some of these hurdles and drivers for the niche of CCS/CCU to use as an interview-guide. These were inspired by Kemp, Schot, & Hoogma (1998) and can be found in Table 4.

Table 4 - Cracks and lock-ins for the niche of CCS/CCU in the current sociotechnical regime.

<table>
<thead>
<tr>
<th>Cracks/drivers</th>
<th>Lock-ins/hurdles</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU legislation</td>
<td>EU legislation</td>
</tr>
<tr>
<td>Image</td>
<td>CAPEX</td>
</tr>
<tr>
<td>Corporate social responsibility</td>
<td>OPEX</td>
</tr>
<tr>
<td>Climate pressure</td>
<td>Outside core business</td>
</tr>
<tr>
<td>Governmental grants</td>
<td>Technological operations</td>
</tr>
<tr>
<td>Competitive advantage</td>
<td>Distribution of product</td>
</tr>
<tr>
<td>New source of revenue</td>
<td>Market uncertainty</td>
</tr>
<tr>
<td></td>
<td>Scepticism</td>
</tr>
</tbody>
</table>

In the current sociotechnical regime, industrial actors and most of our energy providers emit large amounts of greenhouse gases into the atmosphere. This is proven by scientists, who try to find new technologies to solve these issues. Most actors in the regime (industry, policymakers, households) are aware of this situation but due to the intangibility of its effects, a transition to a low-carbon industry is not at the top of their problem rankings. Even though policymakers claim it to be, they contradict themselves by e.g. granting more subsidies to fossil energy than to mitigation technologies (OECD, 2015) and other inconsistencies, damaging
their credibility. Industry is more focused on competition and continuity of its activities, and its existing infrastructure supports GHG emissions. Only a few people think about what the consequences are of the products they consume: user preferences are hard to change. The status quo of our fossil-based culture is preserved because nobody takes responsibility.

The MLP argues that system innovations or transitions happen through the interplay between dynamics at micro-, macro- and meso-level, and defines four transition phases.

- In the first phase, or niche development phase, innovations emerge in niches in the context of the existing regime and landscape developments.
- Next, in the learning and probing phase, the innovation is used in market niches, which provides resources for technical specialisation. A dedicated community of engineers and producers collectively directs its activities to the improvement of the new technology. Because of these learning processes, the new technology gradually improves.
- The third phase is characterised by the breakthrough of the new technology, resulting in wide diffusion and competition with the current regime. This breakthrough emerges because of both internal and external drivers. Internal drivers are e.g. price/performance improvements and external drivers can be e.g. pressure from changes at the landscape level, or technical problems in the regime, which cannot be met with the currently available technology.
- In the fourth and last phase, the final transition takes place, and the new low-carbon technologies break through and are added to the old regime, which is then accompanied by changes on wider dimensions of the sociotechnical regime (Geels, 2005; Geels & Schot, 2007).

Following the reasoning of the MLP, we are currently in the learning and probing phase in the transition towards low-carbon industry. As the landscape is changing, both literally and figuratively speaking, a group of dedicated actors is working on more sustainable technologies that will be part of the low-carbon industry system of tomorrow. One of these technology pools is the niche of CCS/CCU. What we want to achieve in this qualitative analysis, is to understand why industrial actors have not yet applied technologies of the CCS and CCU niches on a large scale and what can change this situation. So, we want to find the lock-in mechanisms (“hurdles”) and cracks (“drivers”) in the sociotechnical regime for upscaling investments in
technologies in the CCS and CCU niches, according to one of the most important actors in the sociotechnical regime: industry. This way, we can find methods to overcome the hurdles or reinforce the drivers, so that this niche, next to other renewable technologies, can break through to accelerate the transition process.

We therefore conducted in-depth interviews about CCS/CCU technologies with industry. In total, five interviews with people who work close to the topic of CCS/CCU were interviewed, all representing a different company in a highly-emitting industry within the most promising regions for both CO₂ availability and potential for utilisation, according to Patricio et al., (2017). We ensured that each company would have a different point of view on CCS/CCU.

The interviews started with general open questions on which technologies in the CCS and CCU niches (Table 3) these regime-actors are most interested in and what they experience as the largest hurdles and drivers to invest in these technologies. We referred to the drivers and hurdles that were already defined beforehand in Table 4, but of course, other drivers or hurdles could be brought up as well. To respect confidentiality, the company names were not included in this study, with the exception of the Port of Antwerp. The interviewees are (1) a representative of the technology development department of a steel company, (2) an engineer of the research and technology department of a company in the energy sector, (3) two representatives of the R&D department from a chemical company, and (4) a manager in the energy development department in the Port of Antwerp.

4.2 QUANTITATIVE ANALYSIS

The quantitative analysis is based on the results from the qualitative analysis: the possible economic incentives that were mentioned by the interviewees are scrutinised for their effectiveness. We investigate (1) an increase in the oil price and three market-based policy instruments of the European Union: (2) an increase in the price of allowances in EU-ETS, (3) the impact of subsidies in the EU and (4) the effect of taxation to influence buying behaviour. Table 5, which shows the current price of the fossil products and the required price to offset the costs to produce the CCU-product, is used as basis for several of the analyses. These types of data are at the moment of this study only available for a limited number of products. We are
therefore limited to five products, for which this data was obtained: methanol, ethanol, formic acid, methane and urea.

Table 5 - Comparison between the market price of the product and the required price to offset the costs for CCU. Retrieved from Pérez-Fortes & Tzimas (2016) unless stated otherwise.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>€ 513.84</td>
<td>€ 1 034.00</td>
</tr>
<tr>
<td>Formic Acid</td>
<td>€ 650.00</td>
<td>€ 1 600.00</td>
</tr>
<tr>
<td>Methanol</td>
<td>€ 350.00</td>
<td>€ 1 400.00</td>
</tr>
<tr>
<td>Methane</td>
<td>€ 4.61 $\times 10^3$</td>
<td>€ 9.79 $\times 10^3$</td>
</tr>
<tr>
<td>Urea</td>
<td>€ 245.00</td>
<td>€ 1 600.00</td>
</tr>
</tbody>
</table>

*a Based on the futures price of ethanol of December 9th, 2016 ($1.65/gallon) and converted to €/tonne (Nasdaq, 2016).
*b Based on El Fouih & Bouallou (2013).
*c Based on the European Union Natural Gas Import Price of December 9th, 2016 (World Bank, 2016a). Expressed in €/m³.
*d Based on the LCOS in a power-to-methane scenario in Chiuta et al. (2016). Expressed in €/m³.

First, we take a closer look at the price of fossil resources in relation to CCU by calculating how much the oil price needs to increase to close the price gap between fossil chemicals and their CO₂-based counterpart (Table 5). The calculations are conducted as follows: the Open LCA software determines the mass of oil and the volume of natural gas required to produce one tonne (or MMBtu in the case of methane) of fossil product over its life cycle. We multiply the mass of oil with the current oil price and the volume of gas with the current natural gas price$^{12}$. Adding up these two prices for each product gives us the relative contribution of fossils in the total price of the product. Next, the difference in the required price for CO₂-based products to become cost-effective and the current market price of the incumbent fossil products is calculated. This price difference is further added up with the fossil price, resulting in the required fossil price for the CO₂ products to become cost-effective. On the assumption that the fraction of oil in the price remains the same and that all other costs (e.g. labour) remain the same (*ceteris paribus*), the required oil and natural gas price for the different products considered can be calculated. We here display the required oil prices and compare these prices subsequently with the current oil price.

In the second part of the quantitative analysis, three market-based policy instruments are evaluated. First, the impact of an increase in the price of EU allowances (EUAs) in EU-ETS is

---

$^{10}$ MMBtu = million British Thermal Units (BTU), a measure for energy content in fuel.
$^{11}$ LCOS = levelised cost of syngas production
$^{12}$ We used the oil and natural gas price and the USD-EUR exchange rate of December 9th, 2016.
evaluated for a CCS, CCU and business as usual (BAU) scenario. To do so, the example of the cost increase to produce one tonne of steel is taken. The necessary data can be found in Table 6.

### Table 6 - Data used for the analysis of the EUA price in EU-ETS.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average CO₂ emissions for 1 tonne steel</td>
<td>1.8 tonne CO₂&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Capture rate of a steel plant (ω)</td>
<td>50%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Capture cost of a steel plant</td>
<td>€ 40/tonne CO₂&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Retrieved from the interview with a representative of the steel industry

<sup>b</sup> Retrieved from Naims (2016), see Table 1 in §2.3.1

We decide not to implement other costs than the capture cost because of two reasons: (1) literature provides rather conflicting data on costs other than capture costs in the CCS/CCU supply chain, and (2) this way we can keep a clear view on the comparison between the different scenarios. Several equations are drawn up, in which the EUA price in EU-ETS is the independent variable, varying from 0 to 100 €/t CO₂ and the cost increase for different scenarios is the dependent variable. The capture rate (ω) is the fraction of CO₂ that can physically be captured at a steel plant.

\[
ETS \text{ cost per tonne steel} = 1.8 \text{ tonne CO}_2 \times \text{ price EUA}
\]
\[
Capture \text{ cost per tonne steel} = 1.8 \text{ tonne CO}_2 \times \omega \times \text{ capture cost}
\]

\[
\text{Cost increase (CCS)} = \text{ capture cost per tonne steel} + (1 - \omega) \times ETS \text{ cost per tonne steel}
\]
\[
\text{Cost increase (CCU)} = \text{ capture cost per tonne steel} + ETS \text{ cost per tonne steel}
\]
\[
\text{Cost increase (BAU)} = ETS \text{ cost per tonne steel}
\]

For CCU, we here make the assumption that the production costs of a CO₂-based product equal its benefits, so the only difference between CCS and CCU is the price of EUAs. The results of these equations are then presented graphically and the three scenarios (CCS, CCU and BAU) are compared for different levels of the EUA prices in EU-ETS.

As a second policy instrument, we evaluate the possibility of granting subsidies to stimulate the learning effect and thus a decrease in the costs of CCS/CCU technologies. We start by discussing existing literature on this topic: Lieberman (1984) provides relevant insights on the learning curve, R&D and cost decrease of new technologies in the chemical sector. Based on the author's findings, we draw up a graph of the possible price reduction of CCU methanol over
time, based on a normal price decrease (5.5\%\textsuperscript{13}), and accelerated price decrease (factor \(\alpha\)), according to the following exponential equation. Here, time \((t)\) is the independent variable and ranges from 0 to 20 years:

\[
p_t = p_0 \times (1 - \alpha \times 0.055)^t
\]

\(p_t\) = price of methanol at time \(t\)
\(\alpha\) = acceleration of price decrease due to extra R&D expenditures

Lieberman’s findings can further relate to subsidies, and thus, the analysis continues by researching which possibilities for subsidies in sustainable technologies are already incorporated in different funding mechanisms of the European Commission and to what extent the topic of CCS and CCU is taken into account to this date. Next, we consider the example of the White Rose project to emphasise the impact government subsidies can have on the behaviour of external investors and how this impact can be used as a leverage to attract more financing.

The last section of the market-based policy instruments treats environmental taxation to change people’s buying behaviour. Here we take a closer look at a tax on carbon dioxide, incorporated in the price of a product. The more \(\text{CO}_2\) emitted during the production process, the higher the price of the product will be. The example of methanol displays graphically how large this carbon tax needs to be to bridge the price gap between fossil- and \(\text{CO}_2\)-based methanol. The data used for this analysis is shown in Table 7 and was retrieved from Garcia-Gonzalez et al., (2016) and Pérez-Fortes & Tzimas (2016). The following assumptions are made in these studies: fossil methanol is produced from natural gas and CCU methanol is produced through hydrogenation of \(\text{CO}_2\). Only renewable energy is used to produce the electricity required for the production process and natural gas is used for the production of the necessary thermal energy. Renewable energy and utilising \(\text{CO}_2\) results in negative \(\text{CO}_2\) emissions.

\textsuperscript{13} This seems like a rather optimistic number and might not be representative anymore, as its source dates from the 1980’s.
Table 7 - Data used for the environmental taxation analysis

<table>
<thead>
<tr>
<th></th>
<th>CCU methanol</th>
<th>Fossil methanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tonne CO₂-equivalents/tonne methanol a</td>
<td>-1.14</td>
<td>1.2</td>
</tr>
<tr>
<td>price methanol [EUR/tonne] b</td>
<td>€ 1400</td>
<td>€ 350</td>
</tr>
</tbody>
</table>

a Retrieved from Garcia-Gonzalez et al. (2016)
b Retrieved from Pérez-Fortes & Tzimas (2016)

We calculated the price of methanol (dependent variable) for different levels of the carbon tax (independent variable). First, for fossil methanol, we both included (1) and excluded (2) this carbon tax. Next, for CCU methanol, two scenarios were considered: either negative emissions result in negative costs (3), or negative emissions just result in not having to pay the carbon tax, but don’t lead to negative costs (4). This is shown by the following equations:

\[
\text{price fossil methanol} = \text{current price fossil methanol} + 1.2 \times \text{carbon tax} \quad (1)
\]

\[
\text{price CCU methanol} = \text{required price CCU methanol} - 1.14 \times \text{carbon tax} \quad (3)
\]

The equations of (2) and (4) are simply (1) and (3) with a carbon tax equal to zero, and are just constants. By equalising the right members of (1) and (3) we can determine at what level of the carbon tax the gap between the price of fossil and CCU methanol is bridged for the current required price of CCU methanol. A similar approach can be followed for (1) and (4).

\[
(1) = (3) \Rightarrow \text{carbon tax} = \frac{\text{required price CCU methanol} - \text{current price fossil methanol}}{1.2 + 1.14}
\]

\[
(1) = (4) \Rightarrow \text{carbon tax} = \frac{\text{required price CCU methanol} - \text{current price fossil methanol}}{1.2}
\]
5 RESULTS AND DISCUSSION

5.1 QUALITATIVE ANALYSIS

The results of the in-depth interviews are presented per industry. First, the current more general situation (“landscape”) of the company is explained. Second, the results of the interviews are summarised and finally, we formulate which hurdles (lock-ins) and drivers (cracks) appear to be the most significant to prevent, or facilitate investments in the different CCS/CCU projects.

5.1.1 The steel industry

Due to the energy intensity of steel production, its reliance on carbon-based fuels and reductants and the large volume of steel produced (1.6 Mt in 2015 (Worldsteel, 2016)), the iron and steel industry is the largest industrial\textsuperscript{14} source of CO\textsubscript{2} emissions (Carpenter, 2012). In the past thirty years, significant CO\textsubscript{2} reductions were achieved by minimising energy consumption and improving energy efficiency by applying best available technology (BAT). This strategy has a limit with some emission reduction potential left in the electrification of energy (Carpenter, 2012). Producing steel has the inconvenient but unavoidable by-product of carbon dioxide. This means that, when a steel company is not allowed to emit carbon dioxide, it must either make sure that the produced CO\textsubscript{2} does not reach the atmosphere (by storing or reusing it) or to not produce any steel at all. Globally, the steel sector is responsible for 30% of industrial CO\textsubscript{2} and for 6.7% of anthropogenic CO\textsubscript{2}.

To this day, European steel manufacturers have been able to reduce the CO\textsubscript{2} emissions to an all-time low of 1.8 tonne CO\textsubscript{2} for each tonne of steel produced, by e.g. reusing steel scrap, which is infinitely recyclable. China is currently the world leader in steel production and was able to quadruple its production in the period 2001-2011 (European Commission, 2013). However, in

\textsuperscript{14} When talking about the industrial CO\textsubscript{2} emissions, the energy sector is generally not taken into account.
China this secondary steel production is not yet in place and CO₂ emissions mount up to about 4 tonnes of CO₂ for each tonne of steel.

European steel manufacturers risk to be penalised for CO₂ emissions. This could lead them to leave Europe for countries where government regulations are milder. However, even though this would lower the carbon dioxide emissions in Europe significantly, it would result in a global increase of emissions, a situation referred to as “carbon leakage”¹⁵. Moreover, the European steel industry employs about 360 thousand people, so the social consequences for the European member states that would accompany an exit of the European steel manufacturing would be devastating (European Commission, 2013). Recently, thousands of people in United Kingdom steel industry have lost their jobs this way (Bowler, 2016).

The interview with a representative of the steel industry took place in April 2016. The results of this interview are summarised in Table 8. Note that we added the option “stop production of CO₂ (in Europe)”.

<table>
<thead>
<tr>
<th>STEEL</th>
<th>Hurdle/Lock-in mechanism</th>
<th>Driver/cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop production of CO₂ (in Europe)</td>
<td>- Technologically impossible to stop producing CO₂</td>
<td>- No subsidies for CO₂-mitigating projects</td>
</tr>
<tr>
<td></td>
<td>- Other regions are currently less attractive (political instability, corruption, ...)</td>
<td>- Expectation of high EUA price</td>
</tr>
<tr>
<td></td>
<td>- Social implications</td>
<td></td>
</tr>
<tr>
<td>CCS NICHE</td>
<td>Storage underground</td>
<td>- Carbon deposit problem (technological issues)</td>
</tr>
<tr>
<td></td>
<td>EOR</td>
<td>- Public perception/scepticism</td>
</tr>
<tr>
<td></td>
<td>Mineral carbonation</td>
<td>- Investment is too risky*</td>
</tr>
<tr>
<td>CCU NICHE</td>
<td>Fuels</td>
<td>- (m)ethanol not recognised as renewable fuel (RED)*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- OPEX*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Low oil price – conventional methods to make products are cheaper*</td>
</tr>
<tr>
<td></td>
<td>Chemicals</td>
<td>- Low oil price – conventional methods to make products are cheaper*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- OPEX*</td>
</tr>
<tr>
<td></td>
<td>Mineral carbonation</td>
<td>- Low oil price*</td>
</tr>
</tbody>
</table>

An asterisk (*) was used to denote an economic hurdle/driver. Abbreviations are explained in the abbreviations overview.

¹⁵ “Carbon leakage refers to the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints. This could lead to an increase in their total emissions. The risk of carbon leakage may be higher in certain energy-intensive industries.” (European Commission, 2016a)
This steel company has been considering most of the technologies in the CCS and CCU niches since 2004. As can be seen in Table 8, every technology has drivers and hurdles. We denoted the economic ones with an asterisk (*). Before 2012, the steel company was interested in the CCS niche, but eventually decided not to invest in CCS, mainly because of technological issues and the difficulty concerning public acceptance. This company expects that storage of CO$_2$ will be necessary to mitigate climate change, but decided not to make the enormous investments themselves: in their opinion, policymakers should take on this responsibility by creating a public pipeline in which everyone can emit its CO$_2$, in a way that it can be stored underground. Different technologies in the CCU niche are still under consideration, although the largest interest goes to biologically converting a combination of CO and CO$_2$ to ethanol through the LanzaTech process. This technology is proven feasible and currently operational at a Chinese steel company (§2.3.3.2.2). The main issue with this project is the fact that the produced ethanol does not conform to all the conditions in the renewable energy directive (RED) to be labelled as a renewable fuel. One of these conditions is, for instance, that the energy for the installation needs to be fully obtained from renewable energy sources (Guarantee of Origin (GO)). This is not the case, as the company is connected to the grid and for example, residue warmth from the steel plant would be used to produce ethanol. Without this “renewable” label, it is not possible to ask a premium price for the CO$_2$-based fuel, resulting in a disappointing business case and making it extremely hard, if not impossible, to convince both the higher management and potential investors. The produced ethanol would thus have to compete with the fossil-based equivalent, even though the costs of producing the product are multiplicatively higher. The fact that the production of one tonne ethanol would save CO$_2$ emissions, is not considered. Other options, such as chemical conversion to fuels and chemicals and mineral carbonation in the cement industry are being explored and negotiated. But the same hurdle remains: the conventional methods to produce these commodities are much more cost-efficient than the CO$_2$-based counterpart. Thus, again, without a premium price or governmental interference, there is no way emitting companies will make the investment.

The company’s long-term vision is as follows: if all plans are worked out to their full potential, some 30% of its CO$_2$ emissions can be converted into products. The remaining 70% should be removed in a storage pipeline provided by the government.
5.1.2 The energy industry

The energy industry is accountable for about 60% of global anthropogenic carbon dioxide emissions, due to fuel (coal, oil or natural gas) combustion, which provided 82% of the global energy supply in 2013. To produce the same amount of energy, coal is almost twice as polluting as natural gas, and the emissions of oil combustion can be found somewhere in-between these two (IEA, 2015).

In contrast with the steel sector, the energy sector has a plethora of possibilities to generate power that do not lead to the emission of carbon dioxide: wind, solar, hydro, geothermal and nuclear power are all proven technologies that generate energy without the release of greenhouse gases. The situation of the energy sector is thus completely different from the steel and cement industry, for which the technologies in the CCS and CCU niche are in fact the only possibility they have to avoid CO₂ emission into the atmosphere.

![Growth chart](image)

Figure 15 - Global new investment in renewable energy by asset class. Retrieved from McCrone et al. (2016).

Production of renewable energy is growing swiftly, as can be seen in Figure 15. In 2015, a record amount of funds (285.9 billion USD) was committed to renewables, exceeding the previous record of 2011 (McCrone et al., 2016). As the investments in renewables are going up, the costs
are going down. For instance, the cost of a typical photovoltaic (PV) rooftop system in Germany decreased by 90% in the last 25 years (Fraunhofer ISE, 2016).

Nevertheless, because of the current oil price (about $45/bbl in November 2016 compared to $100/bbl. in 2014 (Bloomberg L.P., 2016)), it is still cheaper to produce fossil-based energy. A comparison of the Levelised Costs of Electricity (LCOE)\textsuperscript{16} for different energy sources can be found in Figure 16. This figure indicates that coal is still the cheapest method of producing energy (Kost et al., 2013). The global emissions trend remains worrying, as energy-related emissions are not expected to peak until the late 2020’s (McCrone et al., 2016). Therefore, we need to find solutions for the ongoing humongous amounts of carbon dioxide these power plants release into the atmosphere.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure16.png}
\caption{Levelised Costs of Electricity (LCOE) in €2013/kWh. Retrieved and adapted from Kost et al. (2013).}
\end{figure}

Most of the research on CCS/CCU focuses on power plants: they are ubiquitous and serve as the largest anthropogenic source of CO\textsubscript{2}. We therefore interviewed a representative of the energy sector in June 2016. The results of this interview are listed in Table 9. Some of the technologies were not relevant to the company interviewed and were therefore not discussed. Note that the first option considered is a complete shift to renewables.

\textsuperscript{16}“The LCOE reflect the minimum price at which electricity has to be sold to ensure that the investment made pays off.” (Visser & Held, 2014)
The energy company interviewed is slowly transitioning towards renewable energy: they too see that it is a necessary evolution, and the company vision is shifting towards more sustainability. However, as both the oil and the price for EUAs in EU-ETS are incredibly low at the moment, they feel that there are no real incentives to completely shift their current way of working: it is still considerably cheaper to stick to fossil fuels to produce energy (see Figure 16). If both the oil and EUA price would increase, the transition to renewable energy systems would be sped up significantly. If the EUA price were to increase, but the oil price remains this low, the technologies in the CCS niche would become more appealing. In this case, the business case for geological storage would become less negative and the option of Enhanced Gas Recovery (EGR), which they are currently considering, would become more profitable, as it leads to the production of (fossil-based) energy.

According to the energy company, the most compelling technology in the CCU niche would be to convert CO₂ to fuels: only this technology has a market of considerable size that could establish a significant reduction potential. Moreover, as this is not a chemical company, the transformation to chemicals or carbonates is of little relevance to them. There are still some hurdles to the CO₂-to-fuels pathway, as can be seen in Table 9. Most of them are similar to the

### Table 9 - Hurdles and drivers for the energy sector.

<table>
<thead>
<tr>
<th>ENERGY</th>
<th>Hurdle/Lock-in mechanism</th>
<th>Driver/cracks</th>
</tr>
</thead>
</table>
| Complete shift to renewables | - Oil price is too low*  
- EUA price is too low* | - CSR  
- Climate pressure  
- Image  
- Higher oil price*  
- Higher EUA price* |
| Storage underground | - EUA price too low* | - High carbon price*  
- Scale is large enough to make a difference |
| EOR | - EUA price too low*  
- Not sustainable in the long term | - Positive business case* |
| Mineral carbonation | | |
| CCS NICH | Fuels | - Negative business case (CAPEX, OPEX)*  
- Lack of regulatory framework to recognise fuels and pose incentives (subsidies)*  
- Distribution, mainly because price is too high compared to fossil-based*  
- (Carbon price too low)* | - Only way CCU could be significant  
- New source of revenue (by providing service)  
- Climate pressure  
- Image  
- Subsidies for CO₂-based fuels*  
- (High carbon price)* |
| CCU NICH | Chemicals | - Will make too little of a difference  
- No future for electricity production | |
| Mineral carbonation | - Will make too little of a difference  
- No future for electricity production | |

An asterisk (*) was used to denote an economic hurdle/driver. Abbreviations are explained in the abbreviations overview.
ones in the steel industry: high costs (both operational expenditure (OPEX) and capital expenditure (CAPEX)), the unclarity of the regulatory framework surrounding CCU, and the fact that CO₂-based fuels would have to compete with fossil-based fuels. Since it is currently not clear yet whether converting CO₂ to products means that no carbon allowances must be paid in EU-ETS, the argument of the EUA price is put between brackets.

The energy company is looking at the technologies in the CCS and CCU niche from a different perspective than the steel company, as they expect that in an undefined number of years their fossil power plants will have to be shut down to entirely convert to renewables. They are not interested in the CCS/CCU technologies for the carbon dioxide they produce themselves. Of course, it would be an interesting possibility to bridge the time gap between today and that undefined point in time. Yet, at that moment, they want to be ready to provide the CCS/CCU technologies as a service to their clients. To give an example: as a cement company will always have CO₂ as a by-product of its cement production, the cement company would pay the energy company to take over its huge amount of carbon dioxide to avoid paying enormous carbon allowances (assuming, that by then, CCU will allow to subtract the reduced CO₂ emissions from the company’s GHG inventory in EU-ETS). The energy company will then convert this carbon dioxide to fuels, preventing its immediate release into the atmosphere. Providing this service would thus mean a new source of revenue, which is the main driver for this company to consider CCS/CCU technologies. Other drivers are governmental subsidies to overcome the high costs. Image and climate pressure play a role as well, but must remain affordable.

5.1.3 The chemical industry

The chemical industry is in an interesting position in the discussion around the CCS and CCU niches. On the one hand, this industry is responsible for 5.5% of anthropogenic carbon dioxide emissions and 17% of industrial CO₂ emissions (IEA & ICCA, 2013). On the other hand, the sector provides the knowhow for the chemical conversion techniques on which we elaborated supra (§2.3.3). We could thus state that the chemical industry is both on the supply and demand side of CCS and CCU technologies. The industry has already come a long way: in 2014, its European GHG emissions had fallen by 59.4% compared to 1990 levels, whereas the

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17 When talking about “industrial CO₂ emissions”, the energy sector is generally not taken into account.
production of the chemical industry (including pharmaceuticals) expanded by 78% (Cefic, 2016). This is primarily due to enormous increases in energy efficiency.

The European chemical sector faces similar challenges to the steel industry: competition is fierce, as companies in Asia and the Middle East have easier access to raw materials and a cheaper supply of energy and labour. China currently dominates the world market: its sales levels are higher than the next nine countries combined. This is only a recent phenomenon, as is clearly indicated by Figure 17 (Cefic, 2016). Cefic subdivides the European chemical industry into three broad product areas: base chemicals (petrochemicals, polymers and basic inorganics), specialty chemicals (e.g. paints and inks) and consumer chemicals (e.g. soaps and detergents). Base chemicals covered 59.5% of total EU chemical sales in 2015 and is thus by far the largest product area (Cefic, 2016). The company interviewed operates in this part of the market. We conducted an interview with two representatives from this company’s R&D department in July 2016. The results of this interview are listed in Table 10.

![Figure 17 - World chemicals sales by region. Retrieved from Cefic (2016).](image)

The company is working together closely with the steel and cement industry to find solutions that can be beneficial to all parties involved, by taking on both the emissions of other companies and to find a use for their own. Carbon is a building block of many of the
commodities produced by the company: any CO₂ that leaves the chimney and does not get back into the carbon cycle is simply a waste of resources. However, there is only one of the technologies in the CCU niche that really interests them: the chemical conversion of CO₂ to chemicals. Fuels do not provide a solution in the long-term, in their opinion: the carbon dioxide gets released too quickly into the atmosphere, so this results in little environmental benefit. Furthermore, as they say so adequately themselves: “we are a chemical company, not a fuel company: so anything that leads to fuels is a no-go. We’re able to do it, but we simply don’t want to.” For the CCS niche, the interviewees share the same opinion as the steel company: it is a necessary evil if we want to limit global warming to below 2°C, but they do not want to take part in the organisation of it. This is the responsibility of policymakers.

Table 10 - Hurdles and drivers for the chemical industry.

<table>
<thead>
<tr>
<th>CHEMISTRY</th>
<th>Hurdle/lock-in mechanism</th>
<th>Driver/cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop production of CO₂ (in Europe)</td>
<td>- Should be publicly organised</td>
<td>- When publicly organised: it’s a necessary evil</td>
</tr>
<tr>
<td>CCS NICHE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage underground</td>
<td>- Should be publicly organised</td>
<td>- When publicly organised: it’s a necessary evil</td>
</tr>
<tr>
<td>EOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral carbonation</td>
<td>- Should be publicly organised</td>
<td>- When publicly organised: it’s a necessary evil</td>
</tr>
<tr>
<td>COU NICHE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuels</td>
<td>- Is only a temporary solution</td>
<td>- Higher oil price*</td>
</tr>
<tr>
<td>Chemicals</td>
<td>- Oil price too low*</td>
<td>- Governmental support; either financial</td>
</tr>
<tr>
<td></td>
<td>- “Cost avoidance”: doing nothing delivers more value than investing*</td>
<td>or by helping to get cheaper loans*</td>
</tr>
<tr>
<td></td>
<td>- Market uncertainty</td>
<td>- Products are recognised as</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- “renewable”*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- CSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Image</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Climate pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Competitive advantage*</td>
</tr>
<tr>
<td>Mineral carbonation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An asterisk (*) was used to denote an economic hurdle/driver.
Abbreviations are explained in the abbreviations overview.

In the first place, the company is looking at the supply of carbon monoxide (CO) instead of CO₂. For instance, steel mill gases contain large amounts of CO, aside from CO₂. When this CO reaches the air, it reacts with oxygen to carbon dioxide in just a matter of seconds. Thus, by utilising carbon monoxide from flue gases, carbon dioxide emissions are indirectly prevented, because the CO cannot react to CO₂. Utilising CO is thermodynamically much more efficient and this molecule is already used as a raw material for multiple applications in this chemical company. The costs of producing chemicals out of CO is however still much higher than in conventional methods. The products made from anthropogenic CO must compete with their
fossil-based equivalents, making them very difficult to sell. In this scenario, every CO-based product results in a negative business case: either they follow the market price, resulting in a loss for each product sold, or they ask a higher price, resulting in too little sales to reach break-even. Currently, it is more attractive to continue their business as usual instead of investing.

The interviewees identified several drivers that could offset these economic hurdles to some extent. First, an increase in the oil price could reduce the difference in production costs between fossil-based and CO-based chemicals. This evolution is however very difficult to predict. Moreover, according to the interviewees, the oil price will remain relatively low: the demand for oil will decrease as we make the shift to more renewable energy sources. A second driver would be to give official recognition that CO-based products are more environmentally friendly than their fossil-based equivalents, by means of some sort of label. This would have three main benefits: (1) the emergence of a new market for more renewable chemicals, in which customers would pay a premium price for the products, (2) a competitive advantage over other chemical companies and (3) improving the company image, thus reinforcing (1) and (2). Third, by reducing the cost of capital through government intervention, for example by means of a subordinated loan underwritten by the government, the payback time of the investment could become much more attractive. And last, both corporate social responsibility and climate pressure play a role: something needs to change in the industry if we want to avoid the extreme effects of global warming. This change can nevertheless only happen within the economic boundaries of the company.

5.1.4 Port of Antwerp

A fourth perspective is given by the Port of Antwerp, an independently operating company acting as a platform between the different industries and companies in its zone. It manages and maintains the port infrastructure and provides many services to accommodate ships and other transportation methods arriving at, staying in or leaving the port. It further ensures that there is a close cooperation between the private companies and the public authorities. As the Port of Antwerp is the largest port in Belgium and the second largest in Europe, this is a highly industrialised zone and the companies in the port are responsible for a large component (about 12% (Port of Antwerp, 2016b; United Nations Climate Change Secretariat, 2014)) of the Belgian CO₂ emissions. In the past decade, the Port of Antwerp Authorities have given a high
level of priority to sustainability. For instance, they invested heavily in renewable energy and reached an installed capacity of almost 140 MW in 2013 (Port of Antwerp, 2016a).

The interview with a representative of the Port of Antwerp was held in August 2016. We listed the results from this interview in Table 11. This interview was not as extensive as the others, and therefore, only the options that were most relevant were discussed.

<table>
<thead>
<tr>
<th>PORT OF ANTWERP</th>
<th>Hurdle/Lock-in mechanism</th>
<th>Driver/cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop production of CO₂ (in Europe)</td>
<td>- Public opinion</td>
<td>- CSR</td>
</tr>
<tr>
<td>CCS NICHE</td>
<td>- Negative business case *</td>
<td>- Image</td>
</tr>
<tr>
<td>Storage underground</td>
<td></td>
<td>- Need for local methanol in PoA</td>
</tr>
<tr>
<td>EOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral carbonation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCU NICHE</td>
<td>- European legislation*</td>
<td>-</td>
</tr>
<tr>
<td>Fuels</td>
<td>- Large investment*</td>
<td></td>
</tr>
<tr>
<td>Chemicals</td>
<td>- European legislation*</td>
<td></td>
</tr>
<tr>
<td>Mineral carbonation</td>
<td>- Large investment*</td>
<td></td>
</tr>
</tbody>
</table>

An asterisk (*) was used to denote an economic hurdle/driver.
Abbreviations are explained in the abbreviations overview.

The Port of Antwerp was at first interested in the CCS niche, but decided relatively fast that this option would not be viable, both economically and due to the public opinion. After extensive research, they decided to focus on one specific option: the chemical conversion of CO₂ to methanol, based on the technology of CRI (§2.3.3.2.1). The CCU process would serve as a buffer against the fluctuations in the supply of renewable energy. In times of oversupply (windy or sunny days), the renewable energy can be allocated towards the electrolysis of H₂O to hydrogen, which is then to be combined with anthropogenic CO₂ for the synthesis of methanol, taking advantage of the high need for advanced renewable fuels. Moreover, annually 300 kt of fossil methanol is imported from the Middle-East to the Port of Antwerp. If they were to produce methanol locally in a sustainable and cost-efficient way, at least a part of this import could become redundant.

The largest driver for the Port of Antwerp according to the interviewee, is to reach their own and the European goals concerning new energy systems and to shift from the Port’s current energy production and consumption to renewable fuels. However, European legislation leads to a twofold hurdle: (1) since it is hard to prove that all the energy used for this power-to-methanol production is renewable (Guarantee of Origin (GO)), the methanol will probably not
be qualified as “renewable”. They do hope that this will change in the future, to receive a premium price for their product. (2) As has been mentioned supra (§5.1.2), in a CCU scenario the carbon tax from EU-ETS under the current system will still have to be paid, making the interviewee doubt whether EU-ETS even supports circularity. Having to pay CO₂ allowances would make the business case (more) negative, which makes the investment less attractive, even though it could bring net CO₂ benefits: 1.38 tonne CO₂ is necessary to produce 1 ton of methanol (Garcia-Gonzalez et al., 2016). If these European legislative hurdles would disappear – on which the Port of Antwerp is counting – this power-to-methanol project will take off.

5.1.5 Concluding remarks

Interviewing one or two employees of a company is not representative for the whole company, nor for the entire industrial sector. These people have nevertheless been involved with the CCS and CCU niches for years and provided useful insights: they are closer to the practical implications and look at it through industry- and function-specific glasses.

Referring to the multi-level perspective in the introduction of this qualitative analysis (§5.1.1), we now have an idea of what industry sees as lock-ins (hurdles) and cracks (drivers) for the CCS and CCU niche in the current sociotechnical regime. Even though the interviewees came from different sectors, there was overlap in their answers. These answers can be subdivided into three categories: economic, legislative and image-related. First, the economic lock-in mechanisms and cracks in the sociotechnical regime appear to be the most important: at the moment, the costs of the technologies in the CCS and CCU niches are simply too high and the expected returns too low to cope. The market price for the CCU products is significantly lower than the cost of producing them. Moreover, CCS does not even lead to any returns, except for avoiding the carbon tax in EU-ETS. This makes it impossible for products resulting from these processes to compete with their incumbents. As long as emitting CO₂ is substantially cheaper than taking action to prevent it, no investments in CCS/CCU technologies will be made, no matter how much goodwill a company has. Second, according to all interviewees, the fact that European policymakers have not yet made up their minds about CCU, creates uncertainty about the future, staggering the will to invest. This uncertainty is mostly related to whether policymakers will install the right economic incentives, and can thus again be linked to the economic category. Third, corporate social responsibility and climate pressure were mentioned in several interviews, though always on the condition that it brings no financial harm to the
company. CSR and responding to climate pressure eventually improve the company’s image, and thus create returns in the long term.

In the following, we will consider the possibilities that were mentioned by the interviewees to overcome the most significant hurdle: economic incentives that can lower the costs. These can further increase the internal momentum in the niches and push the technologies closer to a breakthrough.

5.2 QUANTITATIVE ANALYSIS

5.2.1 Introduction

In this part, we will evaluate four types of economic incentives by analysing them quantitatively if data is available. These incentives were mentioned in the qualitative analysis supra (§5.1). First, the effect of the price fossil resources on the price gaps for CCU (Table 5, §4.2) will be studied in more detail (§5.2.1). We did not include CCS in this analysis. We expect that an increase in the price of fossil resources will have a limited impact on CCS, because there is no price gap to bridge in this niche. Secondly, we will look at three market-based policy instruments and their potential effect on the breakthrough and upscaling of technologies in the CCS and CCU niches: an increase in the price of EUAs in EU-ETS (§5.2.2.1), the effect of learning and how subsidies can stimulate the learning process and thus, indirectly lower the costs of CCS/CCU technologies (§5.2.2.2), and carbon taxation to make products for which less CO\(_2\) was emitted become more attractive (§5.2.2.3).

5.2.2 Required increase in price of fossil resources

If there was no difference in the price of fossil products and the required price in Table 5, companies would be able to sell their CO\(_2\)-based products and might even get a profit out of it in the long term, as conditions change and costs decrease. Equal prices can be achieved by (1) a (serious) reduction in costs to produce the CO\(_2\)-based commodities or by (2) an increase in the price of fossil-based products. As stated by the interviewees, the price of fossil resources has an impact on the price of chemical products, and this is indeed supported by literature. According to Weinhagen (2006), an unanticipated change in the price of crude petroleum results in a significant positive change in the price of organic chemicals (Weinhagen, 2006).
This positive correlation is not only due to a direct cost effect. In the case of methanol for example, an increase in the crude oil price leads to an increase in demand for alternative commodities, such as natural gas, which in turn leads to an increase in methanol price, as natural gas is the main raw material for methanol. Moreover, an increase in oil price in an oil-driven economy leads to higher inflation and thus higher costs of production (Delavari & Alikhani, 2012).

What we are interested in, is how much the price of fossil resources needs to increase to bridge the gap between the current selling price of chemicals and the required price. The oil price is taken to represent the price of fossil resources. We conducted calculations that give an indication of the required increase in the oil price, *ceteris paribus*, which we explained in the methods part. One can see in Figure 18 that the oil price minimally needs to double if we want one of these products to break through. We now compare this result to the projected price evolution of oil, as determined by the World Bank (Figure 19). Here we can see that 2016 hits a low point. Therefore, oil price will probably increase (as it has done since the crash in January 2016). The global oil market does nevertheless remain substantially oversupplied, so this surge is not expected to go rapidly. It is thus not a realistic option to wait for the oil price to increase to the right level, if we want CCU/CCS to be scaled up as soon as possible. Of course, one should keep in mind that the greatest impact will come from oil shocks that are by definition unexpected, and cannot be forecasted.

![Figure 18 - Current and required oil price for CCU products to become competitive with their fossil incumbents.](image-url)
This rather straightforward analysis results in the conclusion that a necessary increase in the crude oil price to close the gap in price difference, will probably not occur in the near future. The oil price will thus not be a solution to overcome this economic hurdle to the breakthrough of CCS/CCU and therefore, other incentives are called for.

5.2.3 Market-based policy instruments

We now focus on what policymakers can do to lead CCS/CCU technologies to a breakthrough. As was stated by Albrecht (1999): “Waiting always has a price in terms of lost opportunities and therefore we argue that an accelerated technological innovation and diffusion should be
Three market-based policy instruments are discussed in this part. Market-based policy instruments can be defined in the domain of environmental economics as regulations that encourage behaviour through market signals, rather than through explicit directives regarding pollution control levels or methods (“command-and-control regulations”). If these instruments are well designed and implemented, they encourage firms (and/or individuals) to undertake pollution control efforts that are in their own interest and collectively meet policy goals (Stavins, 2003). The point of focus here is the European Commission, as these policymakers are the most resourceful and have the greatest impact on environmental matters inside Europe. First, an increase in the price of EUAs in EU-ETS is considered, followed by the potential of subsidies and last, influencing buying behaviour by means of taxation is treated. Note that this is by no means an exhaustive list.

5.2.3.1 EU-ETS: an increase in the price of EUAs

In the literature review we briefly discussed EU-ETS, the largest emissions trading system currently in action. We mentioned that the present price of the European Allowances (EUAs) is extremely low (around €5/tonne CO₂ in the last quarter of 2016) due to the recent recession and an oversupply of allowances. This results in little incentive for firms to invest in more sustainable technologies, as was confirmed in the qualitative research (§5.1).

CCS is already installed in EU-ETS. In Article 20 of the 2009/29/EC Directive, one can read the following: “The main long-term incentive for the capture and storage of CO₂ and new renewable energy technologies is that allowances will not need to be surrendered for CO₂ emissions which are permanently stored or avoided”. Directive 2009/31/EC further explains the regulatory framework concerning CCS. This framework is based on an integrated risk assessment for CO₂ leakage, including site selection requirements designed to minimise the risk of leakage, monitoring and reporting regimes to verify storage and adequate remediation of any damage that may occur.
CCU is more complex, as many of the CO$_2$-based products only lead to a temporary storage of carbon dioxide and are thus not “permanently stored or avoided”. Therefore, the opinions are rather divided on this subject. For example, the Zero Emissions Platform (ZEP) recently published a policy brief in which they state that “only those forms of CCU that lead to permanent, direct abatement of CO$_2$ have a place within the EU-ETS reporting framework” (ZEP, 2016). Contrarily, Naims et al. (2016) argue that through indirect effects of CCU, such as greater efficiency or the substitution of raw materials, CO$_2$ emissions can be avoided. When these savings are demonstrated for an industrial facility, CCU processes should be taken into account in emissions trading (Naims, Olfe-Kräutlein, Lorente Lafuente, & Bruhn, 2015). The fact remains that at this point in time, CCU is not yet incorporated in EU-ETS. Hence, even if a company would convert its CO$_2$ to a product, it would still have to surrender EUAs. EU-ETS can therefore only be a stimulus for CCS, and not for CCU.

Figure 20 provides an illustration of the evolution of the cost increase to produce one tonne of steel for CCS, CCU and business as usual (BAU) as the price for EUAs in EU-ETS rises. This way we can easily compare CCS and CCU to the BAU scenario. Because we only considered the cost increase for one tonne steel, the difference between the CCS and CCU graph is the EUAs that have to be paid for that tonne steel. One can see that for relatively low levels of EUAs, the BAU scenario incurs the smallest cost increase, as in this scenario no CO$_2$ avoidance cost needs to be paid. At a certain price level, the cost increase for CCS is smaller than for the BAU.
scenario. This level depends heavily on the assumptions we made. Since we have only considered the avoidance costs and the price for EUAs, and no CAPEX or other OPEX, we can assume that the level of the price for EUAs for which BAU overtakes CCS (€40) is at the low end. The cost increase of CCU starts off at the same level as CCS, but then gradually rises with the EUA price: there is a price for which CCS becomes interesting compared to the other options. Because CCU results in products that can be sold, this curve can shift down somewhat, making CCU more attractive than CCS for a low level of EUAs. We know that the market price that can currently be asked for these products is too low to offset the costs, so CCU will not – in the near future – become more appealing than the BAU scenario for low levels of EUAs. Figure 20 thus shows two points in a simple way.

(1) The price of EUAs in EU-ETS has to exceed the costs of CCS to stimulate CCS: the current price for EUAs (~5 €/t CO₂) is nowhere near this required level, which makes emitting CO₂ considerably cheaper than investing in CCS.

(2) A rise in the price of EUAs today only has a negative impact on CCU, as it simply leads to an increase in cost, which, at the moment, cannot be offset by the returns for the CO₂-based products.

Considering that it contributes to a circular economy by partially closing the carbon cycle, investment in CCU should be rewarded. Today, EU-ETS does not reward, on the contrary: if a company invests in CCU, it must still pay allowances for the emissions transformed into products and incurs even greater costs than before. EU-ETS thus needs to be altered so that CCU can be included and stimulates companies to invest in this option rather than to discourage them. However, it is of extreme importance that to realise this, a consistent, transparent and uniform method for calculating the net emissions savings is developed. Both direct and indirect effects of CCU on a life cycle basis should be considered, to recognise what the actual environmental added value of these technologies is. These uniform calculation methods would further have the advantage that different technologies can be compared on a techno-economic and ecological basis, something that was not yet possible at the moment of this study. This need has been identified by several scholars in recent publications. For instance, von der Assen et al. (2014) describes a method to calculate an LCA for CCU (von der Assen et al., 2014). In Figure 20, the effect of the incorporation of CCU in EU-ETS would be that the CCU graph pivots downwards, as for each tonne of steel produced a fraction of the emitted CO₂ would be avoided and thus a fraction of the costs would decrease.
5.2.3.2 The learning effect

Merrow (1989) states that “expectations of rapid cost improvement motivate companies to invest heavily in the development and introduction of new chemical products and processes, even if production from the first pioneer facility is economically marginal” (Merrow, 1989). These cost improvements can be illustrated by “learning curves” and the slope is the level to which costs fall each time the cumulated output doubles. Lieberman (1984) studied the development of the production costs and prices in the chemical industry and discovered that learning curve effects are of greater importance than economies of scale, although the latter play a major role in the chemical industry as well. According to his research of 37 chemical products, the price decreased by 5.5% annually (Lieberman, 1984; Oosterhuis, 2006). Following the (optimistic) results from Lieberman (1984), one can see in Figure 21 that it would take more than 20 years before methanol reaches the price level it needs to compete with its fossil counterpart.

Lieberman (1984) further states that through an interaction effect with the learning curve, R&D expenditures seem to accelerate the rate of cost reduction (Lieberman, 1984). Hence, expenditures in R&D and economies of scale indirectly accelerate cost reductions and can set in motion a self-reinforcing process: as growth in learning and production leads to cost and price reductions, the technologies and resulting products become more attractive to investors and potential customers, further increasing the R&D and so on (Oosterhuis, 2006). However, making expenditures in R&D or scaling up production, requires external finance, which takes a great deal of time and energy to gather and can result in market failure. In the case of CCS/CCU technologies, it is essential that the most promising options take off as soon as possible given the context of climate change. Mamuneas & Nadiri (1996) econometrically prove that publicly financed R&D can make a significant impact on costs in industry, with an elasticity of -0.26667 in the chemical sector. This means that a 1% increase in public R&D expenditures leads to a 0.26667 decrease in costs (Mamuneas & Nadiri, 1996). Figure 21 shows what happens to the price of CCU methanol over time if the learning effect accelerates by a factor 1.5 and 2: the competitive price level is reached much sooner. Public investments further leverage private investments.
With “normal” learning in the chemical industry, it is expected that CCU becomes more competitive within approximately twenty years. Public R&D expenditures can thus steepen the slope of the learning curve, resulting in faster cost and price reductions, and further attracting money from external investors. How large this quantitative relationship between public R&D and cost decrease will be, is not clear at this moment.

The literature review (§2.2.2) already mentions that the EU provides two possibilities for funding sustainable technologies. Horizon 2020, the successor of the Framework Programme (FP7, 2007-2013), is directed generally at Research and Innovation, of which a part of the resources is dedicated to sustainable growth and natural resources. The webpage states that Horizon 2020 “promises more breakthroughs, discoveries and world firsts by taking great ideas from the lab to the market” (European Commission, n.d.). NER300 is based on the “polluter pays principle”: the sale of carbon allowances leads to the “earmarking” for first-of-a-kind (FOAK) low-carbon energy projects. NER300 thus solely focuses on innovative low-carbon energy demonstration projects, and more specifically on renewable energy technologies and environmentally safe CCS.

NER300 awarded 1 billion euros in funding to 18 renewable energy projects and one carbon capture and storage project, and leveraged an estimated 860 million euros from private
sources. All NER300 projects are supposed to be up and running by July 2018. The only CCS project in NER300 received 300 million euros in funding: the UK-based White Rose project, a FOAK oxyfuel coal power plant of which 90% of the emissions would be captured and transported to an offshore storage location in the southern North Sea (European Commission, 2014). Related to the UK government’s decision to end the Carbon Capture and Storage commercialisation competition (supra §2.3.2.1), the development and operations have been terminated as of April 13th 2016 because they cannot proceed in their current form. No CCU projects were included in NER300. NER300 has thus not yet led to a successful operation of CCS/CCU technologies, but there is hope that NER400 (the period 2021-2030), for which the terms are currently under discussion, will have a broader scope and include CCS as well as CCU projects.

Horizon 2020 is a different story. Recently, DG Research and Innovation of the European Commission stated that “a forward-looking approach to carbon capture and storage (CCS) and carbon capture and use (CCU) for the power and industrial sectors will be critical to reaching the 2050 climate objectives in a cost-effective way” (European Commission, 2015a). In the calls for the Horizon 2020 Work Programme 2014-2015, one CCS topic was included (LCE-15-2014, € 9-16 million), but no topics related to CCU. However, in the Work Programme 2016-2017, for which calls are open during this study, both CCS and CCU are incorporated. The relevant topics and budgets of the European Commission can be found in Table 12. Horizon 2020 is further granting a “Horizon Prize CO₂ reuse” of € 1.5 million for which projects can be submitted until April 2019.


<table>
<thead>
<tr>
<th>Identifier</th>
<th>Topic</th>
<th>EC contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCE-24-2016</td>
<td>International Cooperation with South Korea on new generation high-efficiency capture processes</td>
<td>€ 2.5 million</td>
</tr>
<tr>
<td>LCE-25-2016</td>
<td>Utilisation of captured CO₂ as feedstock for the process industry</td>
<td>€ 6.10 million</td>
</tr>
<tr>
<td>LCE-27-2017</td>
<td>Measuring, monitoring and controlling the potential risks of subsurface operations related to CCS and unconventional hydrocarbons</td>
<td>€ 5.10 million</td>
</tr>
<tr>
<td>LCE-29-2017</td>
<td>CCS in industry, including Bio-CCS</td>
<td>€ 4.9 million</td>
</tr>
<tr>
<td>LCE-30-2017</td>
<td>Geological storage pilots</td>
<td>€ 9.16 million</td>
</tr>
<tr>
<td>BIOTEC-05-2017</td>
<td>Microbial platforms for CO₂-reuse processes in the low-carbon economy</td>
<td>€ 5.7 million</td>
</tr>
<tr>
<td>SPIRE-05-2016</td>
<td>Potential use of carbon dioxide / carbon monoxide and nonconventional fossil natural resources in Europe as feedstock for the process industry</td>
<td>€ 250,000-500,000</td>
</tr>
<tr>
<td>SPIRE-08-2017</td>
<td>Carbon dioxide utilisation to produce added value chemicals</td>
<td>€ 6.8 million</td>
</tr>
<tr>
<td>NMBP-20-2017</td>
<td>High-performance materials for optimizing carbon dioxide capture</td>
<td>€ 6.8 million</td>
</tr>
</tbody>
</table>
What happened at the White Rose project serves as a good negative example of the impact policymakers can have on the behaviour of investors. Because the UK government cancelled the 1 billion GBP competition for a carbon capture and storage project six months before the winner was to be announced, it sent the signal to potential investors that there is no future for CCS in general. This eventually resulted in the failure of the White Rose project: “there is no available funding, nor prospect of finding funding” was stated by the UK Secretary of State for the Department of Energy and Climate Change when refusing the Development Consent Order that determined the future for this project (“White Rose Project Fact Sheet,” 2016).

On the other hand, policymakers can have a positive impact on the behaviour of investors as well. If a project does receive funding through the government, most of the time it has already gone through a careful due diligence, thus proving to outside investors that it has a higher success probability than other projects. Government support further gives the prospect of rapid cost improvement through R&D learning and future economies of scale, attracting investments for the development and introduction of CCS/CCU technologies and processes. Government support can thus set in motion the self-perpetuating process of attracting investment and lowering costs, overcoming economic hurdles. Therefore, it is to be applauded that the European Commission has now included both CCS and CCU in Horizon 2020. Whether the money dedicated to these projects will be enough to guide CCS/CCU technologies towards a breakthrough, depends heavily on the project’s magnitude. The Horizon 2020 proposal calls for CCU are mostly directed at bringing technologies to the demonstration phase, and for CCS to a pilot scale. Expanding technologies to a commercial scale will probably not be possible within these budgets: for example, it is estimated that a large-scale methanol plant has a CAPEX of about €150 million (Pérez-fortes, Bocin-Dumitriu, & Tzimas, 2014).

5.2.3.3 Influencing buying behaviour through taxation

To accelerate a breakthrough CCS/CCU technologies and products, they need to become competitive compared to their fossil incumbents. If government subsidies turn out not to be sufficient to make this happen, other complementary policy measures should be implemented as well. To increase the technologies’ competitiveness, we already mentioned in §5.2.2 that either (1) a (serious) reduction in costs to produce the CO₂-based commodities or (2) an increase in the price of fossil-based products is required. The latter can be realised through
government intervention: policymakers can compensate (part of) the price difference by penalising less sustainable technologies and products by levying an “environmental tax”.

There is no clear definition for environmental tax, but the main idea is based on the “polluter pays principle” and harmful emissions are taxed directly, rather than indirectly like in EU-ETS. We would opt for a carbon tax on the final product, which functions similarly to a value-added tax, making its way through the supply chain to eventually be paid by the final customer. As the final customer creates demand, one can argue that he/she is responsible for the production of the polluting product. An increase in the price due to a tax based on the amount of CO₂ emitted during the production process, could change the behaviour of these customers and might lead to a shift in demand in favour of more sustainable products. Lower demand for their products will make industries rethink their production methods, thus changing the complete supply chain of a product. Furthermore, according to the OECD, using taxes to increase the market cost of a more polluting product helps to incentivise the full range of potential abatement options. It can result in cleaner production processes, end-of-pipe abatement (i.e. measures to capture and neutralise emissions before they enter the environment), adoption of existing products which cause less pollution, development of new, less-polluting products and reducing output or consumption (OECD, 2011).

Again, the necessity of thorough and standardised LCAs is pointed out: we need to know exactly how much net CO₂ is emitted during the production process of a product, before it is possible to install such a tax. This should therefore be high on the priority list of policymakers. In the optimal scenario, this carbon tax is levied on a global basis, so that “carbon leakage” cannot occur. If this turns out not to be possible, a tax could be lifted on products imported from outside the EU. This sort of policy instrument would fit well in the recently published Circular Economy Package of the European Commission, which states that “The action plan on the Circular Economy proposes wide-ranging measures that will help consumers to choose products and services that are better for the environment and, at the same time, provide monetary savings and an increased quality of life” (European Commission, 2015b).

We give an example to make this carbon tax more tangible. Let’s say that during the manufacturing of a car, 6 tonnes of CO₂ are emitted and that the price of buying a small car is 10,000 euros. For a carbon tax of 50 euros, the price of a car increases to 10,300 euros. In 2013, about 400,000 new cars were sold in Europe. If we then assume that this number has not
changed and that the emission of 6 tonnes of CO\textsubscript{2} is applicable to all cars, the European Union can collect 120 billion euros in tax money annually. This money can then be earmarked for supporting the expansion of sustainable technologies in the transportation sector, for example for electrical cars or advanced non-fossil fuels. This way, the costs of new technologies reduce, the adoption of more sustainable products is accelerated and the political acceptability of the tax increases. On the other hand, if a company decides to store its CO\textsubscript{2} and can thus reduce (part of) its CO\textsubscript{2} emissions, the price of the product will decrease, becoming more attractive to potential customers. Of course, avoiding CO\textsubscript{2} results in extra costs, which need to be exceeded by the carbon tax before it can make an impact.

For the case of CCS/CCU, the carbon tax needs to be enormous to completely bridge the price gap between fossil-based and CO\textsubscript{2}-based products. Figure 22 gives two scenarios for CCU methanol: (1) negative emissions result in negative costs, seen in the graph with the negative slope, and (2) negative emissions just result in not having to pay the carbon tax, but do not lead to negative costs, which can be seen in the higher graph with a slope equal to zero. In the first scenario, the prices for fossil and CCU methanol are equal at a tax level of about €450/t CO\textsubscript{2}. However, in the second scenario, an even higher tax level is required: before the gap is bridged, the carbon tax needs to be close to €900/t CO\textsubscript{2}. This is of course because there is such a large price difference between fossil and CCU methanol (€350 vs. €1400). Therefore, a carbon tax will only have an impact on CCU products, if the costs first decrease significantly. This would result in a parallel downward shift of the two CCU graphs, leading to a lower required carbon tax to bridge the price gap. For example, if the price for CO\textsubscript{2}-based methanol were to decrease by 50% (€700 instead of €1400), a carbon tax of €150 would be required to equalise CO\textsubscript{2}-based and fossil methanol, which is not that far from the carbon tax on fossils in Sweden ($105/t CO\textsubscript{2} (Sumner, Bird, & Dobos, 2011)). We added a graph representing a region where methanol can still be bought without having to pay a carbon tax: in the first CCU scenario, a carbon tax of over €900/t CO\textsubscript{2} would be required, and in the second scenario, the price gap would never be bridged. This explains why such a carbon tax needs to implemented on a global scale, and if that is not possible, import taxes should to be levied.
A carbon tax is an effective method to stimulate buyers to consume more sustainable products. Since demand steers the production process, this can stimulate the whole supply chain to become more sustainable. However, for CCS/CCU technologies, a carbon tax will only have an impact if the costs first decrease significantly, because the price gap is currently too large to bridge.

Environmental taxes are the most effective to incentivise industries to invest in R&D and technological innovations, according to Albrecht (1999). As we’ve already established in the previous section that R&D investments can accelerate a decrease in costs, environmental taxes could indirectly result in a decrease in costs.

Of course, implementing this kind of tax system affects many stakeholders, such as industry and households, and similar to the case of EU-ETS, it must be designed very carefully to ensure that some of these stakeholders are not infringed more than others. A carbon tax is simpler, more flexible and more effective than emissions trading systems like EU-ETS, which is why several scholars advocate this type of system and over a 1000 companies called for it at the COP20 in Lima. The IPCC has recognised that this kind of measure would indeed induce
investments and would not be too difficult to implement, yet it has not been taken under consideration at COP21 (Paris) or COP22 (Marrakech) (Minten, 2015).

5.2.4 Concluding remarks

In this quantitative analysis, the impact of four economic incentives to overcome the economic hurdle to upscaling CCS/CCU technologies in industry were considered. During the literature research of this study, we established that very limited comparable data is available at the moment, so no elaborate analyses are possible yet. This constraint challenged us to find straightforward calculation methods with the limited data we had. First, the impact of an increase in the oil price on CCU is evaluated. This results in the conclusion that, for the five products considered, the oil price needs to increase to a level that is very unlikely to be achieved in the near future. If CCS/CCU technologies are to take off as soon as possible, one cannot wait for this to happen. Therefore, we subsequently considered European market-based policy instruments. Market-based policy instruments should encourage behaviour towards more sustainable solutions through market signals, and are recognised to be more effective than “command-and-control regulations”. First, the possibility of an increase in the price of EUAs in EU-ETS is examined, by comparing its impact on CCS, CCU and a business as usual (BAU) scenario. In the current system of EU-ETS, CCS is already incorporated, but CCU is not, as utilisation technologies do not always lead to permanent storage of CO₂. An increase in the price of EUAs therefore leads to decreasing CCS costs and rising CCU costs. However, the BAU scenario remains the most attractive up to a certain level of the EUA price. Under our assumptions, this level is 40 euros/t CO₂ instead of the current price level of 5 euros/t CO₂. Below 40 euros/t CO₂, not many companies will make an investment in CCS technology, unless if they want to invest in their image rather than have a profitable business unit. Second, the policy instrument of subsidies is evaluated by looking at the learning effect. According to Lieberman (1984), the prices of chemicals decrease by 5.5% annually due to learning. Even though this metric seems rather optimistic, it will still take more than twenty years before CCU methanol will reach the current price level of fossil methanol. R&D expenditures can stimulate learning and thus indirectly accelerate cost and price reductions of new technologies, resulting in an increase in the competitiveness of CCS/CCU technologies. Since it is often difficult and time-consuming to find external funding for R&D expenditures, subsidies can overcome this problem, thereby accelerating cost reductions and attracting external investors and potential customers. The leverage that subsidies create, can thus set in motion a self-reinforcing process.
Currently, several calls for proposals concerning CCS/CCU projects are included in Horizon 2020. NER300 has only implemented one (failed) CCS project, but there is hope that NER400 (2021-2030), which is currently under discussion, will include CCU as well. The last policy instrument is environmental taxation to influence the buying behaviour of customers. This can be achieved by levying a fixed carbon tax on the amount of CO\(_2\) emitted during the production process of a certain product. The result will be an increase in the price of less sustainable products, thereby making more sustainable products more attractive. Important to note is that the carbon tax needs to be larger than the extra costs of avoiding emissions.

To further emphasise our results, we combine the learning effect and the oil price, which both stimulate upscaling without the interference of policymakers. The same analysis as in §5.2.2 was performed, but this time using forecasted data for the year 2025. In 2025, the oil price is expected to be 82 USD/bbl (see Figure 19 in §5.2.2). After nine years of learning, the required prices of the CO\(_2\)-based chemicals will have decreased substantially, when assuming Lieberman’s optimistic 5.5% annual price decrease (Lieberman, 1984)\(^{18}\). We further assume that no policy measures or subsidies were installed. The results are shown in Figure 23.

Even after almost a decade of learning, the costs of the CCU-chemicals will still not have decreased sufficiently. Except for the case of methane, the required oil price that would make these products competitive with their fossil incumbents, is still more than double of the expected oil price. This again stresses the need for the right policy instruments so that this kind of market failure can be corrected.

\[^{18}\text{We used the formula } p_9 = p_0 \times (1 - 0.055)^9, \text{ in which } p_0 \text{ is the required price of the CCU chemicals to offset the costs in 2025 and } p_0 \text{ is the required price to offset the costs in 2016. The rest of the calculations for the oil price are the same as explained in §4.2.}\]
Figure 23 - Expected and required oil price in 2025.
6 CONCLUSION AND PERSPECTIVES

The objective of this study was to determine (1) why industrial actors have not yet applied carbon capture and storage or carbon capture and utilisation technologies on a large scale (hurdles) and which actions could change the current situation (drivers), and (2) to evaluate the effectiveness of possible economic incentives that can stimulate the upscaling of the CCS and CCU technologies.

In the literature review, carbon dioxide, global warming and its international context were discussed. Since not all carbon dioxide emissions can be avoided, there is a need to prevent these emissions from reaching the atmosphere. The literature research therefore continued with an elaboration on the currently existing CCS/CCU technologies.

To achieve the objectives, we first performed a qualitative analysis, which was discussed inside the framework of the multi-level perspective. The qualitative analysis consisted of conducting in-depth interviews with industry experts and revealed that CCS/CCU technologies do not break through mainly because of economic reasons. Potential investors are uncertain about the return on investment, because products for which CCS or CCU technologies were involved in the production process, are not able to compete with products made in the conventional way.

In the interviews, economic incentives to stimulate the upscaling of CCS/CCU technologies were discussed, which were then evaluated in the quantitative analysis. First, we concluded that the required increase in the oil price is highly unlikely to happen, even after almost a decade, CCU products will not be able to compete with their fossil incumbents. Second, we found that under our assumptions, the price of EUAs in EU-ETS would need to be at least the costs of CCS to break through, which is 40 €/t CO₂ in our example. Since CCU is not included in EU-ETS, the costs of its technologies become even higher when the price of EUAs increases. Third, subsidies can stimulate the learning process of CCS/CCU technologies and attract external investors, thus acting as a leverage. And last, environmental taxation on final products could be effective to stimulate more sustainable buying behaviour. However, before this kind of taxation can make a real impact on the breakthrough of CCS/CCU technologies, a significant reduction in their production costs is required.
Even though the literature on CCS/CCU technologies increased during the last few years, there is little research on why these technologies have not yet been developed to a large scale. Garcia-Gonzalez et al. (2016) and Hendriks et al. (2013) mention some barriers to CCU, but this is not the main focus of their research. The barriers in these studies are both technological and, similar to our results, economic, such as high upfront investments costs and difficulty to compete in an existing market. Our results from the qualitative analysis are in line with what we expected, since the high costs of CCS/CCU technologies are often emphasized in existing research. This is further supported by papers on innovation economics, in which the funding gap (called “The Valley of Death”) between basic research and commercialisation is an often-cited problem (Beard, Ford, Koutsky, & Spiwak, 2009). The quantitative analyses in this study, although straightforward, have not yet been conducted anywhere else. As CCS/CCU technologies seem promising in terms of circularity and sustainability, society can benefit from its employment on a larger scale. Understanding why this transition is going so slowly, can help to speed up the process of upscaling CCS/CCU technologies.

The study has some shortfalls. First, we acknowledge that four interviews are not much for a qualitative analysis, and we realise that interviewing one or two people does not represent a company, nor an entire industry. However, in spite of this low number of interviews, we did receive overlapping answers indicating saturation, and it is unlikely that more interviews would have led to newer insights. We further plan to contact policymakers with our results after this study. Second, in the quantitative analysis, the limited availability of data restricted us to rather simple calculation methods. This allowed only a superficial analysis of the economic incentives to upscaling CCS/CCU technologies in industry, instead of a thorough economic analysis. To do so, we would have needed a large amount of comparable data, which was not yet possible at the time of the study. Nonetheless, even with a limited amount of data, we were able to uncover some critical points from an economic point of view.

Future research should focus on topics where the present study fell short. We concentrated on the drivers and hurdles to upscaling CCS/CCU technologies according to industry. Researching the hurdles and drivers from the viewpoint of other actors, such as policymakers, users and scientists, could result in a better understanding of the slow pace of the transition towards low-carbon industry. Furthermore, going into more detail on the economic incentives discussed in this study, can provide more insight and evidence for better policy instruments. Possibilities are: thorough evaluation of the achieved leverage of public subsidies on private investments.
and how it can be increased, more extensive research on the effect of the carbon taxes for CCS/CCU technologies, or on the effect of a global emissions trading system. This kind of research can help policymakers to make better decisions and to more efficiently allocate their funds.

However, the first priority should be to have reliable and comparable data available. This could open the way for techno-economic and ecological comparisons between technologies, which could substantially improve the decision making of policymakers and industry. Therefore, academics, policymakers and industrials should put their heads together and share data and knowhow to find a consistent and standardised, LCA-based calculation method to determine for each technology how much CO₂ is avoided and what the associated avoidance cost is.

We end on a positive note: less than one week before the due date of this study, an article appeared in the media, titled “Indian firm makes carbon capture breakthrough”. Apparently, after receiving funding from the UK government, two Indian chemists were able to develop a method to capture CO₂ from flue gases, using a new CO₂-stripping chemical that resulted in much lower costs. Their technology is now installed at a subsidy-free plant in southern India, where annually 60,000 tonnes of CO₂ from a coal-powered boiler can be converted into baking soda (Harrabin, 2017). If the right projects get the right stimulation, the breakthrough of CCS/CCU might be just around the corner.


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