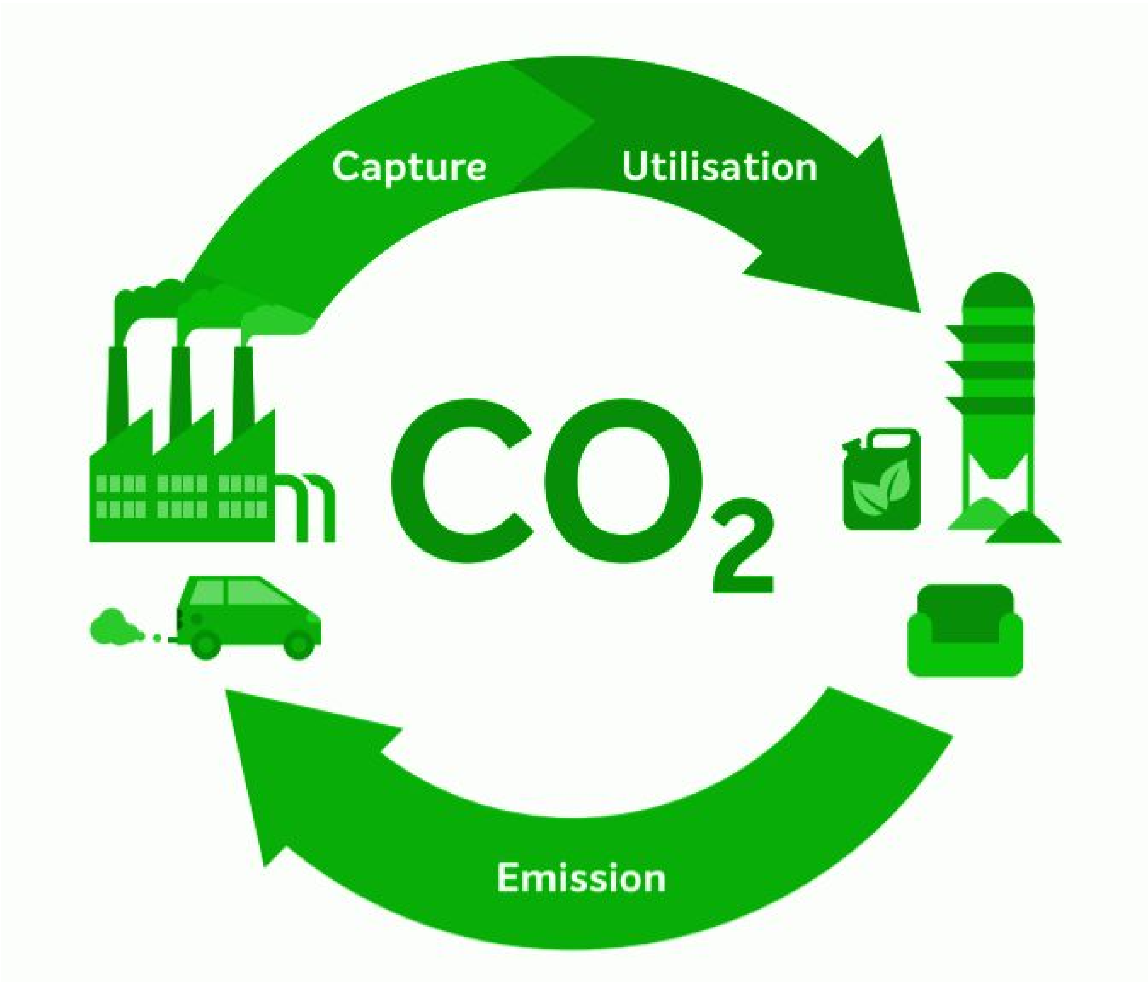
Carbon Capture and Utilisation

An analysis of its potential for climate change mitigation



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Summary

Increased interest has been given to the use of carbon capture and utilisation (CCU) as a tool for climate change mitigation by policymakers and industry. During the process of CCU, carbon dioxide is captured from point sources or from the atmosphere and used a feedstock in a variety of products. Consequently it is argued that the process can deliver positive climate impacts by substituting for fossil feedstocks and by turning products into carbon sinks. However, CCU is still a relatively young technology and debate exists within the academic world about its usefulness in the context of climate change.

The aim of this thesis is to address the potential of CCU and identify challenges and drivers that are connected to the meaningful deployment of the technology. Since this will be done from a climate perspective the overarching research question is: what is the potential contribution of CCU technologies to climate change mitigation? The question is answered by reflecting upon 3 different categories of CCU products: fuels, chemicals and construction materials. Promising pathways for these categories are analysed based on a literature review and their potential for climate change mitigation is explored. Additionally case-studies are done on CCU-based companies or projects to further analyse the present state of the technology. The findings are discussed in the form of a scenario narrative where the future potential and role of CCU will be discussed.

CCU was found to provide significant potential for climate change mitigation for all three considered categories. Due to present barriers around renewable energy requirements its deployment will be limited in the short-term. In the long-term it is plausible that CCU will become more widely deployed, but this will depend on a variety of potential drivers such as its inclusion in policy and technological developments.

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1. Introduction

It is widely accepted that the increase in atmospheric greenhouse gasses since the start of the industrial revolution is the primary cause of climate change. To prevent detrimental environmental and socio-economic impacts, further CO2 emissions should be reduced or even reversed. During December 2015´s Climate Change Conference in Paris, policy makers from all over the world therefore agreed on the ambition to keep temperature increase below 2 °C, while aiming for 1.5 °C (UNFCCC, 2015). Various organisations and institutions that worked out pathways to achieve this goal (IPCC, IEA and EC), argue that carbon capture, utilisation and storage (CCUS) will be a necessary technology to have in our global portfolio of climate change mitigation (IPCC, 2018; IEA, 2019). One of the arguments given is that achieving the goal of 100% renewable energy systems is not feasible within a short to medium timescale and that fossil fuels will continue to play a big role in the transition to carbon-neutral energy system (IEA, 2019). So far the focus has been primarily on storing CO2 and not so much on the utilization of CO2. After all, every tonne of stored CO2 can be counted as permanent mitigation, while this cannot always be said for the utilization of CO2. Unless utilization results in a product that sequesters the CO2 for a long amount of time, from an accounting perspective storing the CO2 will always have more potential for climate change mitigation than its utilization.

Nevertheless CCU is still named as an option in scenarios for future energy systems and has lately been getting increased interest from industry and policymakers as a promising option for climate change mitigation (Zimmerman et al., 2017). Various different arguments for this new trend are given. CO2 Value (an association for CCU implementation in Europe) refers among many things to the technology´s potential to reduce the carbon footprint of hard-to-decarbonise sectors such as the energy-intensive process industries or transportation. Furthermore they state that CCU allows for long-term CO2 sequestration in building materials and can offer alternatives to fossil feedstock for the chemical industry (CO2Value, n.d.). Other arguments for CCU highlight its potential for the storage of renewable electricity through carbon based fuels, its options for the circular economy, but also its capacity to generate revenue to fund carbon capture and storage (Rafiee et al., 2018; Zimmerman et al., 2017). In its report on CO2 utilisation the European commission states that CCU may play a role to de-fossilise the economy, by leaving the fossil carbon in the ground and closing the carbon loop above the ground (European Commission, 2018).

Problem statement

Within the scientific community there is debate around the feasibility of CCU for a climate-neutral energy system. Some authors are really optimistic and see many promising uses for the CCU technology (Carus et al., 2019; GCO Initiative, 2016; Styring et al., 2011), while others see limited potential for climate mitigation and refer to CCU merely as a costly distraction from more promising mitigation strategies such as CCS, energy efficiency, electrification or large-scale hydrogen use (Mac Dowell, 2017). Many technologies within the CCU field are not yet commercialised. This means there are still a lot of unknowns regarding their economic viability and potential for climate mitigation. While certain products or services delivered by the utilisation of CCU are not economically viable in the present, developments or improvements on the technological side might change this in the future. When it comes to the climate mitigation potential of CCU pathways, it might not always be clear how much CO2 emissions are actually reduced, how much carbon is sequestered and for how long that is done.

Questions

To explore the possibilities for CCU technologies in our future climate neutral energy system, the following research question has been formulated:

- What is the potential contribution of CCU technologies to climate change mitigation?

A more complete answer to this question will be given by including the following sub-questions

- What are right now the most promising CCU pathways to achieve CO2 emissions reductions?
- What are the biggest challenges and/or drivers for the realisation and deployment of these CCU pathways?
- What could a (climate neutral) energy system including CCU pathways potentially look like?

2. Key concepts

In this chapter some concepts that are important for this research will be defined. Together they illustrate the complete carbon capture, storage and utilisation (CCUS) process and give some insight in the different (limiting) factors that determine whether carbon capture and utilisation could potentially contribute to climate change mitigation.

Carbon capture, storage and utilisation (CCUS)

CCUS refers to the complete process of capturing CO2 and the consequential storage and/or utilisation (figure 1). With carbon storage, CO2 is handled as a waste product. After capture it is transported to a storage site and deposited in a way that prevents it from entering the atmosphere, usually in a deep underground geological formation such as a depleted oil or gas field. The worldwide storage potential is estimated at about 10.000 Gt of CO2 (IPCC, 2018). While this will definitely allow for very large amounts of CO2 to be stored, it should be noted that the actual potential is probably less because of geographical limitations. Carbon utilisation on the other hand, recognizes CO2 as a resource that can be utilized after it is captured. For this purpose a range of technologies exist that convert CO2 into useful products with potential economic and environmental benefits (Chauvy et al., 2019). In a way CCUS can be seen as a synthetic carbon cycle alongside the natural carbon cycle governed by plants and animals. This synthetic carbon cycle can play a role in restoring the equilibrium that has been disturbed by man (Styring et al., 2014). Because the demand for CO2-based products is limited, it is likely that in the direct future utilisation will always be accompanied by a significant amount of storage as well. Currently only 10-12% of total worldwide CO2 emissions can realistically be used as a raw material and thus be utilized in a circular economy (von der Assen et al., 2014; Chauvy et al., 2019). Therefore it makes sense to look at carbon capture and utilization, as part of a mitigation strategy that also includes the storage of CO2. However, it can be argued that as emissions fall and carbon utilisation becomes more commercialized, the relative ratio of CCU/CCS will increase (Styring et al., 2014).

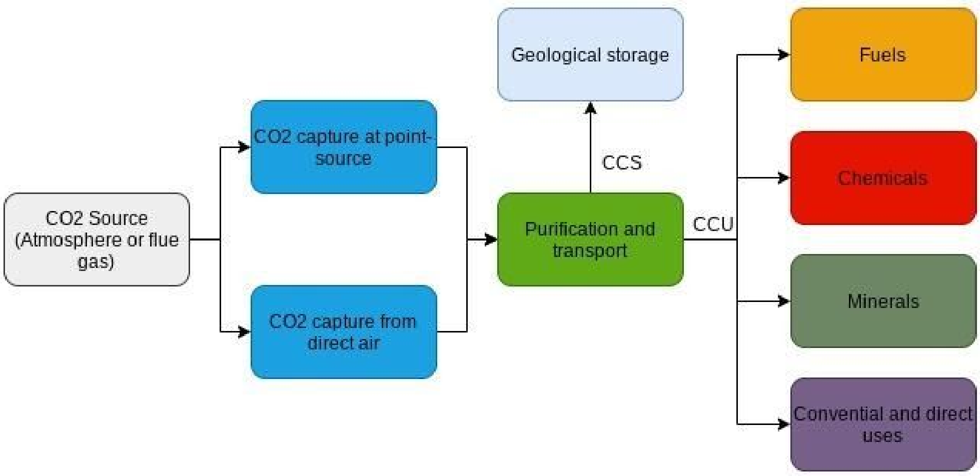

Figure 1: Visualisation of the CCUS process

Climate change mitigation potential

Climate change mitigation refers to the total range of options to reduce or prevent emission of greenhouse gases. To determine the potential of CCU as a climate mitigation strategy, one should look at the complete pathway from CO2 capture to production of the CO2-based product and its following product life cycle. Owing to its standardisation and complete cradle-to-grave perspective, it is useful to conduct a life-cycle assessment for this purpose (European Committee for Standardisation, 2018). In order for the CCU technology to be a true option for climate mitigation, the total life-cycle emissions should be either carbon-negative, carbon-neutral or carbon-reducing (Müller et al, 2020). For each of these options there are a few general requirements that have to be met:

1) Carbon-negative emissions per definition require that the utilised CO2 is taken from the atmosphere (biogenic point sources or direct air capture), permanently sequestered in the product and that the CO2 emissions over the entire lifecycle are lower than the CO2 that has been fixated.
2) Carbon-neutral emissions are obtained when the CO2 that is utilised originates from a fossil point source and is permanently sequestered in the product or when the CO2 is obtained from the atmosphere (biogenic point sources or direct air capture) and is released at the end of its useful life. Both pathways do require that no extra CO2 is emitted during the entire lifecycle than the CO2 that has been fixated.
3) Carbon-reducing emissions occur when in spite of the CO2 emissions over the complete life cycle being positive, the overall emissions are still lower than competing conventional processes. It's not so much the CO2 being utilised that is reducing emissions, but often it´s the CO2 emissions that are avoided by the substitution of raw materials.

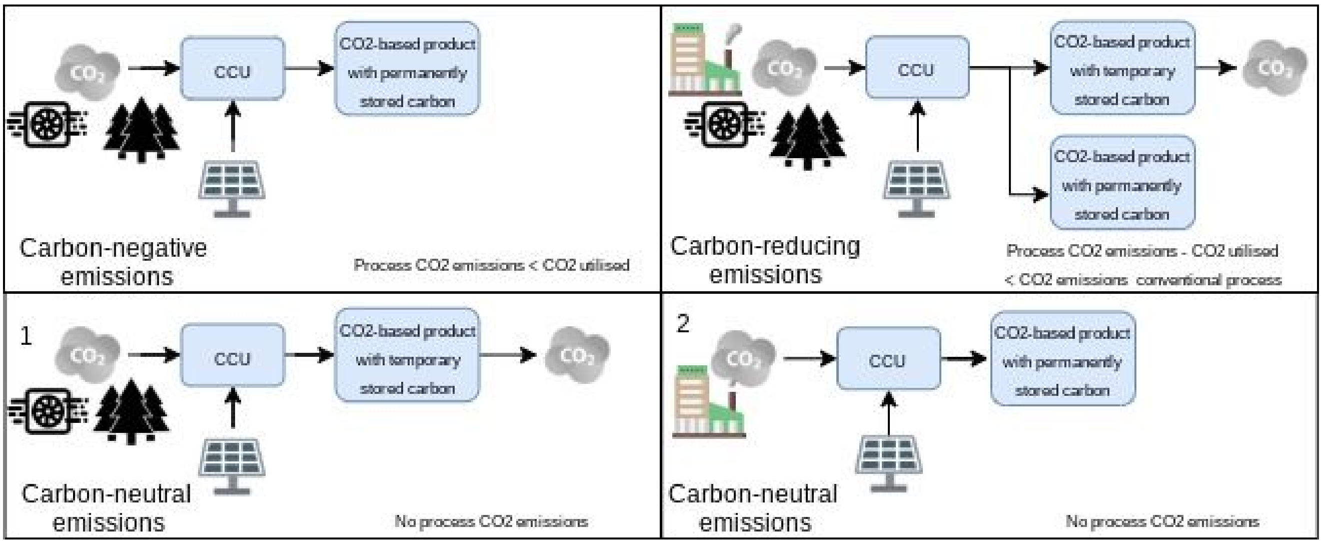

Figure 2: Visualisation of carbon-negative, carbon-neutral and carbon-reducing emissions. Adapted from (Müller et al., 2020).

Because of the chemical inertness of CO2, converting it into valuable products generally requires the addition of either direct energy or use of an energy-rich co-reactant such as hydrogen or epoxide (Porteron et al., 2019). CCU makes most sense when the source of this energy is CO_2-neutral. At last, even when CCU seems beneficial it is also relevant to consider the scale on which CO_2 can be used and if there are other competing pathways that might be more beneficial to climate change mitigation.

Carbon capture and sources of CO_2

In order for CO_2 to be utilised at a significant scale, a reliable source of CO_2 is required to act as an input for the utilisation process. Preferably CO_2 would be captured at a low cost to enhance the economical feasibility of the process. Furthermore it will be important that the method of capturing is not harmful to the environment (e.g. because it is using fossil energy sources), since this would essentially nullify the overall objective of contributing to climate change mitigation. CO_2 can be captured from point sources (industry and power plants) or directly from the atmosphere. The amount of energy that is used for capturing the CO_2 depends on the composition of the flue gas and the desired purity of the CO_2 that has to be seperated (Aresta et al, 2019). From a climate perspective, it would make most sense to capture the CO_2 directly from the atmosphere or from biogenic sources because in contrast to fossil based carbon sources this allows for negative emissions. In line with this, Naims et al. (2015) states that using CO_2 from fossil sources as a feedstock for industrial processes does not seem very consistent with existing policy definitions of ‘renewable’. However since capturing CO_2 directly from the atmosphere requires large amounts of energy, it is more efficient to use industrial point sources (Von der Assen et al., 2016). In the short term, as fossil emissions continue to be emitted anyway, using this CO_2 for CCU might in some cases be justified. Due to efficiency benefits it becomes more feasible to implement CCU technologies and can thus accelerate its development. Especially so-called CO_2 hubs, where multiple heavy industry emitters are packed together and where CO_2 infrastructure is already on the way would be ideal to start deploying CCU technologies. The economies of scale that are delivered by these kind of areas could be beneficial to the overall economical feasibility of CO_2 utilization. Examples of CO_2 hubs are found all over the world and include PORTHOS (Rotterdam, Netherlands) ATHOS (Amsterdam, Netherlands), Net Zero Teeside (Teeside, England) (Global CCS Institute, 2019). In the long-term, as we approach a more and more decarbonised economy, CO_2 utilisation should however be limited to CO_2 originating directly from the atmosphere or biogenic sources. Not in the first place from an environmental perspective, but also because less CO_2 will be available as industry becomes less dependent on fossil fuels. An exception to this is the CO_2 from unavoidable process emissions emitted by cement, steel, iron and various chemical industries (Pérez-Fortes et al., 2014).

Market potential and scale

Only when the CCU product is economically feasible to produce and has enough market potential, it will be able to have a meaningful impact on climate mitigation. To estimate the market potential, one can look at the total demand for the product and the price competitiveness of the CCU product in relation to its competitors in the market. Other important factors might be the ability for a company to earn a sufficient internal rate of return from the CO_2 based product and the timescale on which the product could reach substantial market penetration. The scale refers to the total amount of CO_2 that can potentially be utilized within the product.

Technology Readiness Level (TRL)

TRL´s are used to estimate the maturity of technologies on a scale from 1 to 9 with 9 being the most mature technology. While they have their origin within NASA, they have also been adopted by several other institutions such as the European Commision (Héder, 2017). Because of their consistency they can also prove useful to compare different technologies for carbon utilisation. The definitions of the different levels can be found in figure 3.

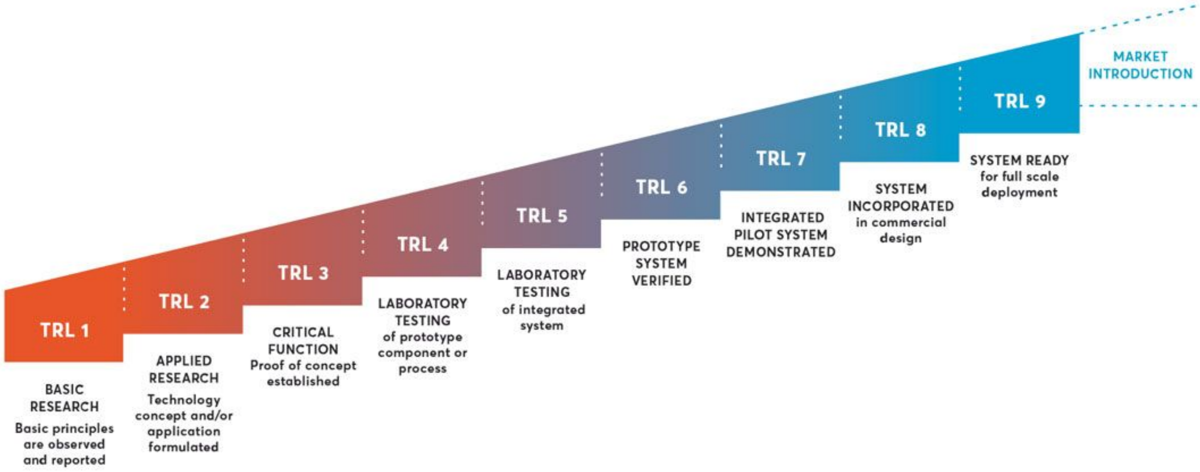

Figure 3: Visualisation of Technology Readiness Levels. Reprinted from (CIW, 2017).

3. Methods

Literature review

A literature review will be conducted to identify the most promising CCU pathways and analyse the challenges and drivers for these pathways. To better define the scope of this research the review will be centered around three different CCU applications, for which different pathways will be discussed. These applications are the conversion of CO2 into fuels, construction materials and chemicals. For the literature review the following scientific search engines will be used:

- Scopus
- Google Scholar
- Web of Science

Search terms include: Carbon Capture and Utilisation, CCU, CCUS, CDU, CO2 recycling, CO2 reuse, circular carbon and carbon economy. Other information on carbon utilisation can be obtained from organisations in the form of NGO´s or scientific networks. Such platforms include: Carbon180. Carbon Capture & Conversion Institute (CMC), CO2Chem, Global CCS Institute, Nova Institute and others. To identify promising CCU pathways, reference will be made in particular to techno-economic analyses in order to address the technological and market potential and life cycle analysis to address the climate mitigation potential.

Case-study

Complementary to the literature review, case-studies of companies and startups that utilise CO2 will be done to further identify challenges and opportunities around specific CCU pathways. These companies and startups can be found in the literature, but also in databases from sources like the Carbon Utilization Alliance and the Circular Carbon Network. Information will be gathered from the company websites, relevant literature and/or (news) articles.

Scenario narrative

A scenario narrative will be created that incorporates all the promising uses of CCU in the global context. Within this scenario it will also be explored for the different CCU pathways what assumptions one has to take in order for them to become a reality on a significant scale. A narrative will be created that explains what developments have to take place in terms of regulations, policies, technical capabilities, the economy or in other areas. This will be accompanied by visual models that illustrate how CCU will fit into the broader context of the energy system.

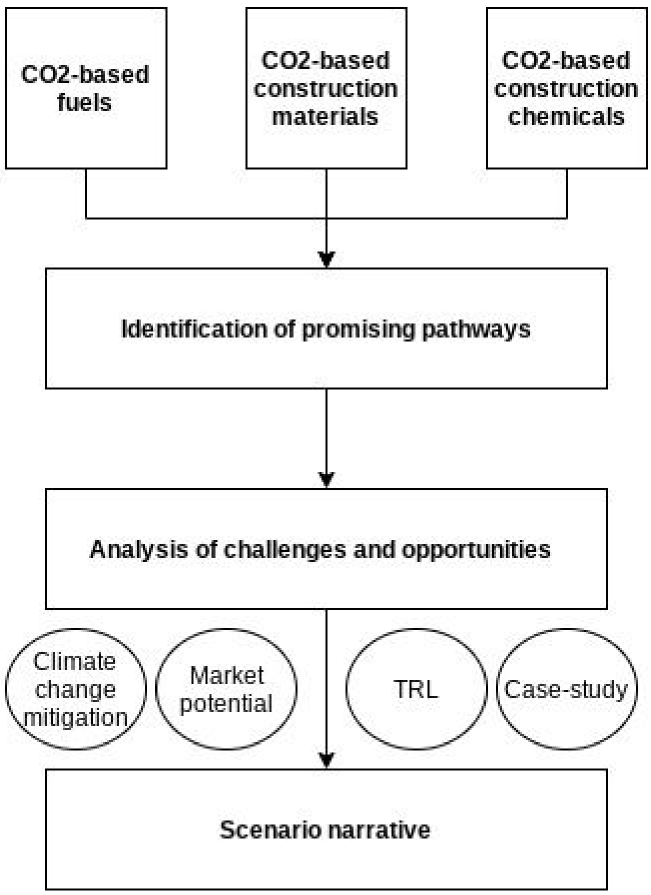

Figure 4: Methodological framework

4. CO2-based fuels

In this section a general analysis will be done for the potential role of CO2 based fuels in contributing to climate change mitigation. These fuels are the product of catalytic hydrogenation processes that convert captured CO2 into hydrocarbons. Intuitively the idea of synthetically produced hydrocarbon fuels actually contributing to climate change mitigation may seem a bit contradictory. After all, they will probably store CO2 for a timescale of no longer than weeks to months till they are combusted and consequently release CO2 to the atmosphere. However, when the life-cycle of these fuels is carbon-neutral or at least carbon-reducing due to the carbon being sourced from the atmosphere or an industrial point source their use might become interesting for multiple reasons. Namely for energy storage and the decarbonization of sectors that won´t be easily electrified, such as aviation (National Academies of Science, 2016). Renewable energy sources such as solar and wind energy are crucial in the transformation to a carbon-neutral energy system and are generating increasingly larger shares of the total electricity production (IEA, 2019). But because of their weather dependency, their output is greatly variable in space and time. In practice this means that in order for an energy system to efficiently run on solar and wind energy there is a need for complementary technologies that compensate its fluctuations. Energy needs to be stored, so it can be made available when needed. Moreover, not every sector can be (easily) electrified, as a result of which either fossil or synthetic fuels will still be needed. Even in a net-zero-emissions world, where electrification is pushed to its absolute limits, significant demand for hydrocarbon fuels will persist (Kraan et al., 2019). CCU technologies can offer solutions to both of these problems through ´Power-to-X´ applications; X in this context standing for either ‘liquid’ (gasoline, diesel, kerosine and additives such as methanol) or ‘gas’ (methane). The power-to-gas (PtG) pathway uses renewable energy to perform water electrolysis, which splits water into hydrogen (H2) and oxygen (O2). After this it is converted to methane by CO2 methanation with the help of a catalyst, according to the Sabatier reaction (Frontera et al., 2017). The power-to-liquids (PtL) approach is based upon the synthesis of a mixture of carbon monoxide and hydrogen (syngas) into liquid hydrocarbons using either the Fischer-Tropsch process or methanol synthesis. Since synthetic CO2-based fuels have the same chemical structure as conventional fuels they can be fed into existing infrastructure (gas and oil pipelines, storage facilities and filling stations), thus reducing the need for time consuming new infrastructure to be built. Moreover they also allow for use within existing end-user applications.

Instead of converting hydrogen and CO2 into hydrocarbons, the possibility of directly using hydrogen should also be considered. Using hydrogen as a fuel would eliminate the need for carbon and the associated additional energy consumption all together and would thus be the ideal fuel in a decarbonized world. Whenever it is feasible to use hydrogen as an energy carrier instead of hydrocarbon fuel, it should be preferred. But because hydrogen is not compatible with most of the current infrastructure and end-use applications it does have its limitations within the energy system (Kraan et al., 2019). For example, its application in the gas grid is restricted to a maximum volume of 0-12% (Newton, 2014). For energy storage there are also other ways to store energy besides the conversion of electricity into

CO2-based fuels such as pumped hydropower, large-scale batteries or compressed air. The downside of these alternatives is that most are limited to short-term storage or bound to geographical locations. Because of their negligible self-discharge rate, enormous energy capacity and existing infrastructure, storing energy in CO2-based fuels is ideal for long-term energy storage (Yan et al., 2019).

Market potential and scale

A roadmap study on synthetic fuels by the World Energy Council Germany (World Energy Council, 2018) provides a rough estimation of the size of a future global market for synthetic fuels in 2050. Within their low case they expect a demand of 10.000 TWh and in their high case they expect 41.000 TWh. This estimation is based upon assumptions of reasonable percentage shares for synthetic fuels in 2050 by sector. Since these are based upon expert guesses they should be approached only as first approximations, but they do illustrate the extensiveness of the synthetic fuel market. Another study made an estimation of the amount of CO2 that can potentially be utilized through the production of synthetic fuels. Based on the review of 11.000 CCU-related papers, a structured estimation process and an expert opinion survey they estimated the amount of CO2 that can potentially be utilized for the production of transportation fuels to be in the range of 0.9 to 4.2Gt CO2 per year (Hepburn et al., 2019). While these estimates might be overestimates if CO2-based fuels don´t become cost-competitive with alternative clean energy or direct sequestration, both studies do show that the potential market size and the amount of CO2 than can be utilised is very significant.

Challenges and drivers

While the potential for CO2-based fuels in terms of climate mitigation is there, it can take a considerable amount of time for CO2-based fuels to reach deployment at a significant scale. The enormous scale of the energy system makes it very time-consuming to build the human and industrial capacity that is required for new technologies like this to be deployed. Kramer & Haigh (2009) illustrate this by reflecting on the deployment of other energy technologies throughout the twentieth century and distill general rules that govern the deployment of energy technologies till they reach materiality and eventually settle at a fixed market share. For new technologies this means they usually go through a few decades of exponential growth, which is a period of learning by doing. This process takes off with building a demonstration plant and it can take a decade to reach the confidence that is needed to build a full-scale commercial plant. After that it often takes another one to scale this up to a dozen. Right now the technology is still operating on a very small scale, mainly through pilot plants. This means that large scale-up in the short term is not a very likely scenario.

For CO2-based fuels to be deployed both on a significant level and in a way that benefits the climate, progression is needed on the level of renewable energy sources, sustainably sourced CO2 and production of clean hydrogen by electrolysis (Hepburn et al., 2019). Since the final product will have to compete with conventional fossil fuels like crude oil, the cost of CO2-based fuels will have to be of approximately the same order as these fossil fuels. With an optimistic yet plausible view on the development of the technology, this means that the cost of a barrel of fuel will have to reach a minimum of about $200/bbl (Kraan et al., 2019). This can be accomplished through optimisation and cost-reductions in the production process and possibly through policy support. Higher shares of renewable energy in the electricity grid will naturally make it more feasible to use this scarce source for the production of CO2-based fuels. With limited renewable electricity available, the optimal thing to do is to use it for technologies that are most beneficial to the climate in terms of energy requirement. It is clear that because of the high amount of energy required for this CCU pathway, other technologies such as power-to-heat or e-mobility (Kätelhön et al., 2019) will be more effective in reducing climate impact on the short-term. When the electricity demand for such technologies is met, utilising it for fuel production will become interesting. Renewables made up 26.2% of global electricity production in 2018 and are expected to rise to 45% by 2040 (REN21, 2019). From an energy perspective, CCU based fuels will therefore most likely become more interesting on the long-term (second half of the century) when renewable electricity is more available. Exceptions to this are the availability of surplus renewable energy or renewable energy from plants that are not linked to the power grid. Furthermore it can be interesting to concentrate the production of fuels in areas where the conditions make renewable energy production very favourable.

Another driver is the availability of low-cost clean hydrogen. This is especially important since electrolysis consumes by far the most electricity within the production process (World Energy Council, 2018). Three electrolyser technologies are available: the alkaline electrolyser (AEC), the proton exchange membrane electrolyser (PEMEC) and the solid oxide electrolyser (SOEC). The AEC and PEMEC are most mature (TRL 9 and TRL8) and already being commercialised, thus being most interesting in the short term. SOEC (TRL 6) has been demonstrated in an industrial environment. but is still in development. SOEC is however more interesting in the long-term because it provides higher capacity and very high efficiency (Zauner et al., 2018). At this moment the costs of electrolysis are still too expensive to produce cost-competitive synthetic fuel. However, this may change in the future when technology targets of $300/kW, as formulated by the US government are reached (U.S. Department of Energy, 2018). At these costs it becomes economically feasible to produce the synthetic fuel of $200/bbl as envisioned by (Kraan et al., 2019). Because of its potential role in a future low energy system, renewable hydrogen is getting more and more attention. Therefore the technology has been positively evolving in recent years and even outperformed forecasted values from 10 years ago (Store&GO, 2019).

Another significant driver of CO2-based fuels could be the successful deployment of direct air capture (DAC). While current CO2-based fuels are based on carbon flowing from the lithosphere (fossil resources) to the atmosphere, future net zero fuels should ideally be based around a cycle from atmosphere to atmosphere. To achieve this there are 2 options, namely DAC and biologically obtained CO2. The former option depends on biomass, which has its limitations because of its land-use requirements and consequential competition with food production. DAC on the other hand would be ideal because because it can be deployed virtually everywhere and has low land requirements. Right now DAC is still a relatively new and expensive technology, but it is slowly gaining momentum as more projects are developed and investments increase. A recent paper based upon a commercial DAC system by Carbon Engineering estimates levelized costs of $94 to $232 per tonne of CO2 captured from the atmosphere (Keith et al., 2018). This offers a perspective for reaching the cost of

$100 per tonne of CO_2 that is needed to reach a competitive fuel price, as it is envisioned by (Kraan et al., 2019).

Case studies

Power-to-Gas

Until now a small amount of Power-to-Gas projects and pilot plants have been developed. In 2013 one of the first big plants was set set up by Audi. They made a PtG-plant that utilizes CO_2 from a biogas plant together with green hydrogen produced with alkaline electrolysis to produce methane which is then distributed in the natural gas grid (Audi, n.d). While this plant is successful in showing the functionality of the PtG technology in practice, the scale is still quite small (6MW). In an effort to explore the feasibility of PtG on a larger scale, the EU cooperated with 27 partner organizations and companies to launch the Store&GO project. The project that ended in February 2020, aimed to demonstrate the feasibility of green methane as a way of coupling the electric and gas infrastructure for storage of renewable energy. The project included extensive research and the launch of 3 PtG pilot plants across Europe. In accordance with earlier statements, it was concluded that considering all sectors within the energy system, the need for fuels in the form of gases will likely stay very high. The study concluded that this will mainly be provided by power-to-gas (hydrogen or methane). Especially considering the intermittency of renewable energy and the limits to electrification, this seems plausible. Yet it is also acknowledged that to be commercially feasible in a timescale that is sufficient to contribute to mitigation targets, policy is needed to accelerate the technology´s development. These include support schemes for research programmes and more demonstration projects, but also policy measures that allow for market penetration of carbon neutral gases. The project roadmap gives a few options, among which are a rule-out of grey hydrogen and prescribing the admixing of carbon neutral gases within the gas system (Store&GO, 2019).

Power-to-Liquid

Where power-to-gas mainly proved interesting as a means of long-term electricity storage, power-to-liquid seems more interesting for connecting renewable electricity to the fuel market. This way it offers a solution for reducing greenhouse emissions in transport sectors that won´t be easily electrified and will continue to rely on liquid fuels with a high energy density per volume and mass. Various companies and projects have been developed within the PtL industry, but these are still limited to small industrial scale plants or pilot plants. One of these plants is developed by Carbon Recycling and has been running since 2012. They utilise flue gas CO_2 from a geothermal plant for the production of 4000 tonne of methanol per year, thus achieving CO_2 reductions of 90% compared to conventional fuel (CRI, 2018). Since then more plants have been developed and the technology has been steadily evolving. Recently a report by Kalavasta proposed a pathway to the large-scale production of synthetic kerosine in The Netherlands (Terwel & Kerkhoven, 2018). It is stated that economical feasibility is mainly dependent on the price of oil and the price of renewable electricity. Based on this knowledge, a few pathways are developed. In a plausible scenario it is concluded that a higher oil price (around $98/bbl), together with a fossil CO_2 tax of 20 euro per tonne, an electricity price of 2.9 cents per kWh and the option to sell oxygen from electrolysis against production price would be enough to make synthetic kerosene competitive. While these requirements might certainly be met in the future, it can be argued whether the timescale that is proposed on which these fuels are to be deployed is realistic. As more renewable electricity becomes available it seems likely that this scarce resource will first have to meet the needs of consumers and/or industry. Nonetheless, the report definitely proves that there is great potential for synthetic kerosene in reducing the climate impact of the aviation industry. Especially when more and more renewable electricity is available and the technology is being further developed. Right now the technology will benefit from experiments and pilot plants such as the one that is in development at Rotterdam/The Hague airport (EDL, 2019). This project aims to build a demonstration plant producing 1000L of jet fuel per day using direct air capture, conversion into syngas using electrolysis and consequently the production into fuel by Fischer-Tropsch synthesis.

5. CO2-based chemical products

In this section it will be analysed what the potential will be of CO2-based chemical products for climate change mitigation. The chemical industry, like many other sectors, will have to make great efforts in order to meet climate goals and reduce their CO2 emissions. While the industry can come a long way by meeting the energy demand with renewable sources and optimising processes through efficiency measures, there is still one obstacle that will remain. This lies in the fact that 58% of fossil resources consumed in the chemical industry, are used directly as a feedstock for chemical products (IEA, 2017). The great majority of end-products from the chemical industry are carbon-based and while it is possible to change the source of this carbon, it is difficult to imagine its substitution (Aresta & Nocito, 2019). The potential of CCU for the chemical industry is therefore grounded in its capability to replace the fossil carbon feedstock with a renewable carbon feedstock. Through a variety of chemical and biochemical conversions CCU technologies are able to transform CO2 into the chemicals (final products or intermediates) and polymers that make up the industry (Zhu et al., 2019).

Instead of using CCU pathways to reduce CO2 emissions from carbon based chemicals, it is also possible to keep using fossil feedstocks, but instead focus on capturing the CO2 at the end-of-life using a CCS approach. In this approach CO2 can be captured from a point-source (where the end-product is incinerated) or from the air to balance out the emissions. In contrast to the CCU pathway this option means that the CO2 will be stored underground instead of recycled back into new chemical building blocks. Gabrielli et al. (2020) performed a quantitative analysis where they compared CCS and CCU application in the chemical industry for the specific case of methanol production. Since the majority of chemical products can be synthesized through methanol (Kätelhon et al., 2018), this seems like a good case to get an idea of the requirements for respectively CCS and CCU for the whole industry. Their comparison showed that in order to neutralize the CO2 emissions from methanol, CCU has an energy requirement that is at least 10 times higher than CCS. Because CCS also has the advantage that it fits within the current infrastructure of the (petro)chemical industry (Gabrielli et al., 2020), it might be the preferred route compared to CCU in the short-term. Utilisation of CO2 in the chemical industry might however still be interesting in some cases:

- where CO2 storage is not possible or fossil resources are limited;
- where the utilisation process is not as energy intensive or excess energy is available;

- as a means of promoting the circular economy.

When considering the latter option, the focus should be on producing chemical products that are easier to recycle and have longer lifetimes (Accenture, 2017). CCU then acts as a last resort for retrieving carbon from non-recyclable products when they have reached their end-of-life.

Market potential and scale

The chemical market that can potentially be reached by CO2 utilisation is quite diverse. The biggest markets in terms of size and potential CO2 uptake for chemicals are urea, ethanol, methanol, formaldehyde, polyurethane, dimethyl ether and various acids (Chauvy et al., 2019). Based on the current market conditions the production of these chemicals through CO2 could potentially allow for CO2 to be utilized on a scale of 300-400 Mt of CO2 annually. This is largely in line with the estimation made by Hepburn et al. (2019), which estimated the potential of CO2 utilization for chemicals to be in the range of 300-600 Mt of CO2. The difference can be explained because Hepburn et al. (2019) considers the market in 2050, while Chauvy et al. (2019) considers the current market.

Challenges and drivers

Just like fuels derived from CO2, the conversion into chemicals is often dependent on hydrogen to co-react with CO2. This makes the application of CCU for the production of chemicals very energy-intensive. Kätelhön et al. (2018) attempted to estimate the amount of energy that would be required to produce 20 of the large-volume chemicals that together account for 75% of the industry´s emissions by 2030 and concluded this would equal 55-97% of the total expected world electricity production. To meet this enormous energy demand, a rapid increase in renewable electricity production would be required. Therefore, just like the CO2-based fuels the implementation of CCU for chemicals will be mostly driven by improvements in the efficiency of water electrolysis and the availability of renewable electricity.

To increase the rate at which fossil feedstocks are replaced by recycled and CCU-based feedstocks there are also policy measures that can help achieve this goal. Carus & Raschka (2018) and other authors in the CCU field discuss a few of those options. These include (but are certainly not limited to): the taxation of fossil carbon in chemicals and plastics, rewarding schemes or quotas for the production of chemicals from renewable CO2 and the introduction of binding targets for the utilisation of CO2.

Case studies

Various companies are utilizing CO2 for the production of polymers, which is done through the process of copolymerization of CO2 and epoxides (Langanke et al., 2014). This pathway is especially interesting since it requires relatively little energy input, the reaction can take place in existing reactors and the CO2 can substitute for a portion of the required fossil-derived epoxide (Zhu et al., 2016). The replacement of epoxide with CO2 can potentially result in both economic and environmental benefits (Von der Assen et al., 2014; Zhu et al., 2016). Covestro is one of the companies in this field and developed a catalyst system that is already being used on a commercial scale to produce polycarbonate polyols containing up to 20% of CO_2 (Robinson, 2016). These polyols can then also be used to produce polyurethanes, which have a large market and an annual production rate of approximately 15Mt (Lee et al., 2012; Aresta et al, 2013). With a CO_2 utilisation rate of 20%, this means that theoretically 3Mt of CO_2 could be used in this sector. While this might not seem like much in comparison to total global emissions, the economical benefit and fossil resource savings can still make it a worthwhile process.

6. CO2 used in construction materials

This section will be dedicated to analysing the potential for climate change mitigation by utilizing CO_2 in construction materials. Therefore 2 options exist:

- CO_2 be mineralised, essentially mimicking the natural process of silicate weathering where silicate rocks are transformed into carbonate rocks (Olajire, 2013). In this artificial process CO_2 is chemically reacted with alkaline calcium- or magnesium-containing minerals to form calcium or magnesium carbonate ($CaCO_3$ and $MgCO_3$). This product can then be used as an aggregate or for other applications in construction materials.
- During the process of curing concrete (which gives concrete its strength and durability, it is possible to inject CO_2 into the wet concrete mix which is then sequestered into the material (Xuan et al., 2018).

In contrast to the previously discussed pathways of chemicals and fuels, CO_2 that is utilized by mineralization or during a curing process has the potential to be stored on a timescale of decades to centuries. This makes the pathway similar to CCS, where CO_2 is also stored for a long period of time and allows it to potentially contribute to negative emissions. Besides just sequestering the CO_2, it also provides an option to re-use it in a useful way while generating economic revenue. In order to actually mineralize CO_2, it will be essential to have some source of calcium or magnesium to react with the CO_2 and form a carbonate. There are different feedstocks that can be employed for this purpose, among which are silicate minerals that contain calcium or magnesium. These minerals are widespread and can be found all around the world in large quantities. Their numbers far exceed the total global CO_2 emissions that could possibly be emitted with our current fossil reserves, theoretically allowing for all future CO_2 emissions to be mineralized (Matter & Kelemen, 2009). However, the potential for mineral carbonation will be limited by our global market demand and disposal capacity (Sanna et al., 2014). It is important to realise that the use minerals to react with CO_2 will also involve extensive mining and transport that can result in additional CO_2 emissions and other negative environmental impacts. An alternative, yet less abundant feedstock to these natural minerals can be found in various artificial forms such as steel slag, waste concrete and incinerator bottom ash (Rendek et al., 2006; Huijgen et al., 2005; Ghacham et al., 2015). The benefit of using these materials for CO_2 mineralization is that they offer a solution for the landfilling of these waste products, thereby promoting the circular economy and preventing the chemical contamination that they can cause.

In order for carbonation to be a feasible option for large-scale CO_2 utilization, the natural process of mineral carbonation proceeds way too slow. Therefore artificial carbonation processes have been designed to accelerate this process by altering the conditions under which the process takes place. These accelerated carbonation technologies utilize different strategies (that can also be combined) that involve raising the pressure and/or temperature under which the reaction takes place or the addition of highly energetic chemicals (Sanna et al., 2014). The addition of a chemical to enhance the mineralisation process will always result in the formation of a (salt) by-product. For that reason this strategy also requires a regeneration step to convert the by-product into reactants again that can be recycled back into the process. It becomes clear that even though the natural mineralisation process is thermodynamically favourable and does not consume any additional energy, the accelerated mineralisation process will require some form of energy. So all in all the mineralization of CO_2 will require both a material input and an energy input. To truly function as a climate mitigation option, CO_2 emissions resulting from these inputs should be lower than the CO_2 that is sequestered in the mineralization process. To achieve this in the best possible way the energy requirement should be minimised and generated by clean (renewable) sources.

In countries where carbon capture and storage is not possible due to a lack of nearby geological reservoirs, CO_2 mineralization can act as an alternative. The carbonates that are formed from mineral composition are highly stable, so there is no risk of leakage. Alternatively, as suggested by (Yeo & Bu, 2019) there might be countries or coastal cities that can benefit from the production of solid carbonates to realise land reclamation and defenses against rising sea levels. Furthermore, curing of concrete with CO_2 can accelerate the curing process and increase strength and durability of the concrete (El-Hassan & Shao, 2014).

Market potential and scale

A recent article estimated the scale on which CO_2 can be utilised in construction materials to be in the range of 0.1 to 1.4Gt per year, with by far the largest potential for the use of CO_2 as a cement curing agent for the production of concrete (Hepburn et al., 2019). While the estimate also includes aggregates that are produced from industrial alkaline waste materials, the scale of this pathway is limited by the global availability of these materials. Annually about 470-610 million tonnes of steel and iron slag is produced, which allows for 143-186 million tonnes of CO_2 to be sequestered (Shi, 2004). The annual production of incineration bottom ash is estimated to be 130 million tonnes, which according to a rough calculation allows for the sequestration of 8-10 million tonnes of CO_2. Apart from these 2 examples there is also the possibility to use a fair amount of cement waste, construction waste, coal ash and red mud, but all together the feedstock will be finite (Kelemen et al., 2019). CO_2 curing on the other hand can theoretically be applied to all precast concrete and masonry where-in closed curing is feasible (El-Hassan & Shao, 2014)

Challenges and drivers

One of the bigger obstacles to CO_2 mineralization remains the high amount of energy that is required to accelerate the process to such an extent that it becomes practical for a wide-scale deployment (Yeo & Bu, 2019). Because of this the process is usually too expensive to make sense from an economical perspective (Kelemen et al., 2019). However, the overall energy requirements of the process can be significantly lowered by by operating mineral carbonation on the flue gases directly, thereby eliminating the energy need for CO2 separation (Verduyn et al., 2011). Opportunities for less energy intensive CO2 mineralization might also arise where favourable conditions come together, for example where a source of concentrated CO2 and waste heat are close to a source of minerals such as a mine or an industry producing highly alkaline waste (Kelemen et al., 2019). Costs might also go down as a consequence of economies of scale. To realise economies of scale and accelerate developments of CO2 mineralization, a good start might be to make use of the low hanging fruits in the form of industrial waste or incineration ash (Yeo & Bu, 2019). From these sources the required calcium and magnesium can be obtained most easily and energy efficient. Developments in this pathway can then potentially result in more diverse applications of the produced solid carbonates or more economically feasible conditions for the use of abundant minerals in CO2 mineralization processes.

Case studies

Because CO2 curing was deemed to be a promising technology, an analysis was done on the climate mitigation potential for a company called Carboncure. This company has developed a process to produce concrete by curing with CO2. It reduces the total emissions of the construction sector by storing CO2 into concrete and by lowering the cement requirement in the curing process. Using data provided by Carboncure and additional literature on the market potential of Carboncure´s product and CO2 intensity of cement, it was calculated that the total amount of CO2 that can realistically be utilised in the product and avoided by lower cement use is respectively 45.5Mt CO2/yr and 93.15 Mt CO2/yr. While these are definitely significant reductions, it does assume that the complete precast concrete industry will be using Carboncure´s method. It was found that the achieved cement reduction will result in savings that are higher than the cost of the CO2 that is injected during the curing process, thus making the process economically feasible.

However, even when the Carboncure technology is deployed among the whole sector, the need for cement will remain. In an optimistic scenario where all the energy requirements for cement production will be met using renewable electricity or a clean fuel, a considerable amount of unavoidable CO2 will still be emitted during the calcination of limestone. In a carbon-neutral society those emissions will have to be captured, either from the flue gas or using negative emissions technologies such as direct-air capture etc. It seems likely that if the cement industry wants to achieve their climate goals, CCS has to be deployed regardless of other mitigation strategies. Therefore being able to use this waste CO2 further along the process chain might become extra interesting. Although it would still require a significant amount of CO2 to be stored or put to another use, since the CO2 emitted cannot be all used in the curing process. In the end, the most Carboncure can do to mitigate climate change is reducing cement use and its emissions by providing a viable business case and in the meantime adhere to the principles of a circular economy.

Besides Carboncure, many other promising companies are operating within the CO2 utilization sector for construction materials. All of them seem to focus on either producing CO2 containing aggregates, concrete blocks that are cured with CO2 and using CO2 to upcycle industrial waste. Blue Planet developed a process that captures CO2 from flue gas with a water-based capture solution and consequently converts it into carbonate. This can then be used as an aggregate for the use in concrete (Blue Planet, 2015). A potential benefit of the Blue Planet process is that they convert the CO2 directly at the capture point, without need for purification (thus reducing energy requirements). Another company called Carbicrete uses the CO2 mineralization process to produce concrete building blocks completely from waste materials. They eliminate the need for cement by curing with CO2 and using a mix of recycled aggregates and steel slag (Carbicrete, 2020). This way the process can deliver CO2 reductions by the avoidance of cement emissions and through the capture of CO2 during curing. Mahoutian (2016) went through the same production process and demonstrated the economical and material benefits that are claimed by Carbicrete. One limitation is that the Carbicrete process relies completely on a source of industrial waste. Other companies include Carbon8 (carbonation of industrial waste to produce aggregates), CO2Concrete (converting flue gas into limestone for concrete production) and Solidia (curing with CO2 to produce concrete).

7. Scenario´s for CCU

In this chapter, an ideal scenario is illustrated for the integration of every respective pathway in the energy system. Below the figures, it is also briefly stated what the pros and cons of the pathway are.

CO2-based fuels

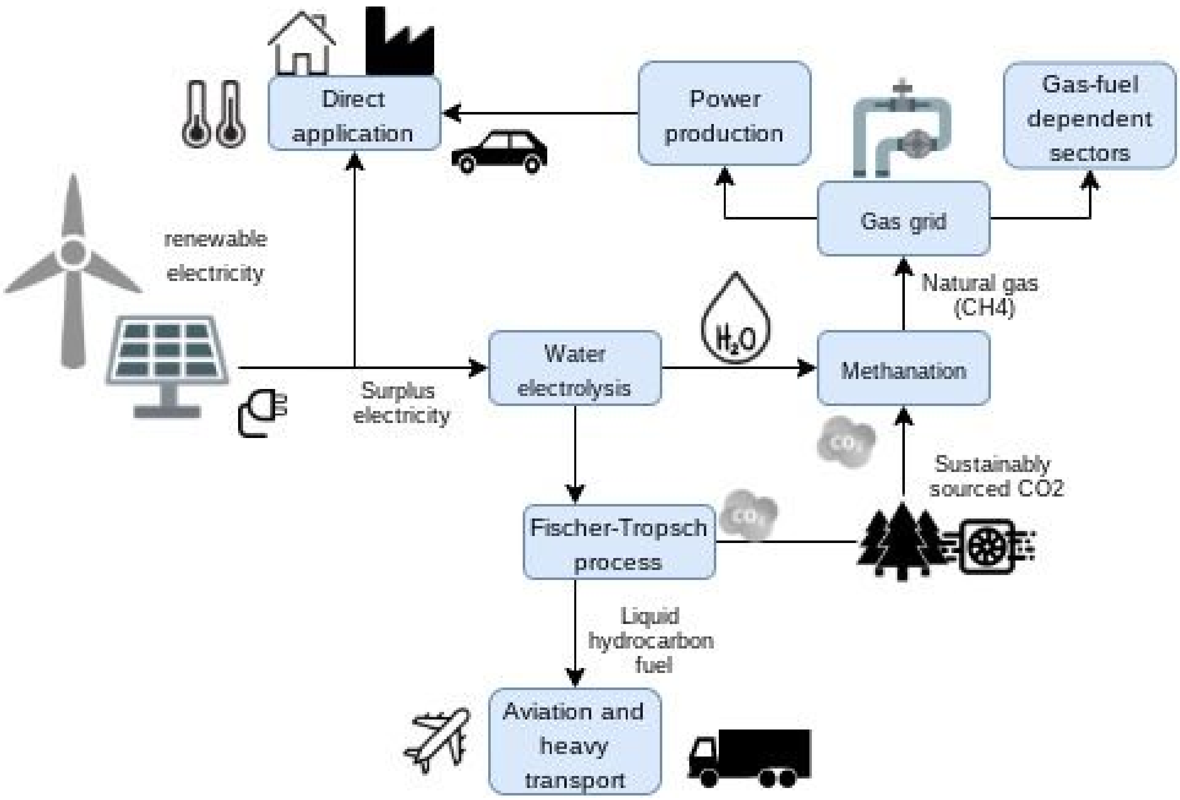

Figure 5. Ideal integration into the energy system for the production of fuels from CO2.

+ Offers flexibility to an electricity grid powered by intermittent renewable electricity
+ Renewable electricity can be indirectly provided to sectors that need high-energy fuels that are easy to transport and store (e.g. aviation and heavy transport).
+ Compatible with current infrastructure
- Very energy intensive
- Not price competitive with conventional fossil fuels

CO2-based chemicals

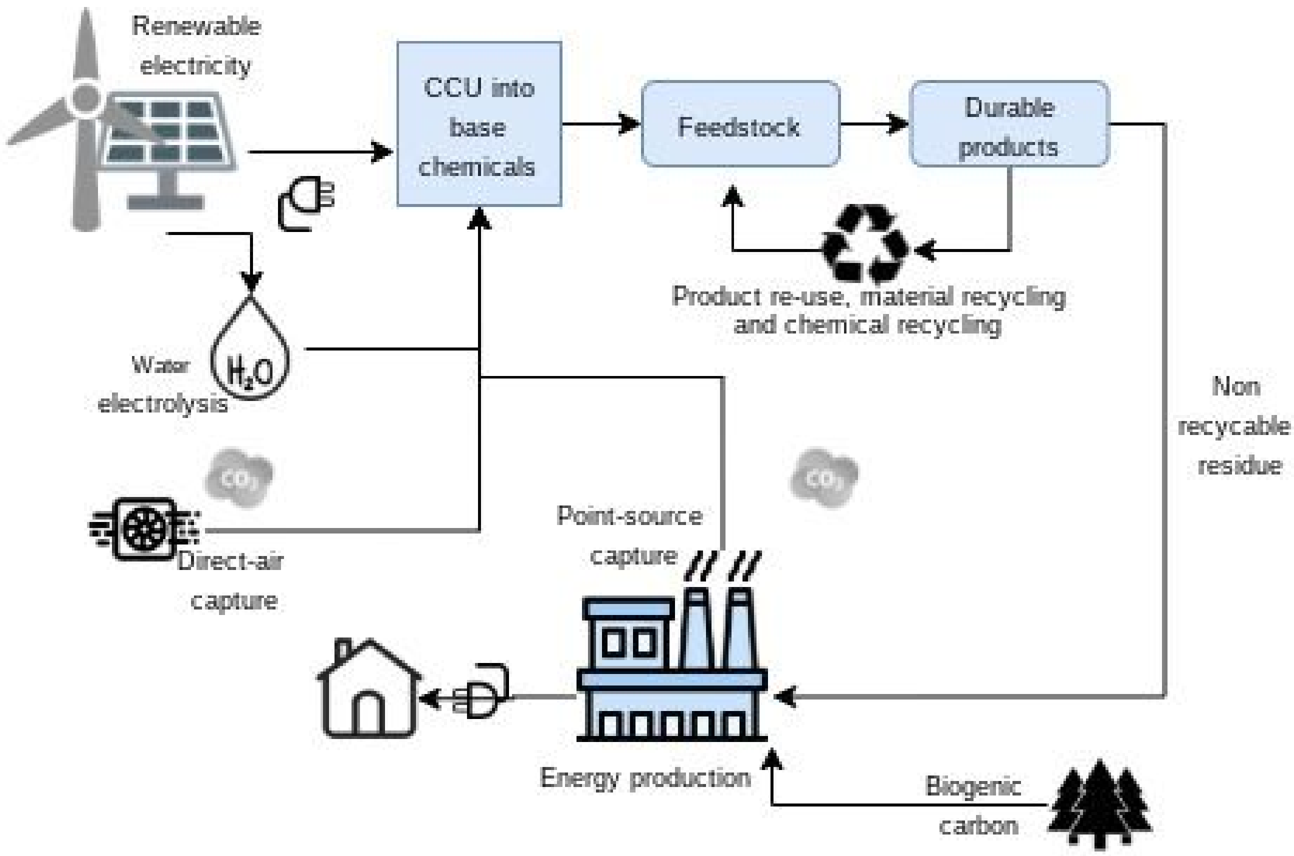

Figure 6. Ideal integration into the energy system for the production of chemicals from CO2.

+ Promotes circular economy
+ Reduction or avoidance of fossil resources needed in chemical production
- Very energy intensive
- Significant changes in production process

CO2-used in construction materials

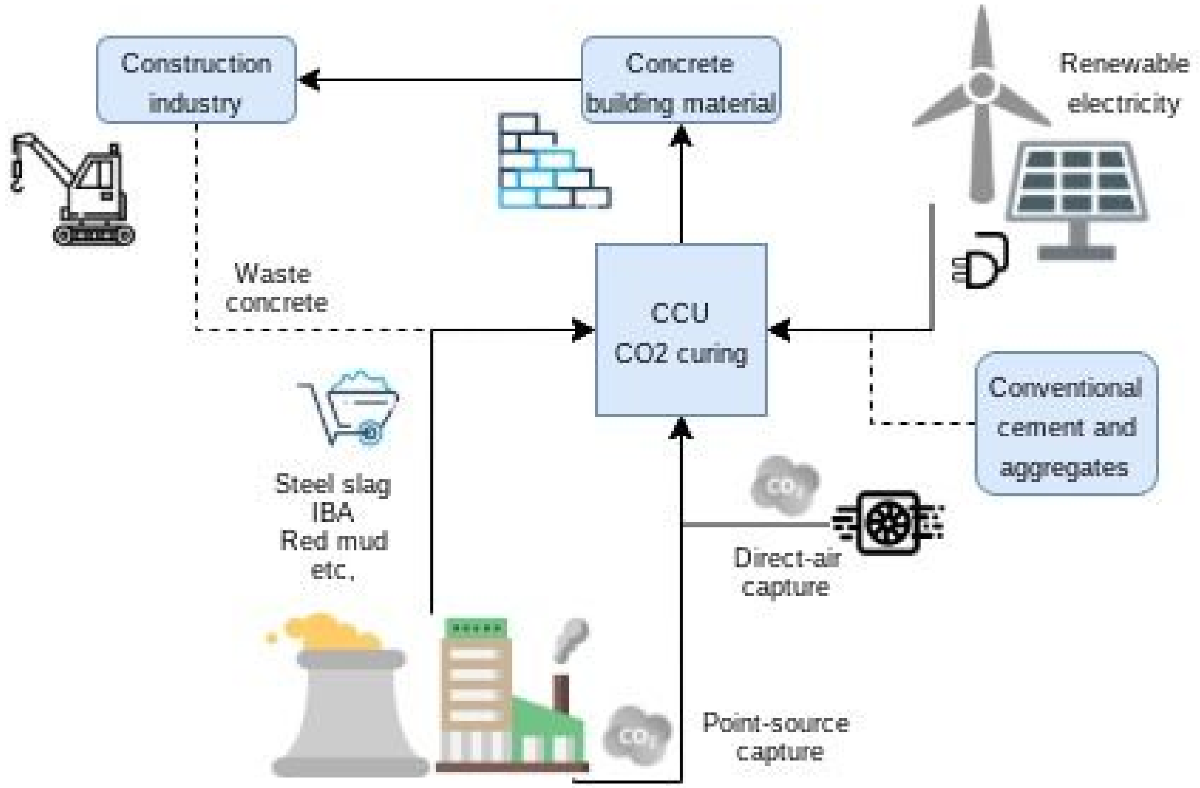

Figure 7. Ideal integration into the energy system for the production of construction materials from CO2.

- \+ Less cement is needed resulting in CO2 reductions
- \+ Waste products can be recycled
- \+ CO2 is permanently stored
- \+ CO2 curing process is faster and results into additional benefits for the product (strength, durability)
- \- Energy intensive
- \- Unless alternative for cement is used, emissions remain and CCS or CDR is required to be carbon-neutral

8. Conclusions and discussion

The potential for CCU to contribute meaningfully in the fight against climate change seems significant in every pathway that was discussed in this paper. Concerning fuels, CCU can be a great option for long-term storage of renewable electricity and to meet the energy demands of sectors that are hard to electrify. The chemical industry on the other hand can benefit from the utilisation of CO2 through the replacement of fossil feedstocks with CCU-based substitutes and the establishment of a closed loop where the carbon within end-of-life materials is captured and re-used in new chemicals. Furthermore, mineralization of CO2 can turn construction materials into significant carbon sinks, while also providing material benefits and recycling options for industrial waste. Most of the pathways that are discussed will however require large amounts of energy that in order to contribute meaningfully to climate mitigation will have to be provided in a clean way without coming at the expense of other more efficient mitigation options. Additionally all the technologies rely to greater or lesser extent on the availability of CO2 and co-reactors such as hydrogen or industrial waste. Since the technology is still at such an early stage and often not competitive with conventional processes, it is likely that when its potential gets realised, this will start by harvesting low-hanging fruits. For most pathways that means at locations with relatively cheap CO2 sources nearby such as at industry clusters (Psarras et al, 2017) or CO2 hubs as discussed in chapter 2. But also locations that are close to a source of clean energy (e.g. wind farms, geothermal energy or other renewables) and the required feedstocks for the utilisation processes. Due to the limited availability of locations with these favourable conditions, deployment of CCU in the short-term will probably remain small-scale.

Based on the findings of this research we can say something about the scale on which CO2-based fuels, chemicals and construction materials can realistically be produced from a market perspective. But in the long term there are various technological, economical and regulatory developments that can influence the exact rate and scale on which CCU will or will not reach this potential (see also table 1). Examples of influential measures that can be taken by governments are:

- including CCU in climate policy;
- increasing CO2 prices which will make CCU more economically attractive;
- offering feed-in tariffs or quotas for CO2-based products resulting in a better business case;
- create subsidies and financing for CCU projects.

Its deployment can also be accelerated through technological breakthroughs in the field of electrolysis, catalysis, CO2 capture or other relevant technologies. Furthermore CCU deployment could be driven by scarcity in fossil resources or the lack of other mitigation strategies being deployed. However, fact remains that for CCU to be widely deployed a very large proportion of the total electricity production will have to be renewable. Because this is unlikely to happen in the short-term, the author expects that if CCU deployment becomes more significant, this will happen from the second half of the 21st century. Around this time it can also be expected that CO2 hubs have become a reality, which will also benefit CCU because of the available CO2 infrastructure. While all the pathways in this sector are likely to experience more adoption in the future, it is expected that especially the conversion into fuels could see the significant application. The reason for this is that increasingly large shares of renewable electricity in the grid will require long-term storage options and sectors such a aviation and heavy transport will almost certainly require high-density fuels.

Category	Drivers
Conditions	- Availability of a CO_2 source - Availability of cheap and clean energy - Availability of required co-reactors - Scarce fossil resources

Technology	- Technological developments regarding efficiency and scalability in the field of:
	    - electrolysis
	    - catalysis science
	    - CO_2 capture
	- (Lack of) development competing technologies

Policy	- CO_2 tax - Financing or subsidizing CCU projects - Inclusion of CCU in climate policy - Feed-in tariffs or quotas for CO_2-based products

Table 1. Potential drivers of more wide-scale CCU deployment.

Discussion

While the arguments presented in this thesis may give a reasonably optimistic image of the use of CCU in terms of climate change mitigation, there are also a fair amount of authors who are less optimistic. Mac Dowell (2017) argues that apart from enhanced oil recovery, CCU technologies will only be able to sequester a small amount of CO_2 in relation to our total mitigation challenge. However, this argument only accounts for CO_2 that is permanently stored as is the case with CCS. The added value of CCU as presented in this thesis is mainly grounded on its ability to replace fossil based resources in the chemical and energy industry or as fuels for the transportation sector. By reducing our need for fossil based resources in sectors like this (where electrification is not an option), CCU still adds to climate mitigation even though it doesn´t necessarily permanently store CO_2. The article by Mac Dowell (2017) might also underestimate the use of CO_2 in building materials, since this CCU pathway can actually sequester CO_2 in the long-term and even add value by producing stronger concrete.

Furthermore it should be noted that the scope of this research is fairly limited, since it mostly looked in a generalised way at the opportunities for CCU. To further address the climate change mitigation potential of CCU it useful among many things to to identify locations with favourable characteristics for CCU, perform detailed life-cycle analyses of promising pathways and perform in-depth comparisons with competing technologies.

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Appendix I. Potential CO_2 uptake and avoidance of Carboncure process

General information	
Goal	Reducing the embodied carbon footprint of the built environment by sequestering CO2 in concrete while reducing cement use. Goal of saving 500Mt of CO2 annually. Cement use is reduced by 5% (Monkman, 2017)
Process	Once injected into the wet concrete mix, the CO_2 reacts with calcium ions from cement to form a nano-sized mineral, Calcium Carbonate, which becomes embedded in the concrete. This makes the concrete stronger, enabling mix optimization while eliminating the CO_2.
CO2 intensities and scale	
Global cement production	4.1 Gt/yr (IEA, 2019)
Estimated cement used for ready-mix and precast concrete (the potential market for Carboncure)	3.45 Gt/yr (Information is hard to find, but estimated on data from the USA Geoliogical Survey: 84.2% (3.45 Gt/yr) of cement is used in ready-mix and precast concrete (Kelly, 2014) Assumptions: 1) Cement use from the USA is representative of global cement use. 2) Proportions different end-uses did not change since 2003)
CO2 intensity cement	0.54t CO2/t cement (IEA, 2019)
Clinker-to-cement ratio	0.65 (IEA, 2018)
Carboncure process	
Potential amount of CO2 utilised in products	45.5Mt CO2/yr (The CO2 that can be added is equivalent to 1.5% by weight of cement and absorbed at 88% efficiency (Monkman, 2016) --> Total potential amount of CO2 stored = 3.45 Gt/yr*1.5%*88%=45.5Mt CO2/yr)
Potential amount of CO2 avoided through products	93.15Mt CO2/yr (5% of cement use can be reduced using Carboncure process. This can potentially add up to emission reductions of 0.05*3.45 Gt/yr*0.54tCO2/t cement= 93.15 Mt CO/yr avoided. Because less cement is needed, there will also be CO2 emissions due to avoided material transport. However these are assumed to be negligible in contrast to the process emissions that are avoided.)
Indirect CO2 emissions.	A small amount of CO2 is emitted as a result of building the equipment, processing and transporting CO2 etc. This amount is however less than the CO2 absorbed (Monkman, 2017) and will thus be cancelled out.
Economic feasibility	No specific costs of processes or labour required can be found, so factors that are taken into consideration are the capture cost of CO2 and the cost of the saved cement. In comparison to conventional concrete production where 100 tonnes of cement are used, Carboncure allows for a reduction of 5 tonnes. Next to that 1.5%* 95 tonnes = 1.425 tonne CO2 is added. Based on an estimated price of 60$/t of cement (Alibaba, n.d.), costs will be reduced by 5*$60=$300. Assuming that CO2 is captured at the cement industry, the capture costs can be estimated at $48/tCO2-$94t/CO2 depending on the capture method (Gardarsdottir, 2019). Based on this scenario a net saving is achieved of $206-$252 for every 95 tonne of cement used.