Feedstock for the process industries and climate action –

The potential of CO_2 utilization

A brief overview

2nd Report of the Thematic Working Group on:

CO_2 capture and utilization

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About the CCUS Projects Network

The CCUS Projects Network comprises and supports major industrial projects under way across Europe in the field of carbon capture and storage (CCS) and carbon capture and utilisation (CCU). Our Network aims to speed up delivery of these technologies, which the European Commission recognises as crucial to achieving 2050 climate targets. By sharing knowledge and learning from each other, our project members will drive forward the delivery and deployment of CCS and CCU, enabling Europe's member states to reduce emissions from industry, electricity, transport and heat.

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Executive summary

This report follows from discussions at the European CCUS Projects Network's third knowledge-sharing event for members, held in Brussels on 23rd January 2020. The aim of the report is to illustrate that Carbon Capture and Utilization is an important pathway to be considered for the chemical industry and to discuss its feasibility as climate action. The report gives an overview about the potential of CCU to reduce GHG emissions and depicts the hurdles to implement CCU technologies on a large scale. Secondly, the report highlights how important it is to find industrial sources of CO_2 that match volumes and requirements from specific CCU technologies.

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Feedstock for the process industries and climate action – The potential of CO_2 utilization

1 Introduction

The chemical industry is currently dependent on fossil raw materials and uses around 28% of the industrial and approximately 10% of the global final energy [1]. The majority of it is covered by oil and gas which are used as carbon feedstock or to generate process energy. A large fraction of the fossil fuels used to power processes can theoretically be replaced by renewable energy sources through electrification. Nevertheless, the chemical industry is dependent on raw materials containing carbon. Therefore, especially between 2030 and 2050, when other sectors like transport and buildings will use less fossil fuels because of electrification, the chemical industry is expected to become the single largest consumer of oil [2].

In order to replace fossil raw materials, the chemical industry evaluates the possibility to use carbon dioxide (CO_2)[1] or biogenic raw materials as alternative carbon sources. Using CO_2 as raw material is referred to as carbon dioxide utilisation. As the CO_2 must be captured from a CO_2 source first, the overall process is called carbon dioxide capture and utilization (CCU). Using biogenic raw materials that intrinsically contain carbon represents another possible pathway to replace carbon feedstock currently coming from fossil feedstock. Thus, it is important to highlight that CCU is a promising pathway to help in the *defossilising* of the chemical industry, which requires becoming independent from fossil carbon sources for the synthesis of organic chemical products.

During the past years, the chemical industry reduced its fossil fuel demand massively by means of process intensification and improved energy efficiency. Unfortunately, the potential of those options to lower greenhouse gas (GHG) emissions are almost exhausted [3]. The chemical industry still emits about 1.5 Gt of CO_2-equivalent GHG emissions per year [4]. Fortunately, besides providing the chemical industry with carbon, CCU technologies can – under specific conditions – contribute to reducing GHG emissions in comparison to the business-as-usual (BAU) benchmark process. The required CO_2 to substitute fossil carbon can be captured from industrial point sources or with help of direct air capture (DAC) from the atmosphere. Carbon Dioxide Capture and Storage (CCS) is an option to lower the GHG emissions caused by the oil, gas, and coal consumption for the generation of process energy.

CCU comprises several independent pathways where CO_2 is employed as a chemical component that is either used without a reaction process or reacts with another substance to form other chemicals, fuels or building materials. Figure 1 depicts the most recognized products from CO_2 and an indication of their market size. Furthermore, the various CCU paths are classified according to their so-called technology readiness levels, whereby TRL 1[2] stands for basic technology principles and TRL 9 for a process that has already reached market launch.

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[1] Note that carbon monoxide (CO) is also considered as a carbon source in some cases.

[2] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

The pathways of direct use of CO_2 do not have the goal to reduce CO_2-emissions in the first place. In these cases, the CO_2 is used because of its characteristics and the consequential function of it. For example, enhanced oil recovery (EOR) can be seen as CCU given that CO_2 is used to produce more efficiently oil from reservoirs. On the one side, the CO_2 is stored in the reservoir, but on the flipside, the produced oil will cause additional GHG emissions [5].

As the target products often have no connection to each other, and the chemistry of different CCU pathways are different, it is difficult to compare CCU pathways, or in other words, it is impossible to discuss a given CCU pathway as being representative for others. Furthermore, different studies on CCU use different definitions. Therefore, the published studies on the potential of CCU have different underlining data as it comes from different selections of CCU pathways.

Nevertheless, evaluations from various institutions highlight that CCU will contribute to lowering GHG emissions and can be seen as one piece of a puzzle in transforming the industry as well as in helping to reach the ambitious EU climate goals for 2030 and 2050 [2][4].

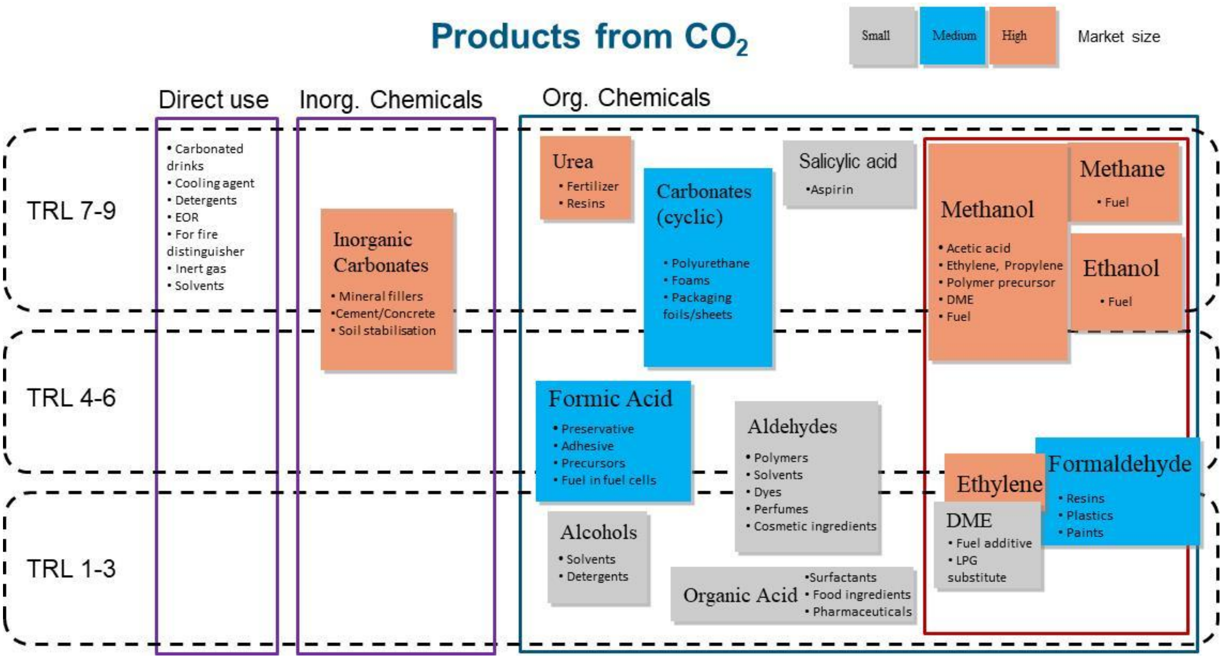

Figure 1: Products obtained by various CCU pathways

1.1 Objective and scope

The present report focuses predominantly on CCU's role in climate change mitigation. The answers for the following questions shall help to understand and exploit the potential of CO_2 utilization for climate action as well as the synergies between the carbon mitigation management options, CCU, CCS and using bio-based raw materials:

- What are the volumes of CO_2 emissions saved for the most relevant CCU pathways (incl. an explanation about set-ups where CO_2 is circulated and examples where CCU can just be seen as efficiency action to have lower CO_2 emissions in comparison to a benchmark case?

- What CO_2 purity is required for CCU processes?
- Where are the synergies between CCU and CCS?

The objective of the report is to discuss how the various CCU technologies can contribute to reduce GHG emissions and what the hurdles for a large roll-out are. Furthermore, the report focuses on identifying and assessing those CCU pathways that have the highest potential to reduce GHG emissions of the industry and/or bring in another benefit in respect to sustainability such as improved carbon circularity.

Members of the European CCUS Projects Network in the CO_2 capture and utilization thematic working group were interested in further discussing the potential of CCU in climate action and how synergies between CCU and CCS can be unleashed. Also, it was concluded that information on the requirements for the purity of CO_2-streams for CCU pathways would be useful to the individual CCUS Projects Network members, as well as for the future work of the group.

1.2 Report structure

This report consists of three main sections. The first section addresses the potential of CCU to reduce GHG emissions and describes the mechanisms by which CO_2 savings are obtained. The second section provides the potential contribution of CCU (in different sectors) towards GHG emission reduction. The third section stresses out the importance of finding the most convenient CO_2 source with respect to the characteristics and availability for CCU pathways.

2 The role of CCU in a carbon neutral future

2.1 CCU as a tool to defossilise the chemical industry

In theory, a considerable part of the chemical industry can apply CCU and replace fossil fuels and feedstock. As mentioned in the introduction, the chemical industry represents a highly energy-intensive sector and is critically dependent on carbon sources for the production of most chemicals and intermediates thus, “decarbonisation” is not an option for the chemical industry. Currently, as production relies to a large extent on fossil feedstock, substantial CO_2 emissions are caused, either directly or indirectly, thus we should aim at “defossilising” the chemical industry. CCU, power-to-X technologies, the use of biomass as feedstock and recycling of carbon-materials to close the carbon cycle offer alternative pathways towards GHG neutral chemical production. How can we get to a consensus on realistic ambitions without compromising the European chemical industry at large? This question still needs to be answered as most CCU pathways are at a low level of technological maturity and require more development and demonstration in an integrated manner, especially bringing down the cost for these new routes is a serious challenge.

2.2 The role of CCU in climate action

In comparing the current, fossil-fuel based processes to future ones based on clean energy and circular processes, the majority of the large scale pathways which integrate renewable electricity into the chemical life cycle would result in the same products that are on the market today. Moreover, the carbon atoms used as a feedstock will be the same regardless of their source of origin (e.g. from fossil fuels or captured CO_2). This assumption is only true if the chemical industry maintains its current structure, having minimal disruption of value chains and supplies, allowing for continuous change at different speeds. For this assumption, the composition of the products will also be exactly the same regardless of the source of carbon atoms used. For this reason, the use-phase of the product is not affected by switching from a conventional to a CCU production route, i.e. essentially just changing the feedstock to produce the same products for the same applications. Thus, while evaluating the GHG reduction potential, only the production of the CCU product must be considered and compared to a benchmark process. From that point of view, the fixation time of the carbon in the product is irrelevant as the GHG emission savings will be generated only within the, so-called, cradle-to-gate phase. E.g. the Covestro process to produce polyurethane saves up to 3 kg $CO_{2\text{-eq}}$ due to the substitution of epoxides that are replaced. The production of epoxides comes with a higher energy demand than using CO_2 for the synthesis instead [6]. A sound estimation of the input and output streams and a comparison to the business-as-usual process is essential to predict the potential GHG emission reduction of any new process. Other considerations of the climate change mitigation potential of CCU are based on the amount of CO_2 fixed into the products [7]. This represents an additional dimension of the possible climate benefits of CCU as CO_2-based building materials might be a carbon sink like CCS.

Cefic presents a comparison between CO_2-based production of chemical and conventional production of the same chemical as depicted in Figure 2. This description underlines the argumentation from above: recycling carbon from CO_2 for the production of chemicals and polymers can avoid the utilization of additional ‘virgin’ carbon (that would, in turn, result in additional CO_2 emissions) and can effectively contribute to permanent CO_2 emissions avoidance, potentially cutting emissions resulting from the production by 50% [8]. Thus, this example illustrates the potential of CCU for cutting emissions in the cradle-to-gate part of the process. The CO_2 emissions in the use phase and end of life of a chemical are independent of the carbon source are not addressed by the process. However, this is still a relevant improvement in comparison to a business-as-usual process. It is important to mention that this conclusion is only valid while substituting a chemical product, i.e. producing exactly the same chemical products that fulfil the same services. It must be taken into account that the success of this approach is dependent on the energy mix that is used for CO_2 capturing and purification processes as well as on the CO_2 emissions that occur while transporting the CO_2 and most importantly the energy used to produce the other reactants that will react with CO_2 such as hydrogen (H_2) [8].

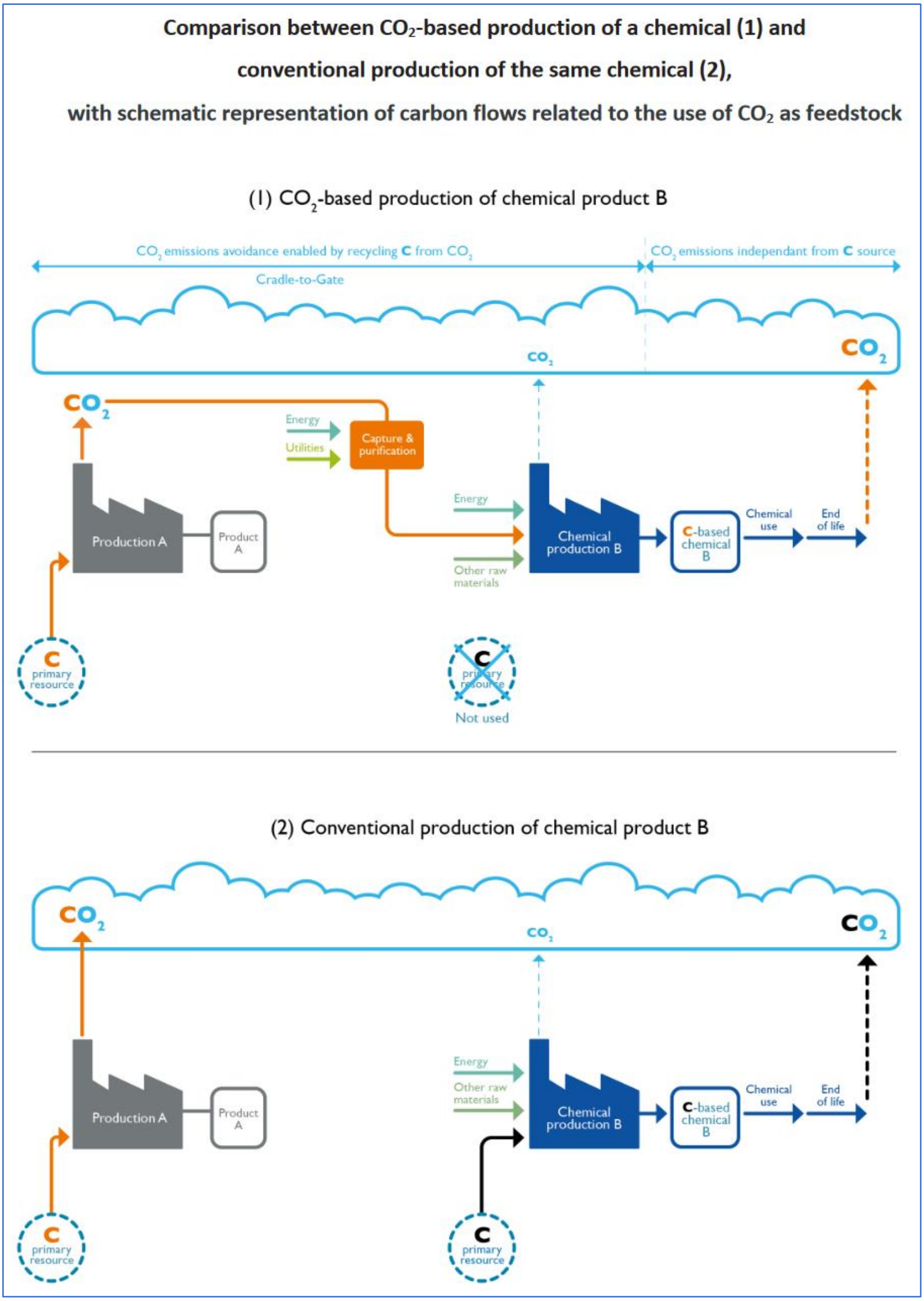

Figure 2: Comparison between a CCU and a conventional process for the same chemical product [8]

2.3 CCS, CCU and bio-based routes to reduce climate impact of industry

Even more complicated is a comparison between CCS, CCU and bio-based routes. Figure 3 shows a simplified schematic of the three options that can help lower the GHG emissions of the process industry. In all three options, GHG emissions continue to be emitted into the atmosphere by industry. In order to serve CCS and CCU with CO_2, CO_2 is simultaneously removed from the atmosphere via DAC. In the third route, the carbon cycle is closed by integration into biomass and its use. There is no clear hierarchy among the three options, as each one has its pros and cons and these may differ depending on the local characteristics. CCS has in the past been faced with the accusation that it keeps the oil industry alive, and public acceptance is low in many countries although this is changing, see e.g. the CCUS Projects Network report on public perception. There is not enough renewable energy available to convert the entire chemical industry to CCU processes (see chapter 2.4), and the bio-based processes are accompanied by an immense need for land use - whereby land use for agriculture that is meant for food production would be decreased (plate or tank) [9]. However, all three options will most likely be necessary if we want a carbon-neutral chemical industry.

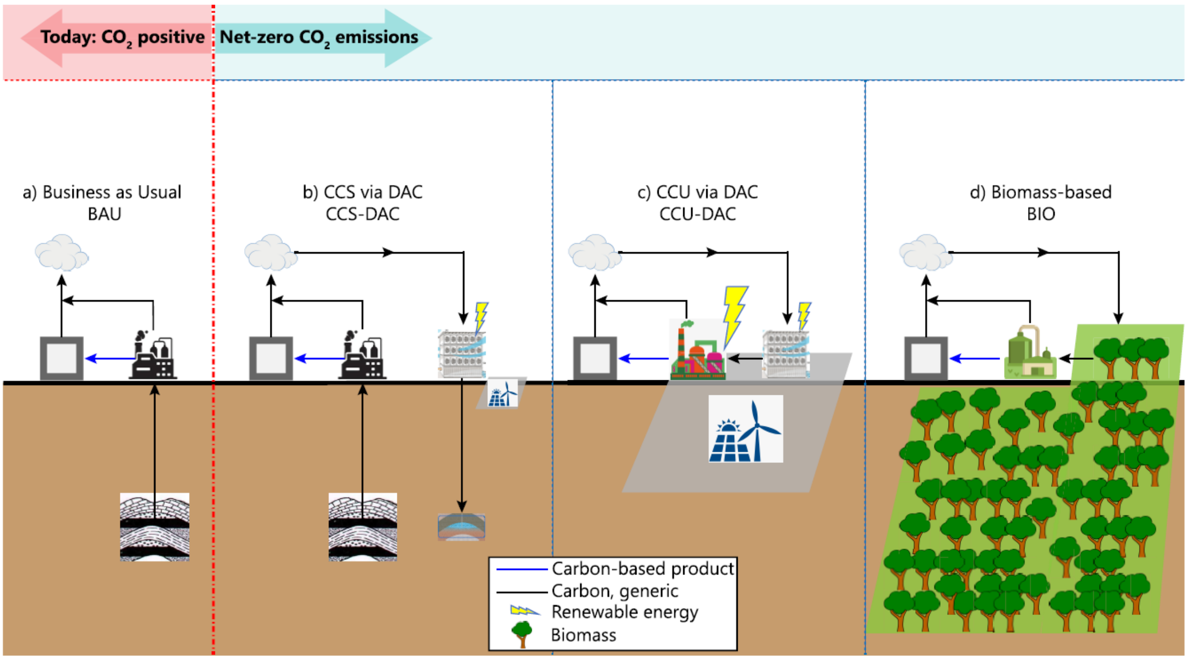

Figure 3: Pathways to lower GHG emission of the process industries [9]

Consequently, the quest is to find the optimal mix, which might also change over time, that should be applied and how synergies can be created across CCS, CCU and bio-routes. The question on whether one technology can be the solution for the entire system should not be asked, as there is no silver bullet solution; rather, the question should be: which option makes the most sense in what place and time with respect to the CO_2 emission reduction potential and cost performance at the specific location.

3 Assessing CCU's contribution to GHG emission reduction

As described above, each CCU route has its own potential for reducing GHG emissions. Thus, in the present chapter, the different processes are clustered into the main topics (chemicals, fuels and building materials).

When evaluating technologies in terms of their contribution to GHG emission reduction, it often depends on the perspective taken as well as on the underlying assumptions of the analysis. Assuming that the goal of being climate-neutral by 2050 means that almost no CO_2 from industrial plants may be released into the atmosphere, carbon neutral technologies must be evaluated differently than technologies that continue to emit GHG but which make an important contribution to reducing GHG emissions in the short term. Therefore, the challenge is also to understand from when and until when technologies should be used sensibly.

3.1 Chemicals

Around twenty bulk chemicals[3] account for more than 75% of the GHG emissions by the chemical industry as depicted in Figure 4 [10]. CCU technologies can substitute the conventional fossil based production routes of various chemicals including basic chemicals, fine chemicals, and polymers. Thus, CCU can lead to lower GHG emissions while decoupling chemical production from fossils as carbon source. The RWTH Aachen estimated that up to 3.5 Gt $CO_{2\text{-eq}}$ in 2030 can be reduced globally per year via CCU while taking into account a bottom-up model investigation of the production of 20 large-volume chemicals via CCU [11]. Nonetheless, this would require a lot of renewable energy– exceeding the production estimations for 2030 [2]. The reason for the high energy demand is the need for "green" hydrogen for the synthesis of most CO_2-based chemicals. The assumption behind this conclusion was based on the expectation that all technically feasible pathways will be fully deployed and powered with clean-electricity such as wind [12]. To exploit the global potential of CCU, more than 18.1 PWh of low carbon electricity would be required, representing about 55% of the projected global electricity production in 2030. [2]

Reaching CO_2 emission reduction goals by 2050 would entail a demand in power with a low GHG footprint that considerably exceeds the amount of such power sources predicted by the IEA to be available in Europe by 2050. The amount of renewable energy demand for an ambitious scenario is 4900 TWh [4].

The high demand of renewable energy for a large scale roll-out of CCU processes brings up the question for which processes renewable energy should be used first. Competitive technology such as power-to-heat or electro mobility cause a better reduction of GHG emission: therefore it can be said, in general terms, that renewable energy should be used primarily for these processes. Thus, the availability of renewable energy will be key and the limitation of the scale-up of most of the large scale CCU pathways on chemicals (and fuels).

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[3] Acrylonitrile, ammonia, benzene, caprolactam, cumene, ethylene, ethylene glycol, ethylene oxide, methanol, mixed xylenes, phenol, polyethylene, polypropylene, propylene, propylene oxide, p-xylene, styrene, terephthalic acid, toluene, and vinyl chloride.

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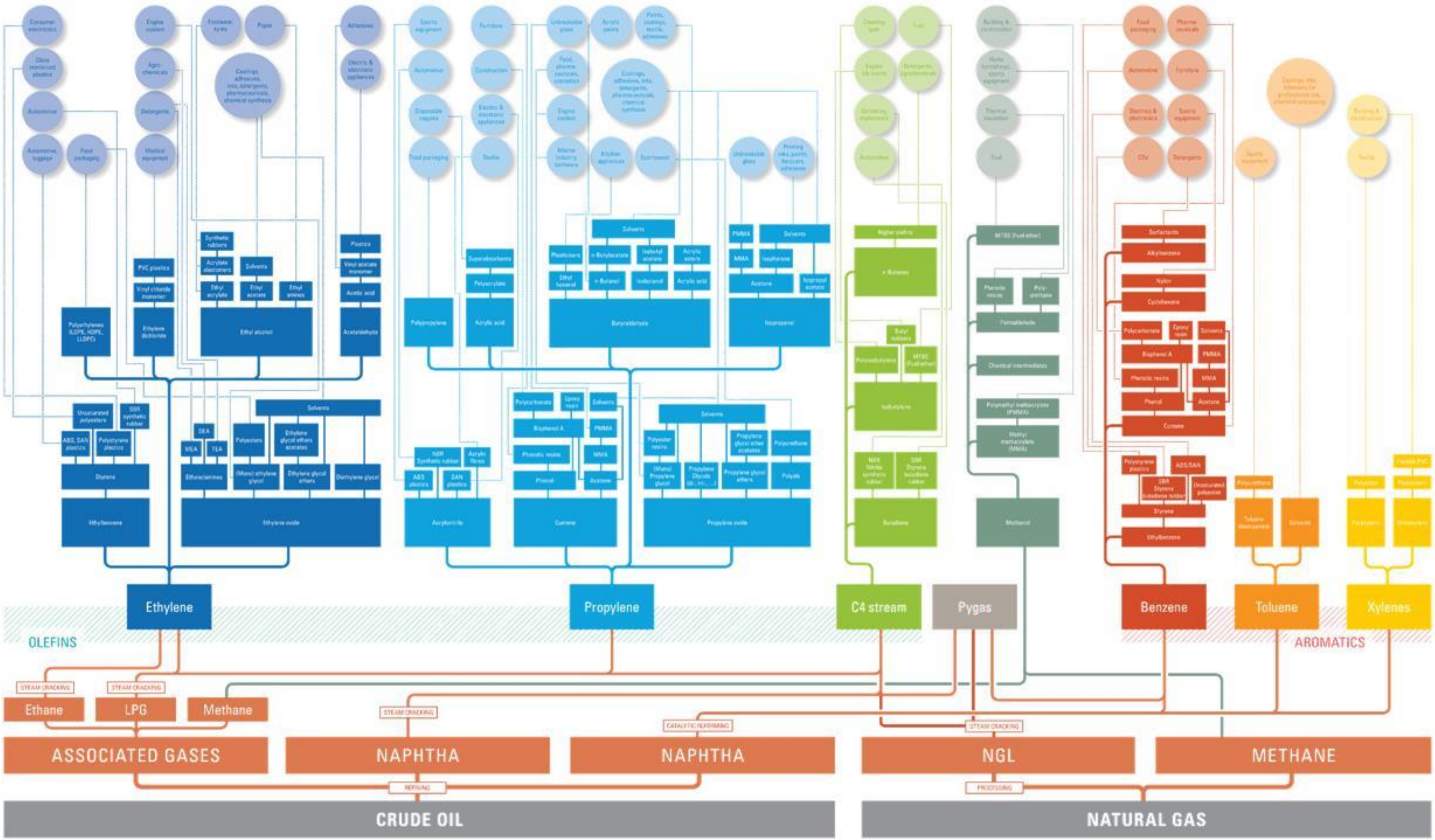

Figure 4: Structure of the chemical industry [10]

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An efficient and cost-effective CCU pathway is to use CO_2 directly for the formation of polymers. E.g., 1 kg CO_2 for the production of CO_2-based polymers can reduce up to 3 kg CO_2 emissions due to the avoided conventional production [2]. Given the global volumes of polymer production, the CO_2 global reduction potential is roughly estimated to be around 1 Mt CO_2 per year. This is not the big leap towards climate neutrality, but it is an important contribution to polymer chemistry.

3.2 Fuels

If the production of fuels is added to the production of chemicals, the demand for low carbon energy increases depending on the scenario between 2.000 TWh to 11.700 TWh [4]. The GHG emissions reduction with CCU chemicals and fuels could reach 186 $MtCO_2$ in Europe in2050 if all fossil fuels are replaced by CCU [4]. Water electrolysis is the key to fuel production based on CO_2. From the point of view of climate protection, non-bio-based sources of CO_2 require the use of electricity from renewable sources as mentioned above. The production of hydrogen from water is the first step in the process chain for the use of CO_2 for fuels (and most chemicals) and is the process that is mainly responsible for the high energy demand for many CCU pathways.

Application of power-to-x concepts need to find the niches at the moment – whereby those niches can still have an important impact on the synthetic fuel market. Decentralized locations where surplus energy caused through fluctuating renewable energy supply may offer a good opportunity as starting point for power-to-x plants, while making the business case challenging. Furthermore, power-to-x is a method to link renewable energy with the chemical industry and the transport sector.

From a climate mitigation perspective, it is not advisable to continue using fossil or synthetic fuels where they could be replaced. Particularly in local passenger transport, preference should be given to electric mobility. E.g. CCU fuels should predominantly serve aircraft, marine and long distance heavy road transport.

Besides electricity or hydrogen-driven technologies other technologies emerge that directly use sunlight to produce building blocks for chemicals or fuels. This artificial photosynthesis technology is at the moment immature and far from being economically viable. On the other hand, the technology is considered to have a very high potential for GHG emissions reduction. Further research in the area is needed.

3.3 Building materials

Besides the production of chemicals and fuels, CO_2 can also be used to produce building materials such as concrete. During CO_2 mineralisation, like in the case of carbonates (e.g. $CaCO_3$ or $MgCO_3$), the CO_2 is firmly bound and cannot enter the atmosphere for a long time. In fact, CO_2 mineralization is very close to the concept of CCS, plus adding a second value – the product. The success of climate change mitigation in achieving net-zero GHG emissions depends on technologies that are climate neutral or have, so-called, negative GHG emissions. CO_2 mineralisation has the potential to exploit CO_2 from industrial point sources and help companies supplying the CO_2 to reduce greenhouse gases in the long term. When coupled with DAC, this CCU technology could even be a CO_2 sink. The current Emissions Trading Directive (ETS), which regulates emissions trading until the end of 2020, does not provide for special treatment for operators that capture CO_2 from point sources and use it as a material. Reduction is only considered if CO_2 is permanently removed from the atmosphere. The only exception to this, so far, is the possibility of using CO_2 emissions for the production of precipitated calcium carbonate ($CaCO_3$) in the lime industry. This was only made possible in 2017 by a ruling of the European Court of Justice [12]. This means that the producer of carbon dioxide emissions now has the option of deducting the amount of CO_2 passed on (used for the production of calcium carbonate) from his total greenhouse gas emissions for which he has to surrender allowances. The right to free allocation remains unaffected by this regulation.

Mineralization of CO_2 to produce building materials can contribute significantly to lower CO_2 emissions. Estimations forecast that globally around 12 $MtCO_2$ emissions can be reduced annually when 20% of CO_2-based cement types are applied. However, the technology pathways must be further discovered and develop in order to gain an impact. Also some after lifetime concepts with recycling and additional CO_2 processing to produce a material that can be used in new cements are promising and under research investigation currently. This might enable additional GHG emission savings of around 13 Mt $CO_{2.}$

3.4 Data uncertainties

Reliable data are essential to obtain robust results. However, especially for technologies that are classified as having a low technology readiness level (TRL), like many CCU technologies, it is necessary to consider the fact that at the moment, data uncertainty are high. The LCA4CCU Project[4] funded by the European Commission is working on the establishment of life cycle assessment (LCA) guidelines for CCU technologies. Especially the difficulties to evaluate low TRL technologies are addressed by the project.

It is difficult to estimate the potential contribution from CCU to reduce CO_2 emissions, as several factors have an impact on the performance of the processes. LCAs have been performed on single CCU routes, but the combined potential of CCU in general is only addressed in studies with a bird's eye view based on stoichiometric assumptions. Furthermore, all the analyses of the potential that might be exploited depend on the prediction of the future, e.g. how much renewable energy will be available, what is the market size of the product or how much will be the price for capturing CO_2.

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[4] https://www.ifeu.de/wp-content/uploads/LCA4CCU-March-2020-Release-v1-0.pdf

4 Requirements on CO_2 streams for CCU

According to the requests from CCUS Project Network members, this chapter explores the requirements on CO_2 streams for CCU. Each CCU pathway requires certain purity of the CO_2 to be used. Further, different catalysts react negatively to different substances so that 'catalyst poisons' such as heavy metals need to be avoided. Thus, each CO_2 point source needs to be analysed and matched to the needed characteristics of the CCU pathway that will be served. In general, for CCU, it is better to use the carbon point source with the highest purity as it leads to less CO_2 treatment expenditure (related to energy demand) and, as such, lower processing costs.

Unfortunately, almost no data are available that CO_2 emitters could check in order to know if *their* CO_2 complies with a certain CCU pathway. The CCU process specifications, especially information about the catalysts, are highly confidential and corporate secrets. Nevertheless, companies that aim to reduce CO_2 emissions are eager to learn to whom they need to speak in order to find a pathway to transfer their exhaust gas to a venture that uses it as valuable feedstock. While there is enough amounts of highly concentrated CO_2 available for the CCU technologies that might enter the market soon, matchmaking between companies that emit CO_2 and companies that want to use CO_2 as a raw material would lead to an increase in the yield of the potential of CCU [13]. On the other hand, highly concentrated CO_2 is available in sufficient amounts for the CCU technologies that might enter the market soon.

In order to make the best possible use of the various industrial CO_2 sources for CCU processes, it must be determined which source fits best to which process. The CO_2 sources must be evaluated according to their characteristics, including:

- CO_2-concentration
- Temperature
- Pressure
- Concentrations of other gases, e.g. CO, H_2, H_2O, N_2, NO_X, SO_2
- Concentration of other relevant impurities e.g., trace metals
- Annual flow: t or Nm^3 per year

Furthermore, it is important to evaluate whether a CO_2 source will still be available in the future. Coal-fired power plants will be shut down in the future and many production processes can also be electrified. This means that many CO_2 sources will no longer be available for long-term use. For cement production, there are currently no processes in sight that could influence a reduction in CO_2 emissions. These sources will therefore be available in the long term. As mentioned before, from an energy point of view, sources that provide CO_2 in high purity or high flue gas concentration are preferable to those with low concentrations. In the case of processes with realistic reduction options, it must first be investigated which alternative processes can be used to avoid or minimize CO_2 emissions. The use of CO_2 as a carbon source in CCU processes is only meaningful if unavoidable CO_2 is used. Efficient DAC would raise CCU to the next level in respect to GHG emission mitigation.

Other aspects are subject to opposing influencing factors and must be considered in a differentiated manner. This is the case, for example, with questions of volume availability, geographical distribution and costs for the provision of CO_2. In general, especially for large-volume processes with correspondingly high CO_2 emissions, the implementation of separation technologies through the economy of scale makes economic sense. On the other hand, such plants are often limited to a few locations or industrial parks, so that CCU plants could also be implemented at such locations to avoid cost-intensive transport of CO_2 over long distances. In contrast, smaller plants are geographically dispersed over a large area, where the challenge is relatively high relative investment costs for CO_2 capture and limited available quantities. This chapter therefore considers both larger processes with (> 0.1 million t CO_2 per plant and year) and smaller processes (with a few t to kt CO_2 per plant and year).

Table 1 provides an overview of the most suitable industrial CO_2 sources for CCU with typical amounts and CO_2 concentrations. More detailed information on CO_2 sources in Europe can be found in the CarbonNext[5] deliverable 1.1 Mapping of CO_2/CO sources.

Table 1: Key sources of CO_2 for CCU in Europe. Adapted from E-PRTR and Naims, 2016. [14]

CO_2 Source	CO_2 concentration [%]	Emission per year [Mt CO2/year]	Cost [€/t CO_2]	Number of point sources emissions over 0.1 Mt/yr
Hydrogen Production	70-100	5.3	30	15
Natural Gas Production	5-70	5.0	30	10
Ethylene oxide Production	100	17.7	30	6
Ammonia Production	100	22.6	33	27
Paper Pulp Industry	7-20	31.4	58	35
Coal to Power (IGCC)	3-15	3.7	34	3
Iron and steel	17-35	151.3	40	93
Cement	14-33	119.4	68	212
Total		**356.4**		

In order to implement CCU on a large scale, CO_2 sources that are not highly pure would also have to be used. As described, only those sources that will continue to exist in the future should be used here, e.g. the construction industry will not be able to do without clinker production and the resulting cement in the foreseeable future. Wherever possible, cement is sourced locally, so that the dependence on imports is less in the industry than in other sectors. The clinker factor, i.e. the proportion of clinker in cement, has been declining slightly for years and currently amounts to 0.71. Even assuming a further reduction of the clinker factor, large quantities of clinker will continue to be produced in the future and correspondingly large quantities of raw material-related CO_2 will be emitted. Apart from CCS, the cement industry has only limited options of technologies to further reduce its GHG emissions, so that cement plants can also be considered as CO_2 sources for CCU in the future. The composition of the exhaust gases is strongly dependent on the raw materials and fuels

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[5] CarbonNext was an EU funded project (2016-2018) with the goal to evaluate industrial CO_2 sources in Europe that can possibly be used as feedstock for the process industries.

used and the combustion process. Technologies for the use of oxyfuel technologies are currently being tested. These have the potential to reduce the NOx content of the exhaust gas almost completely.

The CO_2 emissions of mineral origin resulting from lime production are also unavoidable and cannot be reduced by alternative technologies. Emission reductions are only possible for energy-related emissions by improving the energy efficiency of the furnaces. Thus lime production as a source of CO_2 is also available in the long term at comparatively many locations. The quantity of 7.4 million t would be sufficient for approx. 20% of the basic chemical production based on CO_2.

Due to their large number and spatial distribution, biogas plants are interesting sources of CO_2. The concentrations of CO_2 are subject to strong fluctuations, but are higher than those of many other industrial sources (cement works, steel works and fossil fuel industries).

5 Concluding remarks and recommendations

The roles that CCU pathways can play in the future as a tool for climate change mitigation are manifold. On the one hand, CCU pathways can help to reduce process related GHG emission in the cases of the production of chemicals and fuels. For the chemical industry, CCU is key to reducing GHG emissions and becoming independent from fossil fuels in the cradle-to-gate phase of a products' lifetime by minimizing the utilisation of additional fossil carbon atoms. In a carbon neutral world, a CO_2-compensation is required for all unavoidable GHG-emissions that are vented to the atmosphere. This compensation can be achieved by e.g. CCS or planting trees/biomass. CCU will help to reduce the total demand for compensation. Additionally, CCU gives CO_2 an added value and is crucial for defossilising the chemical industry by using CO_2 as carbon feedstock. Secondly, CCU may also function as CO_2 sink in the case of CO_2 mineralisation. Nevertheless, there are barriers which delay the market entry of many CCU technologies or prevent some paths from reaching their full potential. **The lack of sufficient spare renewable energy** and consequential **limited availability of green hydrogen** is one of the highest hurdles for rolling out CCU technologies in large scale. Additionally, many CCU technologies, especially those which include photo catalytic processes are classified as **low TRLs**. The assessment of the potential with respect to GHG reduction is difficult because of the **lack and uncertainty of data**. Finally, it is also important to question whether a technology that could already reduce CO_2 emissions today should be used, even if, in the future, it might not be compatible with the 2050 climate goals (e.g. consider **the problem of lock-ins**). Most CCU pathways are relatively new; even those that have already entered the market are in early stages regarding their maximum theoretical efficiency. As technologies improve over the years, the implementation of promising CCU technologies should therefore not be delayed on the basis of fundamental arguments that claim that those technologies are currently not CO_2 neutral, for it risks of not having the technology available when needed.

CCU (including power to X technologies) pathways cannot work alone to defossilise the chemical industry. The use of biomass as feedstock and recycling of carbon-materials to close the carbon cycle, need to be considered as complementary and crucial pathways towards a GHG neutral chemical production, too. But how can we get to a consensus on realistic ambitions without compromising the European chemical industry at large? This question can only be answered by evaluating and using the synergies between all possible pathways addressing climate measures, including especially synergies between CCS and CCU. E.g. CO_2 capture technologies and a sufficient CO_2 transport infrastructure are highly important for both concepts. Thus, CCS and CCU should not be seen as competing pathways; an urgent, time pressing roadmap for the solutions should be defined in order to support the best mix of both and use synergies wherever possible to reduce GHG emissions and to provide the chemical industry with non-fossil carbon sources. Such a roadmap should take into account the particularities of decarbonisation in the carbon-dependent chemical industry. In a next step, a higher exchange between CCU and CCS experts within the CCUS Project Network will be promoted in order to assess the potential synergies of CCU and CCS in more detail.

6 Glossary of abbreviations and units

BAU	Business as usual
$CaCO_3$	calcium carbonate
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture utilisation and storage
CO_2	carbon dioxide
DAC	Direct air capture
EOR	enhanced oil recovery
EU	European Union
ETS	Emissions trading scheme
GHG	greenhouse gas
Gt	Gigatons
LCA	Life cycle assessment
Nm^3	Standard cubic metres
TRL	Technology readiness level
t	ton

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