CO_2 Capture and Utilization (CCU) Matters

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Positioning in the sustainable transition landscape

Seven years ago, the Intergovernmental Panel for Climate Change (IPCC) proposed a pathway for the global reduction of CO_2 emissions, to limit the expected temperature increase to an anomaly of 2, ideally 1.5 °C, by the end of this century (see Figure 1). The CO_2 emissions originate from the burning of fossil fuel, industry and land-use and should be rapidly reduced (>350 Mton CO_2/year), while 'negative' CO_2 emissions are gradually introduced, starting from 2030. This last strategy consists of the capture of CO_2 from the air and its permanent storage under the ground or in materials, for which an 'eternal' lifetime can be assumed.

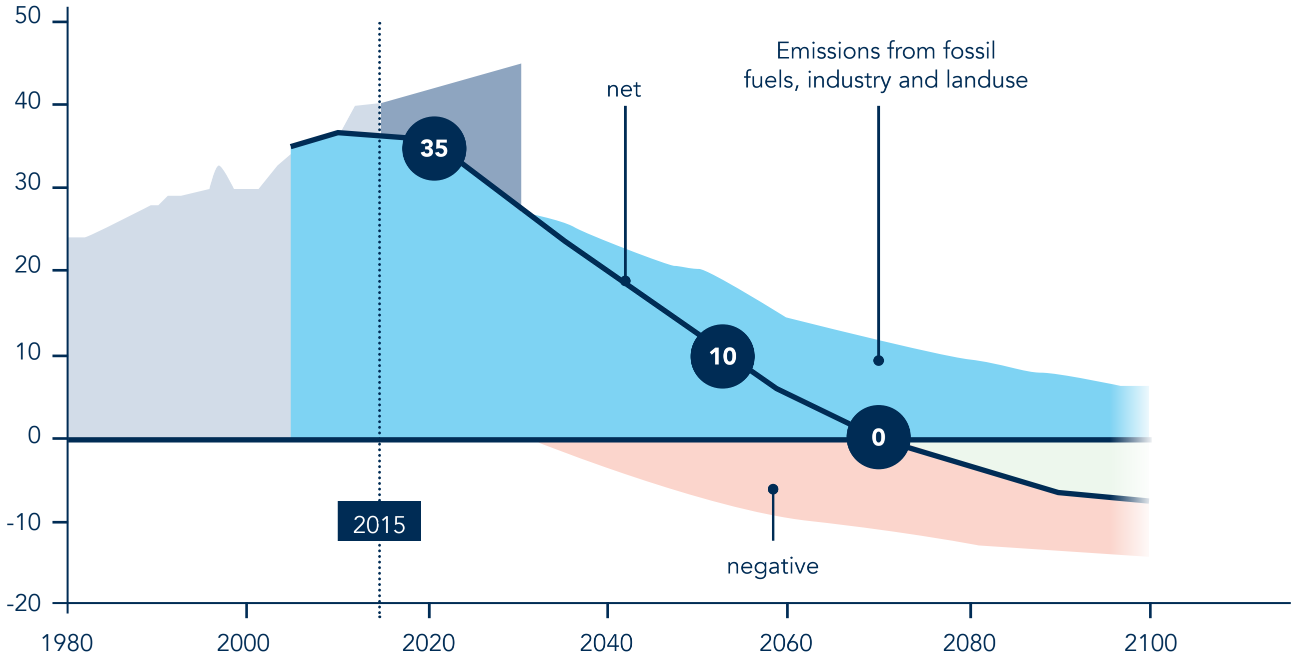

Figure 1: IPCC CO_2 reduction scenario to reach net zero emission in 2070[1]

Which CO_2 reduction strategies exist?

The International Energy Agency (IEA) investigated possible strategies, e.g. the more efficient use of fossil-based feedstocks and fuels in our industry and energy sector, which represents the 'low-hanging fruit'. They described their contribution in the CO_2 reduction pathway towards a net-zero CO_2 emission in 2070 (Figure 2). In parallel, the IEA elaborated a more stringent roadmap, to achieve a net-zero emission by 2050. Important examples of such strategies are electrification, green hydrogen production, the use of renewable feedstocks and CCUS (incl. storage of captured CO_2). Together, they lead to a cumulative yearly reduction of CO_2 emissions by 35 Gt in 2070.

1 Anderson, K.; Peters, G., Science 354 (6309), 2016, 182–183.

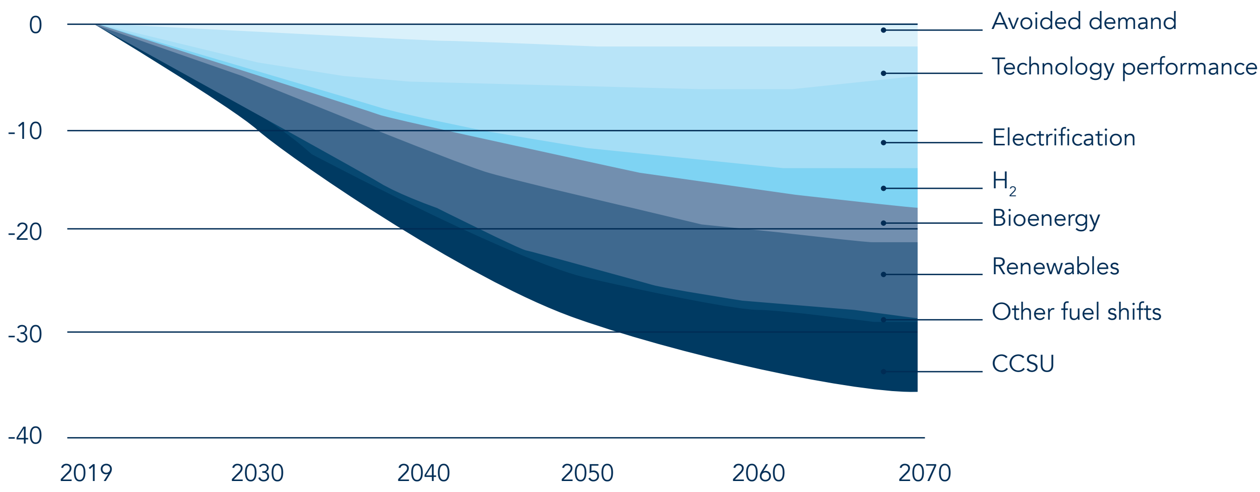

Figure 2: Sustainability strategies to reduce the net yearly CO_2 emissions[2].

Which CO_2 reduction strategy should we focus on?

The use of renewable electricity. If we take into account a local scarcity of renewable electricity today and in the future, strategies should be prioritized. A first fair set of criteria would simply consist of the 'MWh of renewable electricity' or 'the EURO's' invested in a strategy, in order to reduce the yearly emission by given ton of CO_2 (Figure 3). In addition, the anticipated potential for CO_2 reduction, related to the market size of given CO_2-based fuel, chemical or other products, should be included in the screening. Last but not least, the corresponding renewable electricity required to supply such a market could even become the most important criterium.

However, the former criteria may not suffice and other factors should be taken into consideration in such a decision-making framework: the application's 'readiness level', with regards to the technology development, its deployment in the market, compatibility with the existing energy and industrial system, amongst others. Also, possible local synergies between stakeholders, legislative frameworks to close possible financial gaps in the business case, availability of infrastructure, geography for deployment should not be overseen. To conclude such screening, the strategies should be ranked not only within, but also between different sectors, such as energy production, buildings, mobility and industry. As internationally active research institute, the Flemish Institute for Technological Research (VITO) combines its competences to tackle these cross-border, cross-sector and cross-vector challenges, within the field of CCU.

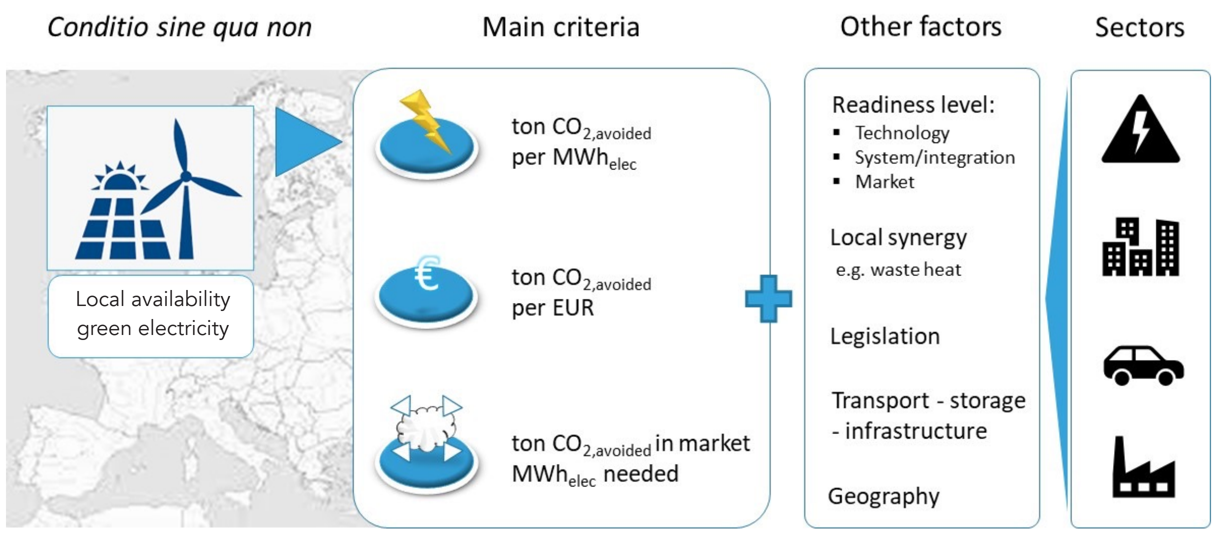

Figure 3: Selection criteria for sustainability/CO_2 reduction strategies.

2 https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf

To come back to the IEA's (International Energy Agency) proposed strategies, an avoided demand and enhanced efficiency of existing applications, will prevail in such decision framework, while new technologies, processes and value chains are to be assessed by their efficiency, in the use of renewable electricity (Figure 4). Point of attention here is that sub-optimization of one sustainability strategy (e.g. green H_2 production, CCU, …) should be avoided and options of direct electrification always considered, while screening innovations and new value chain, within different sectors.

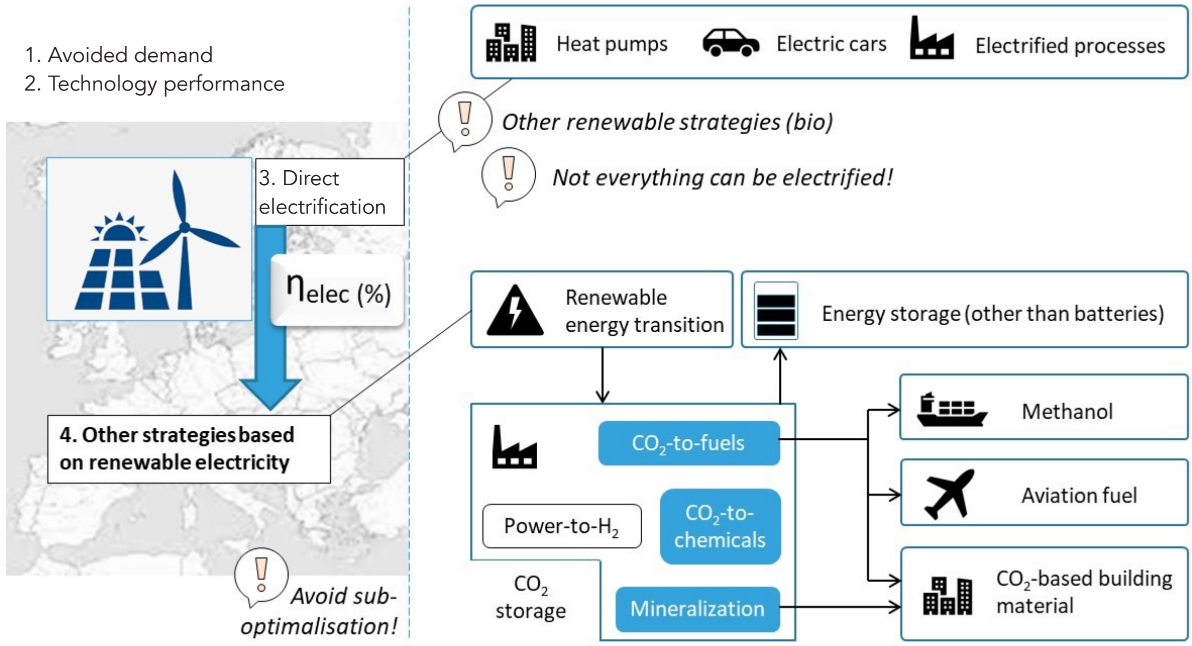

Figure 4: Ranking of sustainability strategies according to efficiency (use of renewable electricity) with given points of attention, while given CCU use cases interconnect different sectors, where direct electrification is no viable strategy to reduce (net) CO_2 emissions.

It is clear that direct electrification would take an important position in the selected strategies, with heat pumps for buildings, electric cars for transport and electrification within the industry as important examples. Two points of attention can already be noted here: 1. other options exist, based on alternative feedstocks, e.g. biofuels, and 2. not everything can be electrified, such as high-T processes in the industry. Green H_2 production and most of the CCU routes also involve (partly) electrified processes. However, the production of energy carriers, fuels and chemicals is less efficient than the direct electrification routes. On the other hand, they are important in the chemical industry, which heavily relies on H_2 and carbon feedstock. CO_2 can act as alternative for fossil-based sources here, and CCU can support in the sustainability transition in other sectors:

- The renewable energy transition: energy storage solution in the so-called Power-to-X application, where electricity is stored in liquid, energy-dense carries, such as ammonia and methanol;
- Mobility: methanol as e-fuel for the maritime sector and aviation, large sectors that cannot be de-carbonized by electrification;
- Buildings: CO_2-compensating building material;

How do CCUS-based value chains contribute in the battle against climate change and to the IPCC scenario?

When you consider the capture of CO_2[3], from fossil, biogenic sources or directly from air, different types of CO_2 emission reductions can be identified, that contribute to the IPCC scenario, depending on the application, i.e.:

1. Capture from fossil-derived CO_2 and utilization, where the following aspects are important in the definition of the CO_2 emission reduction:

Product CO_2 footprint

- This product feature is quantified through the sum of CO_2 footprints of 1. the feedstock (mining) and 2. production process;
- The use of CO_2 as feedstock is reflected by a negative value in this calculation;
- The use of renewable electricity or waste heat implies a reduced or even zero contribution (as assumed by the IEA for the 2050 scenario) in the calculation of the production process' CO_2 footprint.

Comparison within the same application/use case

i.e. fuels and chemicals, production of which relies on fossil-based feedstocks and/or the use of heat, as a CO_2-intensive energy source. The alternative process relies on CO_2 as a feedstock and renewable electricity as an energy source:

- The value chain boundaries cover the product's production and its end-of-life (e.g. combustion after x lifetime), with given CO_2 footprints. Of course, processes for re-use can also be included as intermediate step (e.g. recycling);
- In the case of the CO_2-based alternative, the CO_2 feedstock, as initially captured at the point source, is released again upon combustion;
- The footprint of the CO_2-based alternative is lower and CO_2 emissions are net avoided in the replacement of the fossil-based product in given application.

This approach is only reasonable for applications and CO_2 point sources, where:

- Electrification/H_2 strategies are not optimal, e.g. e-fuels in maritime application;
- Electrification/H_2 strategies for industrial process heat and steam production, currently based on combustion of fossil fuels, are possibly limited by overall (future) availabilities of renewable electricity: these sources would continue to exist next to the unavoidable process-CO_2 emissions from e.g. steel and cement industry.

2. Capture from fossil-derived CO_2 and utilization via mineralization or permanent CO_2 storage: the intended CO_2 emissions are not released into the atmosphere and therefore avoided. The permanent incorporation of CO_2 into building material is related to the application based on concrete.

3. Use of biogenic CO_2 - as captured from the atmosphere by and released from biomass – or CO_2 directly captured from the air (DAC – Direct Air Capture) and utilization: CO_2 emissions are avoided within given application, by replacing fuels and chemicals, as in case 1. However, its impact would be significantly higher, as the CO_2 at the product's end-of-life (combustion) is captured again in a cyclic way[4].

4. Capture as described in case 3, combined with utilization via mineralization or permanent CO_2 storage: this represents the real negative CO_2 emission as CO_2 is 'extracted' from the atmosphere and fixed permanently. The IPCC scenario assumes the need for such negative emissions to reach the targeted CO_2 reduction by 2070, starting from 2030.

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3 *The CO_2 capture process itself also generates CO_2 emissions, via the use of heat and electricity. The process CO_2 footprint should be negative in order to justify the capture. The CO_2source is present as diffused molecules in the atmosphere and still contains CO_2 from industrial point sources. In this way, an allocation of the CO_2 source to post-combustion of the CO_2-based fuel is not applicable. 'Cyclicity' implies that the emission of fossil-based CO_2 from industrial point sources can be reduced in the meantime and the term would theoretically be the most valid, in complete absence of industrial point sources.*

Figure 5 summarizes the described contributions of the CCUS-based value chains to the CO_2 reduction scenario of IPCC.

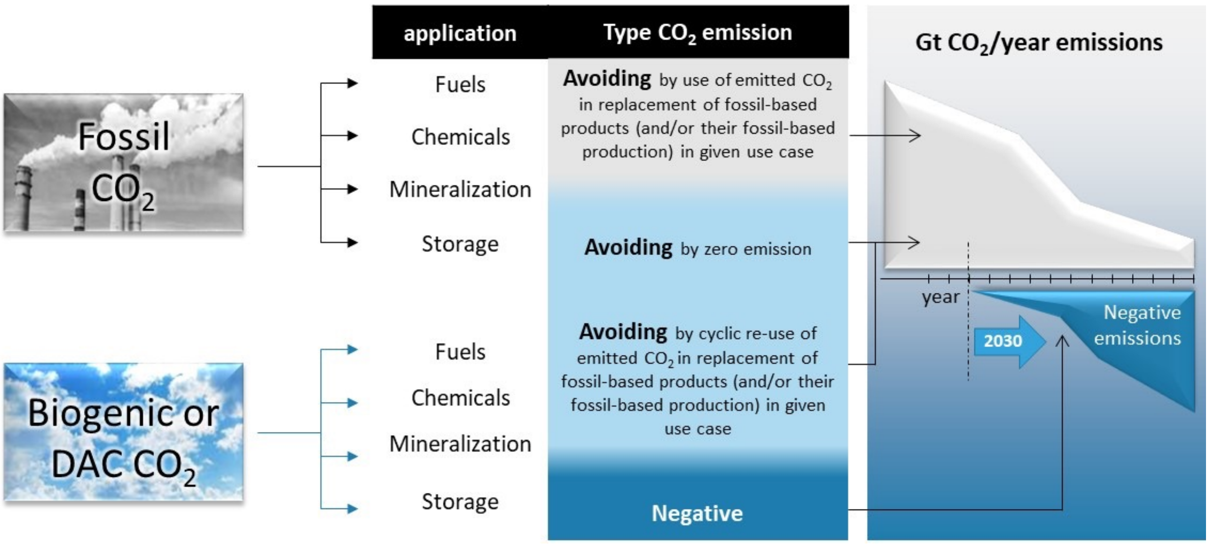

Figure 5: Type of CO_2 emission reduction for value chain starting from fossil- or biogenic/direct air capture (DAC)-derived CO_2 and its use in different application.

How to evaluate the CO_2 based value chains in practice?

Earlier in this paper a set of decision criteria was introduced (Figure 3). Two criteria (i.e. ton CO_2 avoided per MWh electricity and CO_2 avoided in the market) are elaborated to demonstrate how these can be used in practice. Three CCU-based value chains starting from fossil-based CO_2 point sources are selected as an example (Figure 6):

1. **CO_2-to-fuel**, where 2.25 t CO_2-based methanol replaces 1 t diesel or 1.07 t bunker fuel, to deliver the same energy content upon combustion, in the European maritime fuel use case;

2. **CO_2-to-chemicals**, CO_2-based methanol replacing grey methanol production in the European chemical industry, with an assumed lifetime of 2 years for both and;

3. **CO_2-to-building material**, based on waste slag (SSS, stainless steel slag) or other alkaline (waste) material, replacing concrete and assuming permanent CO_2 fixation.

For these processes, capture is done from fossil-derived CO_2 point sources and is based on the state-of-the-art, amine-based scrubbing technology. This process also emits CO_2 by its use of stripping heat for the recovery of bound CO_2 (1 178 kWh/t CO_2captured). Renewable electricity use is assumed in both the capture and conversion steps: resp. 196 kWh/t CO_2 captured, 11 770 kWh/t methanol and 29 kWh/t building material (next to 63 kWh heat/t) [5,10].

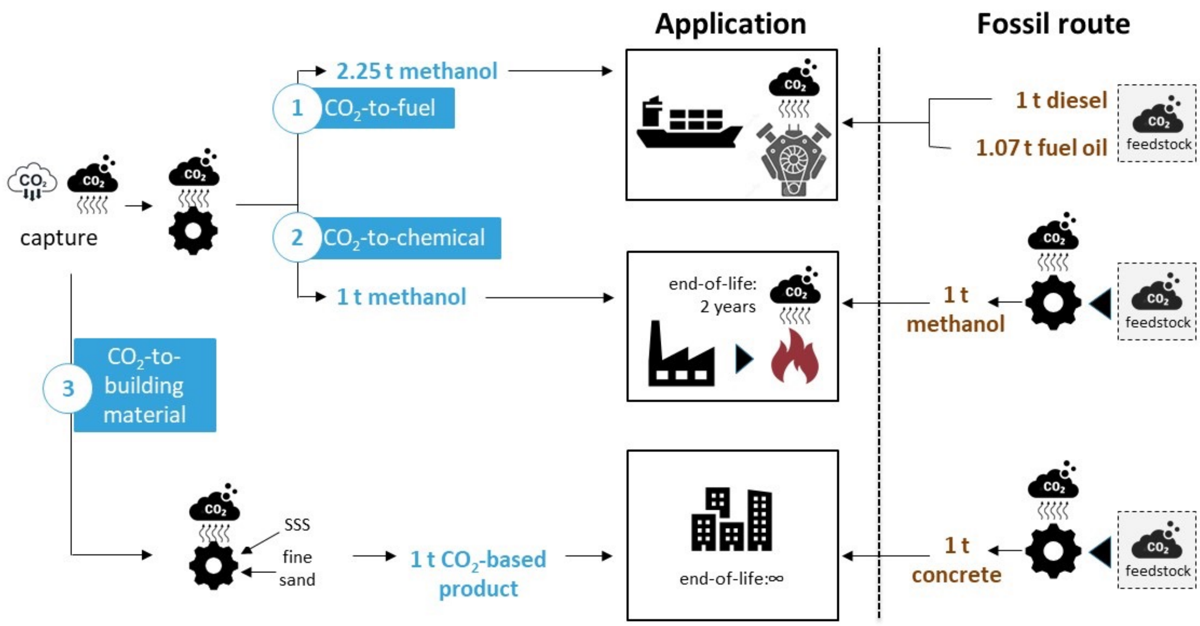

Figure 6: Illustration of three CCU-based value chains (starting from capture from fossil-derived CO_2 point sources) in given applications and alternative fossil-based routes.

In the marine fuel and chemical use cases, the replacement by CO_2-based methanol results in a factor 15 higher CO_2 reduction potential than in the building material case. However, the production of methanol requires large amounts of electricity. Conversely, the corresponding CO_2 reduction potential per unit of renewable electricity, applied in the CO_2-to-methanol conversion process, is significantly lower.

The total replacement of European marine fuel results in a CO_2 reduction potential in the range of 100 Mton CO_2/year. This is a factor 15 higher than in the smaller chemical use case, related to the European methanol production capacity. The building material use case also shows a significant potential, based on the availability of alkaline waste material in Europe. As a yearly renewable energy production of 3400 TWh is anticipated in Europe by 2050 [4], the European marine fuel use case becomes restricted by its yearly renewable electricity need of 1000 TWh.

The results are summarized in table 1.

It is clear that no unambiguous selection of a viable scenario can be made in this exercise, focusing on only the CO_2 reduction potential and one use case, in extremis. A balanced combination of different CCU strategies is preferable. It starts from the current and future availabilities of renewable electricity as conditio sine qua non, with deployments spread over time. The production of CO_2-based fuels with electrified systems can support the renewable energy transition in an energy storage strategy. The production of CO_2-based building materials is a feasible short-term pathway, if proper supply chains for alkaline waste feedstock can be guaranteed. In the meantime, opportunities arise in the field of energy import, which influences the boundary conditions for CCU: Renewable electricity can be produced in an economic feasible way, at far locations in the world, where solar and wind energy are abundant. In such scenarios, CCU not only serves as a storage strategy for the low-carbon and low-cost energy, but also facilitates its transport towards Europe, in the form of molecules with a high energy density. Indeed, the role of methanol as fuel or platform chemical could then be extended to an 'easy-to-transport' liquid energy carrier. Therefore, VITO concludes that the positioning of CCU within the sustainable transition landscape not only rests on many, different pillars, but also on global trends and the dynamic nature of its boundary conditions.

CO_2-TO-FUEL: METHANOL				CO_2-TO-CHEMICAL: METHANOL			CO_2-TO-BUILDING MATERIAL		
footprint ($t\ CO_2$)	**Diesel**	**Bunker**	**CO_2-based**		**Grey [6]**	**CO_2-based**		**Concrete**	**CO_2-Route [7]**
Quantity (t): 44.8 MWh	1.00	1.07	2.25	Quantity (t):	1.00	1.00	Quantity (t):	1.00	1.00
Feedstock/production[8]	1.05	0.44	-1.37	Feedstock	0.97	-0.94	Feedstock	0	-0.092
Combustion[4, 9]	2.85	3.36	3.09	Production	0.85	0.33	Production	0.085 [10]	0.019
Total	3.90	3.80	1.72	Total	1.82	-0.61	Total CO_2	0.085	-0.073
$t\ CO_2^{avoided}$/t fuel	**2.17**	**2.08**	**-**	**/ t grey**	**2.43**	**-**	**/ t concrete**	**0.158**	**-**
$t\ CO_2^{avoided}/MWh_{elec}$	**0.08**		**-**		**0.20**	**-**		**5.45**	**-**
European marine fuel use (Mt/y)[11]	13	37	-	Both combustion after 2 y: 0.69 t CO_2 /y), European prod. Cap. 2.8 Mt/y[12]			Lifetime: ∞, CO_2 emission = 0, European market based on (34 Mt slag /y) 78 Mt/y total alkaline waste material.[13]		
Methanol need (Mt/y)	29.3	77.8	-						
European CO_2 avoidance potent. (Mt/y)	**28.2**	**76.8**		**6.8**			**27.6**		
Renewable elec. energy need per year (TWh)	**352**	**1000**		**34**			**5**		

Table 1: Product CO_2 footprint calculation of the production of methanol as fuel or chemical and building material, by making use of CO_2 as feedstock, compared to the fossil-based route, next to the renewable electricity need per t product, European CO_2 avoidance potential and corresponding total renewable electricity need.

How can technology developments contribute to the selection and improvement of CO_2-based strategies?

Technological improvements and technology selection can favour CO_2-based over fossil-based value chains, impact-wise (CO_2 avoidance potential), independent from external factors such as electricity price, …: e.g. in the case of CO_2 conversion: novel catalysts with enhanced product yields, increased energy efficiencies, …, which affect the energy need within the thermodynamic boundaries of the CO_2-based reaction.

Base case scenario (BCS): production of CO_2-based methanol from fossil-based CO_2, captured at a point source, in the replacement of all European marine diesel.

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5 *CRI process with 75 % H2 prod. efficiency: 11.8 MWh/t MeOH and 1.38 t CO_2/t methanol [see (5)], incl. capture: heat use = 1178 MWh/t CO_2 - 0.44 t/t methanol @ 0.27 t CO_2/MWh, elec. use = 196 kWh/t CO_2, DSP = 0.33 t CO_2/t methanol*

6 *Dechema Technology study (2017): Low carbon energy and feedstock for the European chemical industry*

7 *per t Carbstone: 480 kg SSS, 480 kg sand, 107 kg water, 92 kg CO_2, drying 63 kWh heat, mixing electricity 27 kWh, curing electricity 2 kWh , footprint extracted from LNE study see below*

8 *https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf , from CO_2 emission factor list*

9 *https://www.egcsa.com/wp-content/uploads/CO_2-and-sulphur-emissions-from-the-shipping-industry.pdf, https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html*

10 *LNE study (2016): Onderzoek naar mogelijk ondersteuningsbeleid m.b.t. nieuwe toepassingsmogelijkheden van CO_2 als grondstof*

11 *https://www.concawe.eu/wp-content/uploads/2017/01/marine_factsheet_web.pdf*

12 *https://www.icis.com/explore/resources/news/2019/01/31/10313703/chemical-profile-europe-methanol , 2019 data.*

13 *https://www.eurofer.eu/assets/Uploads/European-Steel-in-Figures-2020.pdf , total slag utilization 34.1 Mt in 2019*

14 *https://www.science.org/content/article/industrial-waste-can-turn-planet-warming-carbon-dioxide-stone , extrapolation of 43.5 % steel slag contribution on global level to European market of alkaline waste materials (fly ash, cement waste, …) and taking into account a similar stoichiometry of alkaline waste/ CO_2 in building material, as for the Carbstone building material*

Development 1: use of less energy in the production of CO_2-based methanol.

- Technology: an efficiency increase from 75 to 90 % in the production of H2 via water electrolysis, as intermediate in the CO_2 conversion step;
- Impact: total renewable electricity need is reduced by 16 %, from 352 to 294 TWh, still remaining in the same order range, while avoiding 28.2 Mt CO_2/year.

Development 2: BCS, but CO_2 emissions are avoided by cyclic re-use (capture) of end-of-life emitted CO_2 (combustion), instead of making use of fossil-derived CO_2 from point sources.

- Post-combustion CO_2 is re-used and thus eliminated from the CO_2 footprint calculation of the total chain, consisting of feedstock use, fuel production and combustion;
- Technology: the value chain starts from Direct Air Capture, by making use of waste heat (no CO_2 footprint allocated to this energy source);
- Impact: respectively 5.27 and 0.20 t CO_2 is avoided per t marine diesel replaced and per MWh renewable electricity used in the methanol production process, compared to resp. 2.17 and 0.08 t CO_2 per t marine diesel and MWhelec in the BCS. This means that the total CO_2 avoidance potential increases by factor 2.4, from 28.2 to 69 Mt CO_2 per year;
- Comparison with development 1: If the total CO_2 reduction potential of 28.2 Mt/y is maintained as in the BCS, the total renewable energy need can be reduced by 59 %, from 352 to 144 TWh, which is more significant than in example 1.

It should be noted that the above comparison only takes into account the CO_2 avoidance potential with corresponding renewable electricity need, and relies on given assumptions (e.g. use of waste heat for DAC in development 2). The economics are not considered, may alter the ranking and indicate the requirement of other developments: i.e. CO_2 capture via DAC is still more expensive than point source capture, whereas increased productivities and learning curves should decrease their future cost. As electricity use/cost is important in the v conversion's operational cost breakdown, an efficiency increase in H_2 production is more effective (compared to a more efficient DAC), in the setup of competitive value chain, on the shorter term.

In order to justify CCU approaches and the setup of new value chains, business cases and technology development, multi-disciplinary expertise is required. For this, VITO relies on its research domains of sustainable energy, chemistry and materials. In practice and as (partly) elaborated on above, such exercise always starts from a climate goal and insights in the context, while support is provided by scenario, life cycle and techno-economic analysis, next to CCU value chain assessment.

Authors

Miet Van Dael, miet.vandael@vito.be
Walter Eevers, walter.eevers@vito.be
Guy Vekemans, guy.vekemans@vito.be
Metin Bulut, metin.bulut@vito.be

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VITO NV
Boeretang 200
2400 Mol
Belgium
Tel. + 32 14 33 55 11