Renewable carbon products by using CO_2

Project deliverable D2 of KB Circular & Climate Neutral: Exploring CO_2 options (KB-34-003-007)

Marieke E. Bruins, Marc P. Lanting, Alexander T. Boedijn, Anna Dörper, Juliën A. Voogt, Jan Peter Nap, Daan van Es, Martijn Bekker.

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Summary

A sustainable future will require a phase out of fossil-based resources if we want to reduce greenhouse gas emissions. Carbon dioxide (CO_2) can be an alternative to fossil-based carbon as a renewable carbon source. Future CO_2 sources include direct air capture (DAC), CO_2 point sources from industrial biobased processes, and biogas from residual biomass. DAC is promising but costly and energy-intensive. Biomass residues and point sources from biobased processes offer more practical short-term solutions due to lower costs and higher efficiency.

Captured CO_2 can be used directly in e.g., carbonated drinks or for greenhouse enrichment, but also indirectly through chemical or microbial conversion. Chemical routes often require the conversion of CO_2 to the more reactive, hydrogen enriched, syngas, which is very energy-intensive, while microbial routes leverage organisms to produce complex molecules but face scalability and cost challenges.

A techno-economic analysis on conventional and alternative production routes for methanol and ethanol show that conventional methods remain the cheapest and most energy-efficient, while CO_2-based routes demand significant energy and infrastructural investments. In optimisation, trade-offs occur between costs, energy use, CO_2-emissions and land-use.

Using CO_2 from biogas is the most promising alternative route, as identified in the studied cases for methanol and ethanol production, while other CO_2-based routes require major technological progress and extensive policy support. A systems approach integrating technical, economic, and environmental considerations is essential for developing sustainable, circular solutions. Redesigning production systems, fostering collaboration among stakeholders, and implementing measures like carbon taxes and reduced fossil subsidies are needed to enable a transition toward renewable carbon use.

1 Setting the scene

The intensive use of our fossil raw materials - such as oil, gas, and coal - as energy or carbon sources fuels climate change through the emission of carbon dioxide (CO_2) during production , use (e.g. fuels), and disposal. CO_2 is the greenhouse gas (GHG) often primarily focused on in terms of climate change as it accounts for 75 % of the GHG emissions worldwide (Ritchie et al., 2020a). In 2022 the annual GHG emission was 53.85 billion tons CO_2 equivalents, of which 65 % was caused by the use of fossil fuels (Ritchie et al., 2020a, 2020b). This is a huge part of the total emissions which urgently requires alternative solutions. Renewable alternatives for energy are found in the use of sun, wind, water, and possibly nuclear energy. These sources produce electricity, but do not provide carbon. However, fossil sources are also used as a carbon source to produce materials and chemicals that we use on a daily basis, from plastics to medicines. To further reduce the use of fossil materials by the industry, we also need to focus on sources of renewable carbon. Which renewable carbon sources to use in future practice is however not yet clear. The solution we are considering here is the use of carbon dioxide (CO_2) as renewable carbon source. There are many technologies under development to capture CO_2 and convert it into usable materials, these include direct (air capture) or indirect (biomass) capture of CO_2 and conversion via chemical or microbiological routes. These different routes will be discussed in the following parts of this report starting with the capture of CO_2.

2 Future Carbon sources

To produce chemicals and materials from non-fossil CO_2 in the future, an essential first step is to map out the development of available CO_2 sources through to 2050. The technologies we consider must be scalable and applicable well into 2050 and beyond. In this section, we examine the anticipated developments for a selection of renewable CO_2 sources (Figure 1).

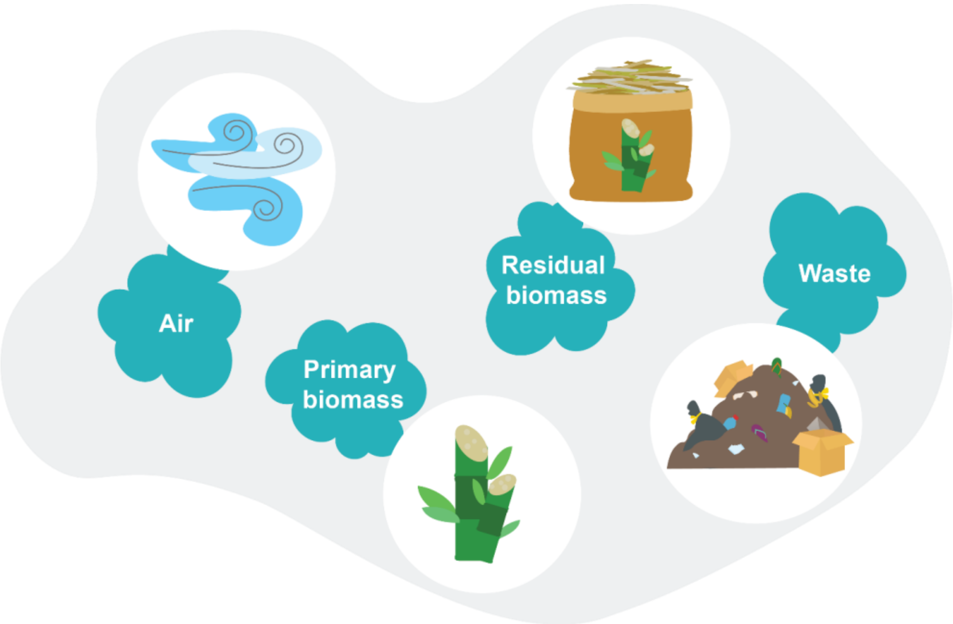

Figure 1 ***Proposed renewable sources for carbon such us air, primary biomass (for example sugar cane), residual biomass (for example sugar cane bagasse) and waste streams.***

2.1 Conventional: CO_2 from fossil sources

Fossil fuels such as coal, oil, and natural gas have long been the dominant energy sources worldwide. Still, their role is gradually declining as the urgency of climate change increases. Until 2050, dependence on fossil fuels is expected to decrease significantly, partly due to tighter government regulations, growing societal pressure, and increasing competition from renewable energy sources. The reduced or phased-out use of fossil resources will likely have serious regional ramifications for Europe. Investments in developing new fossil energy projects are already under greater scrutiny. In many regions, there is a notable shift towards more sustainable alternatives. Fossil fuels remain a significant source of CO_2, especially in economies that are slower to switch to green energy. Next to production from energy generation, fossil materials industry such as cement and steel producers emit considerable amounts of CO_2 in their production processes. These could be a “CO_2 point source” from local high production of CO_2.

2.2 Direct Air Capture

Direct Air Capture (DAC) technology is emerging as an approach for reducing CO_2 in the atmosphere. This technology captures CO_2 directly from the air to store it permanently or use it for various purposes, such as producing climate-neutral synthetic fuels. Permanently storing captured CO_2 is known as 'carbon capture and storage' (CCS), while using the captured CO_2 is referred to as 'carbon capture and utilization' (CCU). According to the International Energy Agency (IEA) scenarios for Net Zero Emissions by 2050, DAC technologies are expected to capture more than 75 Mtonnes of CO_2 by 2030 and around 980 Mtonnes by 2050, requiring significant scale-up of current capacity (IEA, 2022).

Currently, there are 27 DAC facilities operational in Canada, Europe, and the United States, and there are plans to build many more. These facilities mainly capture CO_2 for storage, not for usage. Governments and industry support DAC with significant financial allocations, such as the United States, which has allocated nearly $4 billion specifically for DAC development and deployment, and other countries, such as Australia, Canada, Japan, the United Kingdom, and the European Commission, which have also announced major initiatives and funding aimed at boosting DAC technologies (IEA). Also, $1 billion of private investment has been made, mainly in the private entity ClimeWorks.

Although DAC is currently the most expensive form of carbon capture - due to the low concentration of CO_2 in the atmosphere - costs are expected to fall due to scale-up and innovation. Cost projections for large-scale DAC installations vary considerably. The major challenges are further cost reduction of capital investments, energy efficiency and the right policy support (Young et al., 2023). With optimizations and access to cheap renewable energy, stakeholders claim the costs could fall below $200 per tonne of CO_2 by 2030. If DAC continues to advance and scale up, it will significantly broaden the range of applications for captured CO_2. Its flexibility in terms of location, combined with increasing support from governments and the private sector, highlights the potential of this technology.

2.3 Industrial CO_2 from biobased processes

Various energy- and food-based processes, such as the production of bioethanol and beer, release large amounts of CO_2. Europe is not a large producer of bioethanol, but bioethanol production in Brazil is a vast industry producing 80 Mtonnes of CO_2 annually (US Departement of Energy, 2022). The annual global beer production is around 190 Mtonnes (Barth-Haas Group, 2023), releasing about 9 Mtonnes of CO_2. This high local production of CO_2 can be used as a point source. Capturing and using such CO_2 is easier and cheaper than using DAC. Two other biobased processors that produce large amounts of CO_2 are the pulp and paper industry and the sugar production industry. The CO_2 is generated from energy and power production, but also from on-site production of lime that is used during processing.

2.4 CO_2 from (residual) biomass

Biomass utilization and waste incineration are often considered renewable CO_2 sources because of their potential to balance the carbon cycle. Biomass, derived from plants and animal waste, can be CO_2-neutral, provided the CO_2 released during combustion is offset by the CO_2 absorbed by new growth. The development of this sector until 2050 will rely on technological progress, the availability of sustainable residual biomass, and the actual production costs. The costs of CO_2 emissions will largely determine whether it is possible to achieve competitive processes compared to current fossil-based processes.

Europe is strongly committed to biogas production from biomass residues, intending to produce 35 billion m^3 of biomethane from biogas by 2030 (European Biogas Association, 2023). The methane fraction is commercially valuable as “green gas”, leading to the separation and on-site venting of the CO_2. This CO_2 stream has a high concentration, typically over 98% CO_2. In Europe, this activity is estimated to release around 35 Mtonnes of CO_2 annually by 2030, which could be used for further valorization. In some cases this CO_2 is already sold to greenhouses to stimulate crop growth.

Recycling of biobased material is never 100% efficient due to practical limits in the maximum conversion. Therefore, some biobased material will still have to be incinerated. Such incineration reduces the waste volume going to landfills and simultaneously generates energy. In the Netherlands, 911 ktonne of CO_2 emissions (AVR, 2021) are released annually through waste incineration. Equivalent European figures are not available to the best of our knowledge. Innovations in waste sorting and processing will reduce the amount of incinerated recyclable material.

3 Carbon routes to fuels, chemicals, and materials

The previous chapter discussed the different sources for carbon, while this chapter will focus on the different use and conversion pathways of carbon captured from different sources.

3.1 Carbon from air captured CO_2

Despite being despised as a greenhouse gas, CO_2 has a variety of practical applications. Many technologies that convert CO_2 to a higher-value commodity exist. Some technologies are already applied at industrial scale, in other cases, they are only demonstrated at the laboratory scale (Bos et al., 2023; Hepburn et al., 2019; IEA, 2019). Figure 2 shows different conversion pathways of captured CO_2 to produce different materials. The pathways shown are the direct use of CO_2, and indirect use of CO_2 via chemical or microbial conversion.

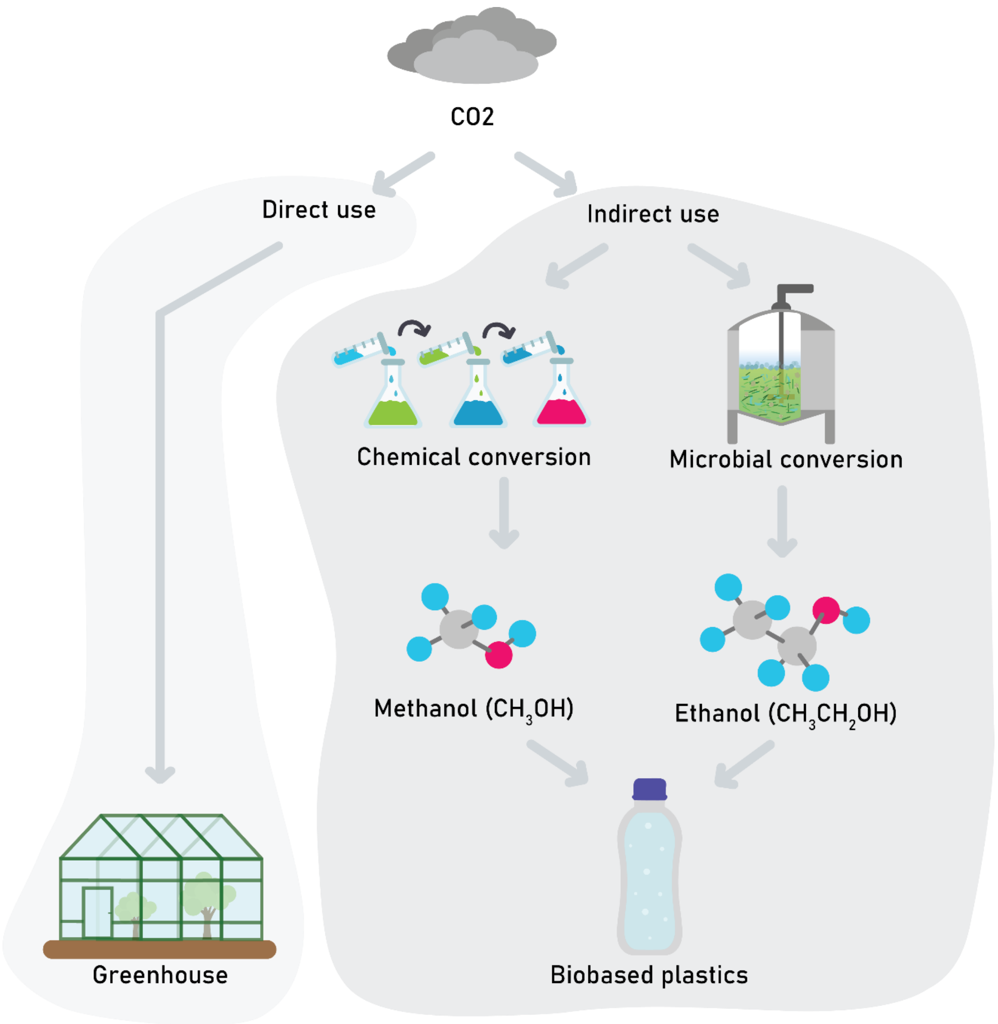

***Figure 2** Schematic overview of three conversion pathways of air captured CO_2. For each pathway a potential chemical building block is shown as intermediate product. These may be used to produce chemicals and materials.*

3.1.1 Direct use

After air capture of CO_2 the molecule can be directly used in several products. Examples of direct CO_2 utilization in various industries are: the production of carbonated drinks such as sparkling water, by infusing CO_2 to beverages at high pressure; carbon dioxide-enhanced oil recovery, where CO_2 is pumped into oil reservoirs to pump up more oil; and the production of supercritical CO_2 as a solvent, which is obtained by maintaining CO_2 at specific pressure and temperature conditions.

3.1.2 Direct use for plant growth

Also greenhouses can be direct users of CO_2 through OCAP (Organic CO_2 for Assimilation by Plants), which yearly delivers 300 ktonne of pure CO_2 to greenhouse horticulture in the Westland, Lansingerland, Delfgauw and Wilgenlei. This saves around 115 million m^3 of natural gas per year, which would otherwise been used to generate heat and CO_2 for the greenhouses, reducing CO_2 emissions by 205 ktonne per year. They get this CO_2 from Shell Pernis that produces it as a side-product from hydrogen production. The CO_2 is transported through a system of pipelines that were previously in use for oil transportation.

3.1.3 Indirect use

Alternatively, besides the direct use of CO_2 in industrial processes or greenhouses, CO_2 can also be indirectly used. CO_2 functions then as a carbon source to produce new materials and chemicals, which involves the conversion by chemical or microbiological routes.

3.1.4 Indirect use through chemical conversion

There are several pathways possible to convert CO_2 into products of greater value, the first step however often involves the breakdown of CO_2 into carbon monoxide (CO), an even smaller molecule. This reaction is not available yet on an industrial scale and very energy intensive. It is done because CO is more reactive and therefore easier to convert into other molecules such as methanol, which can be used as an alternative fuel for ships. These small, single-carbon molecules are called C1 molecules because they contain only one carbon atom. From these C1 molecules, larger molecular structures are built, involving a large number of chemical reaction steps.

3.1.5 Indirect use through microbial conversion

Many organisms can utilize CO_2 through a large variety of biosynthetic pathways. Such pathways always require a significant energy input to catalyse the reactions from CO_2 to biochemicals. This energy can be supplied by an external electron donor (H_2 or CO being the most commonly tested) or (sun)light. Photosynthetic organisms such as algae and cyanobacteria use energy from the sun(light) through photosynthesis and utilize CO_2 to produce sugars and other useful compounds. Those are either stored in the microbial biomass or excreted. Algae for providing polyunsaturated fatty acids in fish feed can be grown photosynthetically, which has been done already for a long time. Other attempt to directly produce chemicals such as ethylene, isoprene and even polylactic acid (Guerrero et al., 2012, Zhou, 2010, Angermayr et al., 2014). While these processes theoretically offer high yields per acre, achieving such efficiency in practice remains challenging due to biological and technological constraints (Anemaet at al., 2010, Liu et al., 2021). Furthermore, the high costs associated with algae production facilities significantly limit the scalability and economic viability of these systems.
Non-photosynthetic bacteria, like *Clostridium autoethanogenum* can metabolize H_2 and CO_2 to produce ethanol and a variety of other products (Wan et al., 2023, Karim et al., 2020, da Souza et al., 2019). Such products are in general excreted by the bacterium allowing straightforward isolation from the fermentation broth, although some such as PHB are produced intracellularly (da Souza et al., 2019). The microbial route presents unique advantages compared to chemical processes, notably the ability to efficiently convert CO_2 directly into complex molecules with minimal side-product formation, due to the high specificity of enzymes (Fackler et al., 2021). Solubility of the hydrogen is a challenge leading to the requirement of recycling of hydrogen from the off-gas. Also, the conversion of gasses to products occurs at rates that are very low compared to current industrial fermentation processes, necessitating large facilities and therefore high investments that in general make the economics on the overall processes challenging.

4 How to select routes for carbon use

There are many options for using CO_2 in novel processes for biobased products and their contribution to - or promise for - the future material transition away from fossil resources. Also, there are many ways to evaluate and compare all options. Many parameters must be considered, including the technology itself, its economy, its environmental impact, and any social, ethical, or regulatory issues associated with using and disposing of a new biobased product (Figure 3).

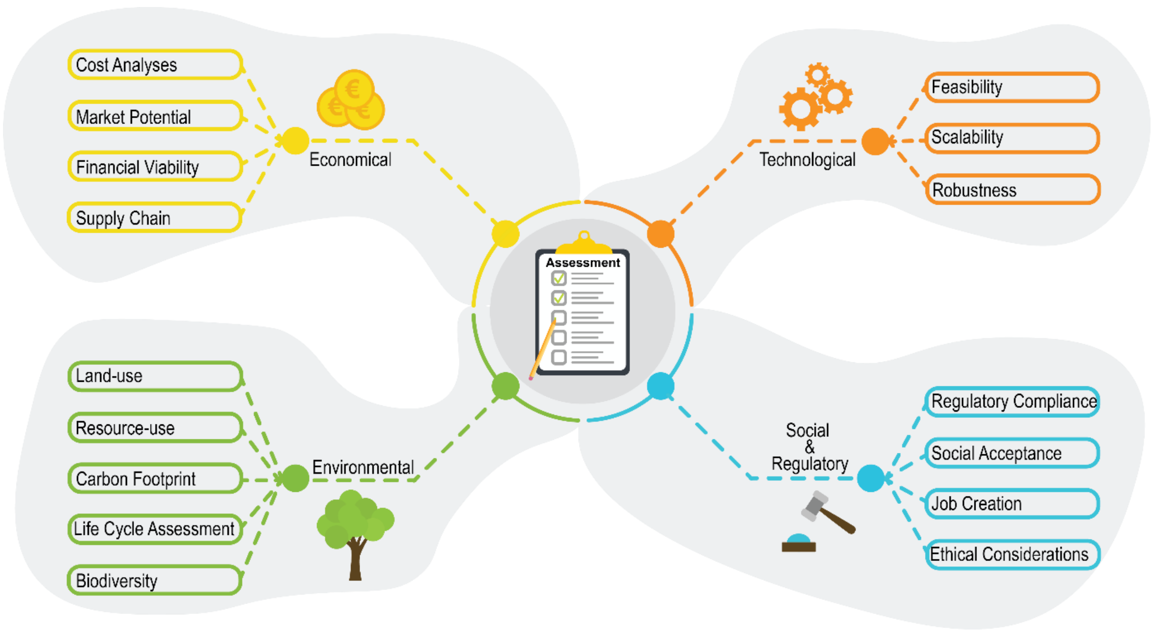

Figure 3 Overview of the key elements of an assessment framework, including examples of economic, environmental, technical and social & regulatory considerations.

As a first step in our assessment of CO_2 use for renewable chemicals, we performed an analysis that focussed on the technical feasibility and energy use, as well as on the economic aspects resulting in a comparative assessment of costs and investments. Land use was included as an additional important sustainability parameter. Methanol and ethanol were selected as examples of molecules that are used as a starting point for other products, also called chemical building blocks.

5 Methanol and ethanol production from CO_2

Methanol and ethanol are important chemicals used in a wide range of applications, including fuels and the manufacturing of medicines, perfumes, and cosmetics. Their supply is essential for many consumer goods, which is why we decided to focus on these bulk chemicals in this project. We compared new, renewable pathways for producing ethanol and methanol from captured carbon with conventional methods for producing these bulk chemicals (Lanting et al. 2025).

5.1 Scenario's for methanol and ethanol production from CO_2

The conventional method for producing methanol involves using natural gas. Natural gas is a fossil fuel and therefore not a sustainable source for methanol due to its finite nature and release of GHGs during processing. Renewable routes that were compared to this conventional production process were the use of biogas from anaerobic digestion of biomass and air captured CO_2.

Ethanol on the other hand is conventionally already produced by fermenting biomass with microorganisms. This route does not require the use of fossil fuels, however, ethanol production competes with other sectors for biomass such as the feed and food sector. This is because biomass used for ethanol production, such as sugar cane, can also be used for animal feed and the land used to grow sugar cane could be used to produce other food and feed crops. Alternative routes explored in this project include the fermentation of biomass residues such as corn stover for second generation fermentation, biogas from anaerobic digestion, and again utilizing air captured CO_2. The routes were compared to each other based on the techno-economic feasibility, energy-use, and for ethanol production also land-use.

The techno-economic results of the three methanol production routes are shown in Figure 4 (adapted from Lanting et al., 2025). CAPEX, raw materials, and High Temperature (HT) heat show the highest costs for the conventional route. For both alternative routes, CAPEX and electricity (assumed 50 €/MWh), especially for the route based on CO_2, show high contributions to the overall costs.

The ethanol results are shown in Figure 5 (adapted from Lanting et al., 2025). Again, the ethanol conventional production route, first generation fermentation, show lowest costs. In this route, main costs are associated with CAPEX and raw material costs, i.e. sugar cane. The highest costs in the second generation route are also CAPEX and raw material costs. For the alternative routes, electricity costs are increased and show high contribution to the overall costs.

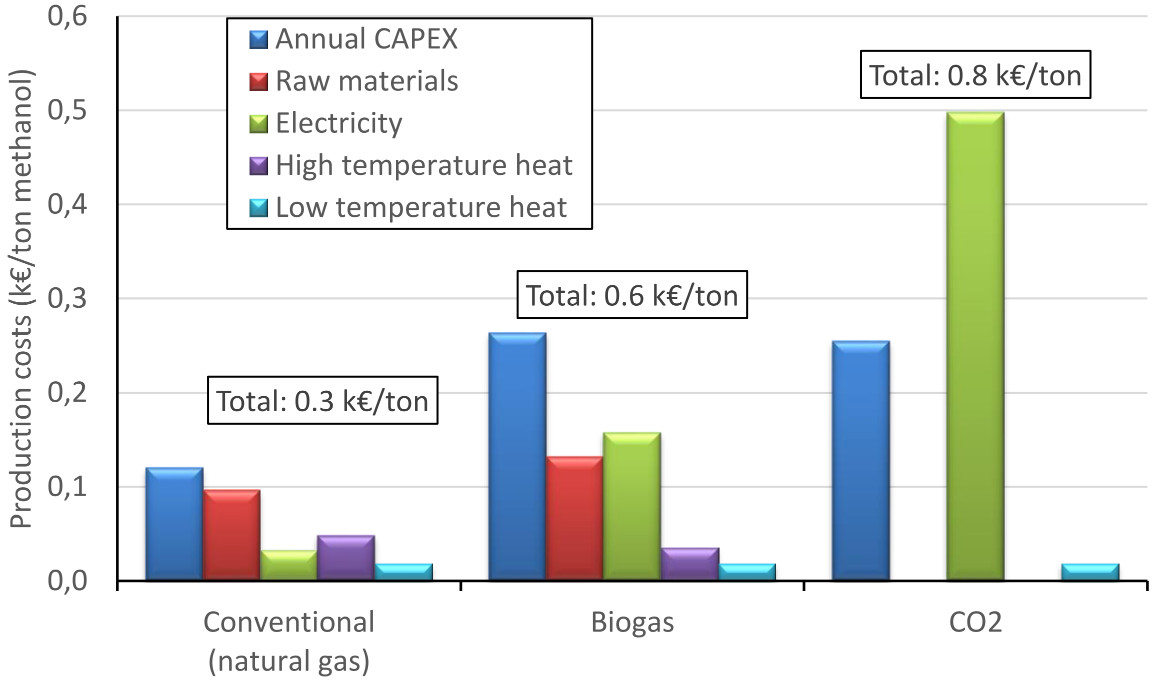

Figure 4 ***Techno-Economic Assessment results of the evaluated methanol production routes (adapted from Lanting et al., 2025). The production costs (€/ton ethanol) are the sum of annualized CAPEX, raw material, electricity, heat (Low Temperature), heat (High Temperature) and consumables.***

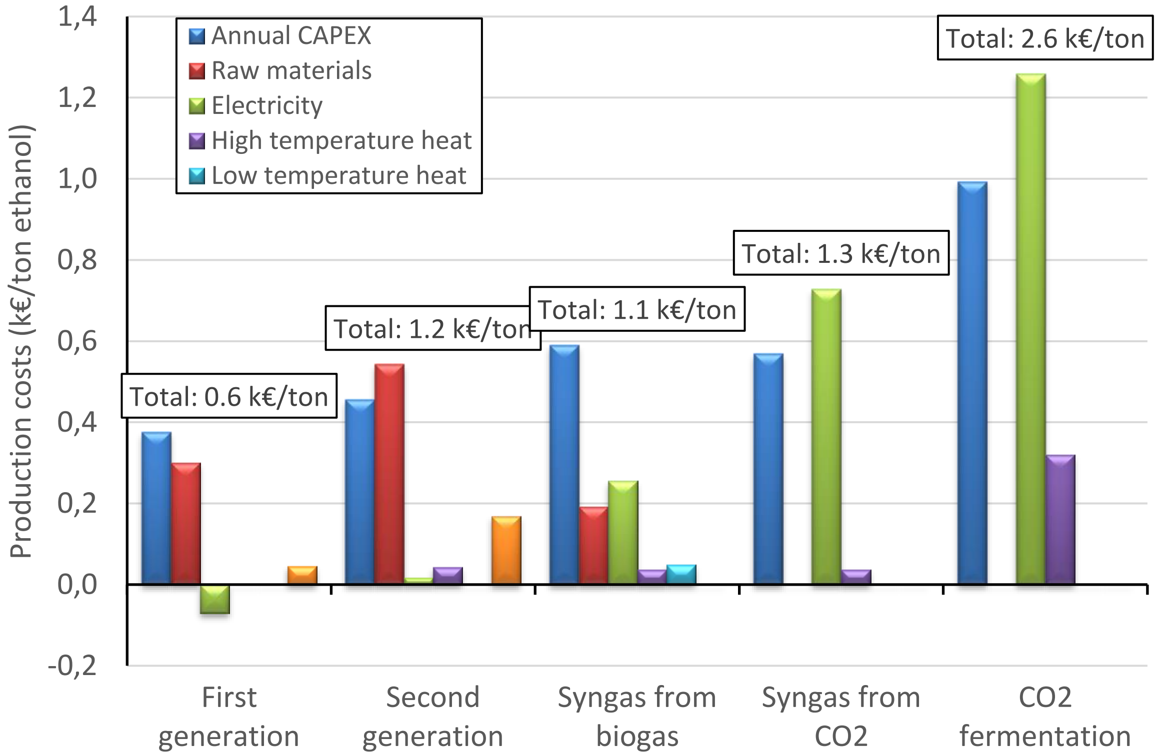

Figure 5 ***Techno-Economic Assessment results of the evaluated ethanol production routes (adapted from Lanting et al., 2025). The production costs (€/ton ethanol) are the sum of annualized CAPEX, raw material, electricity, heat (Low Temperature), heat (High Temperature) and consumables.***

5.2 2050 techno-economic outlook for ethanol and methanol production

5.2.1 Conventional methanol and ethanol production routes will be the cheapest methods to produce methanol and ethanol

The techno-economic analysis of our current situation clearly shows that the conventional routes are the cheapest. Also when technology readiness of the new routes increases, the conventional methanol and ethanol production methods will still be the cheapest routes to produce these bulk chemicals when nothing else changes. We therefore also studied the influence of other factors, such as CO_2 source, energy pricing, CO_2 tax, and land use allocation.

5.2.2 Alternative methanol and ethanol routes require more energy than conventional routes

The conventional methanol production route consumes energy rich fossil methane as feedstock. Conventional ethanol production route uses sugar cane as feedstock. Besides, biomass residues are co-generated to produce electricity, resulting as 'negative' electricity consumption in this study, since the produced electricity is regarded as a by-product. These two conventional routes start thus with energy rich feedstocks. This means that the electricity consumption of these routes is less than the alternative routes, which can also be seen from Figure 4 and 5.

Regarding the alternative routes, the biobased routes are more energy efficient than the CO_2 based routes. This is obvious, as energy is already stored in the biomass/feedstock. Conversion of energy poor CO_2 to energy rich syngas, which is used as intermediate for both methanol and ethanol production, requires much energy (Figure 4 and 5).

It can be concluded that transition towards a CO_2 based society requires much extra energy, whether in the form of hydrogen or not. This leads to the necessary investment in infrastructure.

5.2.3 Incentives, such as CO_2 tax, play an important role in enabling alternative fossil free production routes

In the study of Lanting et al. (2025), different scenarios were outlined. Including CO_2 taxes in the TEA, which would increase the conventional methanol production costs, was one of these scenarios. The alternative route based on biogas would become cost-competitive with the conventional route when CO_2 taxes will reach 145 €/ton CO_2. The route based on CO_2 will become cost-competitive when CO_2 taxes increases to 182 €/ton CO_2. The current carbon tax in Europe is 74 €/ton CO_2 (Trading Economics, 2025). When we adjust the TEA by only considering CO_2 taxes, these routes could become realistic before 2050, as CO_2 taxes are estimated to increase to roughly 750 €/ton CO_2 in 2050 (Matthey and Bünger, 2019, Quinet, 2019).

Table 1 Required CO_2 taxes to reach cost parity for renewable methanol production to the fossil route at different energy prices.

Methanol route via	Required CO_2 tax at 25 €/MWh (€/ton CO_2)	Required CO_2 tax at 50 €/MWh (€/ton CO_2)	Required CO_2 tax at 100 €/MWh (€/ton CO_2)
Biogas	117	145	200
CO_2	101	182	344

5.2.4 CO_2 from point sources instead of DAC is cheaper, a good starting point for cost reduction

Results from the TEA show that CO_2 costs using DAC will be about 125 €/ton CO_2 in 2050. When CO_2 would be obtained from point sources instead, the CO_2 costs could drop to about 60 €/ton CO_2 (Hong, 2022). This possible reduction in CO_2 feedstock costs would lead to a decrease in the overall costs for the CO_2 based methanol route of about 90€/ton methanol. For the CO_2 based ethanol production route, the overall production costs would decrease with 230 €/ton ethanol.

5.2.5 Decreasing electricity costs would make alternative routes more attractive

Another scenario that was outlined, was by adjusting electricity costs. Some people hypothesize that the amount of renewable electricity production will increase in short-term, resulting in a decrease in electricity costs. However, this will require serious improvement of and investments in the current energy infra structure. Lower energy costs would have a significant impact on overall costs of the alternative production routes, since these routes require large amounts of electricity. These energy requirements are mainly linked to obtaining CO_2 from air and converting energy poor CO_2 into energy rich syngas.

Regarding the alternative methanol production routes, only the methanol route based on CO_2 will become cost-competitive when lowering electricity prices. The required electricity price is then 6 €/MWh. The only alternative ethanol production route that could become competitive to the conventional route under this scenario is the CO_2 based syngas fermentation route. This requires electricity prices to fall to 5 €/MWh. However, when combined with CO_2 taxes, cost parity already be achieved earlies as illustrated in table 1.

5.3 Trade-off between costs, energy efficiency, and land-use

Required land-use is another important factor besides costs and energy efficiency for ethanol production routes. Although the conventional ethanol production route is cheap and energy efficient, this route requires (arable) land to grow sugar cane, i.e. 0.2 ha·y/ton ethanol. The same amount of land is needed for second generation route when using corn stover. The alternative routes based on gas fermentation require 0.02-0.06 ha·y/ton ethanol when energy is generated via solar panels and/or for producing biogas from a maize silage/manure slurry. This leads thus to a trade-off between costs and land-use for ethanol production. When we move toward a fossil free society, carbon should be obtained from biomass, CO_2, or via recycling, increasing the pressure on land-use. As land is already used for the current food and feed production, this will only be feasible when there is e.g. a reduction on land-use for feed enabled by a reduction in the use of animal products (the protein transition). Predicted land-use for materials is maximal 5% of the available land, but biofuel production will require much more land (Bos et al., in preparation). This will make the alternative routes via CO_2 even more important in the future.

Across the different alternative pathways investigated, the most promising were the once using biomass residues, regardless of whether methanol or ethanol was produced as the end product. This is because production cost, energy efficiency, and land use were best using residual biomass as a starting source compare to air captured CO_2. One reason for that is that CO_2 air capture and production of syngas from CO_2 are currently still at an early technical developmental stage with a low TRL and require not just great investments, but also great amounts of energy. We calculated using the most positive scenario approximately 59 GJ of electricity is required for 1 ton of ethanol produced. Practically this would mean that to replace current global ethanol production (29.5 billion gallons) with CO_2 produced ethanol about 1450 TWh of electricity would be required (5% of global electricity production). We therefore foresee the greatest short term potential in using alternative pathways based on biogas from residual biomass (e.g. manure and a co-substrate) as these have both limited land use and electricity demand and only minimally affects overall costs.

5.4 Product selection

In this case study, ethanol and methanol were selected to illustrate the potential use of CO_2 for renewable products. However, the selection of the required product will also influence feasibility of a CO_2-based route. An important aspect to consider is the oxidation state of the product. CO_2 contains two oxygen molecules for every carbon molecule. Most products, just like ethanol and methanol, contain relatively less oxygen. the amount of oxygen that needs to be removed to get to the product is important as this requires a lot of energy. (van Vliet et al., 2025) Making chemicals that contain relatively high amounts of oxygen, or even equal amount to CO_2, such as oxalic acid will lead to processes that require much less energy.

6 Conclusions

A techno-economic analysis on conventional and alternative production routes for methanol and ethanol was performed to illustrate the feasibility of using CO_2 as a renewable carbon source. The production processes show trade-offs between costs, energy efficiency, CO_2-emissions and land use. For new routes to be attractive, a combination of CO_2 taxes, CO_2 from point sources, increased fossil raw material prices, and a decrease in electricity costs will be needed. In many cases, conventional fossil routes still show the lowest production costs when comparing to biobased alternatives.

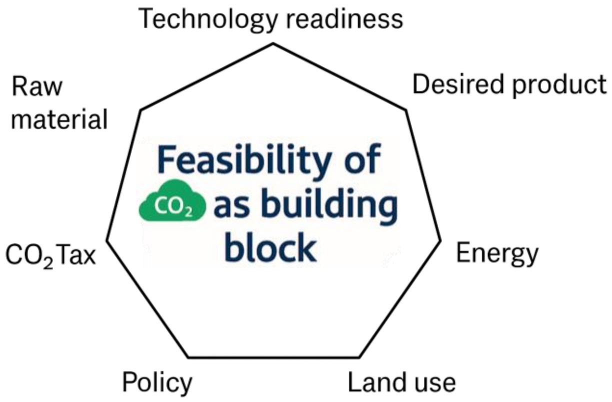

Figure 6 Parameters that interact on the feasibility of using CO_2 as a chemical building block.

The high costs calculated for the alternative methanol and ethanol routes are associated with the conversion of CO_2 to the more reactive, hydrogen enriched, syngas. CO_2 based routes require large amounts of renewable energy. However, there are ways to reduce production costs by lowering energy prices, obtaining CO_2 from point sources instead of DAC, and by implementing CO_2 taxes. The implementation of a carbon tax, starting from around 100 €/ton CO_2 for methanol production routes can be a way to reach cost parity with fossil-based routes. Difference in raw material pricing can also increase the feasibility of the alternative routes. Methanol production from biogas will become feasible at a combined natural gas price of 500 €/ton and a CO_2 tax of 74 €/ton.

Using CO_2 from biogas is the most promising alternative route as identified in the studied cases for methanol and ethanol production. The 1^{st} and 2^{nd} generation processes for bioethanol are limited by the amount of available land to grow the biomass. The level of technology development is an important factor for the alternative routes to become implemented. In the end, there are multiple variables that influence the feasibility of the alternative routes. A combination of market price development and governmental measures can allow for cost parity.

Finally, it is important to consider the type of molecule that you want to produce while using CO_2. The relative amount of oxygen that needs to be removed to get to the product is important as this requires a lot of energy. Making chemicals that contain relatively high amounts of oxygen will lead to processes that require much less energy.

7 A way forward

The intensive use of our fossil raw materials as energy or carbon source fuels climate change through the emission of carbon dioxide (CO_2) during production processes leading to global climate change. Considering CO_2 as renewable carbon source should be part of a sustainable, biobased future, in addition the current focus on biomass use and recycling (figure 7). Biomass is an important attractive starting material as it is a dense C-source. However, the availability will never be enough to fulfil future biobased demands. In addition carbon re-use is needed and all systems need to be circular. Additional CO_2 capture may not only be needed as a carbon source that neutralises CO_2 emissions, but also to restore the environment (mitigate CO_2 increase in the atmosphere).

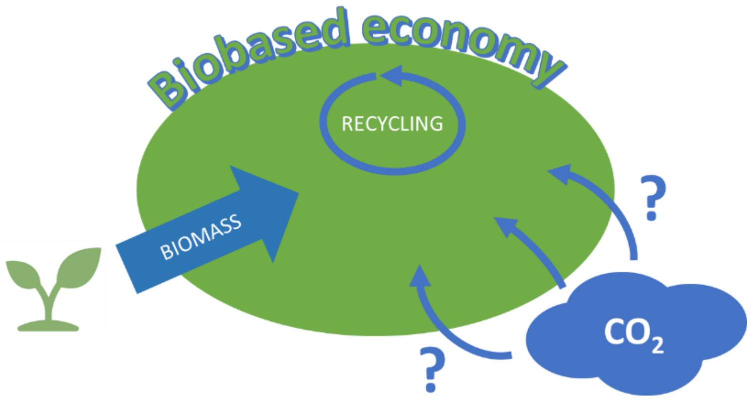

Figure 7 Biomass is an important starting material for the biobased economy. It needs to be complemented by carbon re-use. CO_2 capture may be needed as additional carbon source to meet future demands.

As there is not just one magic bullet, we need to integrate information on availability, technical possibilities, specific demand and economic factors. Potential feedstock use (primary, secondary, tertiary) and their synergies and trade-offs need to be taken into account. A high-over systems-approach should be combined with detailed calculations on techno-economics, sustainability and circularity to get to new insights in chain development and better choices in routes for CO_2 capture and use (CCU). These new systems should not just be improved versions of the old ones, but we need to redesign systems to develop future materials and chemicals that are sustainable and recyclable. End-of-life solutions should become an integral part of production and use.

The new developments can have many unintended side-effects. Increased competition for cheap biomass and waste will drive the price for biomass. The actual allocation of land-use will have to be reconsidered in LCA models to compensate for the better use of side-streams. The new systems are also likely to operate on a smaller scale than the current fossil based system. Sources from the agri-food domain and their processing are diverse and often require a local approach, considering where to install new systems. Point sources within agri-food can e.g. be a starting point for the design of new chemical or microbial routes and chains for CCU starting from digesters or crop processing.

Next to the technological improvements that may be provided by science and industry, other stakeholders are at least equally important. The motivation from consumers and the commitment of NGOs are needed to direct policy makers and industry towards more sustainable alternatives. Current subsidies on fossil fuels are hampering a level playing field. Education and communication are important tools to inform all stakeholders and get everyone on the same (sustainability) page.

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